Artificial Intelligence in RoboCup

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Abstract. From the RoboCup Website: "The Robot World Cup Initiative (RoboCup) is an attempt to foster AI and intelligent robotics research by providing a standard problem where wide range of technologies can be integrated and examined. For this purpose, RoboCup chose to use soccer game, and organize RoboCup: The Robot World Cup Soccer Games and Conferences." The aim of the paper is provide an AI research perspective on RoboCup, based on the experience gained as the team leader of ART, the Italian Robot team which partecipated in RoboCup-98 and 99 Middle-size League.

1 INTRODUCTION

RoboCup has been launched a few years ago [32] as a framework for testing research ideas in the design of cooperative-multi agent systems.

Since then, RoboCup has been very successful in organizing 3 World Championships [46, 8, 17, 18], with associated scientific Workshops [30, 6, 36] and several local events, including promotional and educational activities.

RoboCup [7] is nowadays regarded as a *landmark* project which identifies "playing soccer" as a standard problem to be faced by research in the field of Intelligent Robotics and has the rather challenging long-term goal of building robots that play soccer as humans.

The scientific scope of RoboCup spans over the fields of Robotics and Artificial Intelligence and, in this paper, we admittedly regard RoboCup mainly from the standpoint of Artificial Intelligence.

There are several motivations for getting involved in the design and development of a RoboCup team, the most significant ones being the following.

First of all, it poses interesting scientific problems and after 3 years of exciting competitions, it is possible to identify some outcomes of the research carried out in RoboCup.

Secondly, Robocup is very attractive for students, giving them with strong stimuli to work in Intelligent Robotics and providing them with a significant experience of competitive project work.

In this paper, we present a research perspective on RoboCup based on the experience gained in building Azzurra Robot Team the Italian national team of robots which partecipated in the Middle-size league of RoboCup-98 and RoboCup-99.

The paper is organized as follows: we first provide some detail on RoboCup, by describing the league structure; we then discuss the overall research goals, activities and results; next we focus on our own experience by first describing the ART team organization and then addressing some research issues that we have been pursued in designing our robotic soccer players.

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2 ROBOCUP

RoboCup [23] organizes several kinds of competions: computer simulated soccer and soccer played by mobile robots, in which there are further differentiations based on the size and on the equipment of the robots.

The *Simulation* league is played by computer programs. Each team is formed by 11 players, each of them implemented by a separated program. The simulation is run by a Soccer Server [29]. Each player has limited resources both in terms of sensing and in terms of motion capabilities. Communication among players is allowed and provides the basis for the development of cooperative strategies.

The *Small-Size* league is played on a ping-pong table by 5 real robots, whose size is 15 cm^3, approximately. The sensing capabilities rely mainly on a global vision system which allows for tracking in real time the robots in the field. Communication is allowed.

The *Middle-Size* league is played within a 5x9 meters field and the body of the robot must be within a cylinder of 50 cm diameter and 80 cm height. The teams are composed by 1 goal keeper and 3 middlefield players and are distinguished by cyan and magenta markers. The ball is a size 4 orange (size 4 is the standard for indoor soccer). All sensing devices must be onboard the robots, in particular global vision as well as other external sensing devices are not available.

The *Legged Robot* league has been introduced in 1999 and is played by 3 four-legged robots: the SONY Aibo [53]. The field has a slightly bigger size than the Small-size one and it is equipped with additional color markers. The Aibos have on board a color camera and their mechanical structure provides 18 degrees of freedom. A programming environment, together with the basic functionalities to control the robot is provided. The Aibo can execute programs that are previously stored on a memory stick and do not have wireless communication.

More recently, RoboCup has been considering new kinds of competitions. RoboCup Rescue [34], concerning the design of systems to search and rescue for large scale disasters, and RoboCup Junior, involving younger generations in robot design and implementation on toy-like commercially available platforms.

The long term goal of RoboCup is to build a humanoid robotic team [31] and a humanoid league is expected to start in 2002.

Below we provide a few additional details on the Middle-size league, also called F-2000, since it is more closely related to the scope of the present paper.

The distinguishing feature of the robots of the Middle-size league, the largest today competing, is the autonomy of the players, which is imposed by the constraint that all the information on the playing environment must be acquired through sensors that are positioned on board of the robot. Therefore, a team can be regarded as a multiagent robotic system, each of whose robots can process the data coming from sensors and select the most appropriate playing actions, coordinating them with those performed by the teammates.

Even though some of the teams in the Middle-size league are based on high bandwidth communication for implementing centralized control systems, most of the teams are designed as fully distributed systems, carrying on board not only the sensing devices but also all the computational power. In addition, a significant role is played by kicking devices, which can enable the robot both to move the ball more efectively and to develop coordinated actions.

Building a robot with the above capabilities requires a significant effort and needs different kinds of competences. Consequently, a large number of teams chose to start with commercially available robotic platforms. However, the hardware capabilities of the available products do not match the requirements for playing soccer in RoboCup and adapting robotic platforms is a time and resource consuming task as well. It is worth noticing that, even though some robot manufacturers have provided some RoboCup oriented devices, designing ad hoc solutions can provide a player with additional features that can lead both to a better performance and to interesting technical insights.

3 RESEARCH PERSPECTIVE ON ROBOCUP

In this section we first briefly look at the challenges that are being pursued through the RoboCup initiative and then hint at some of the scientific contributions originated from RoboCup, mainly focussing on the Middle-size league.

3.1 Research challenges

The scientific goals of RoboCup have been presented in several papers [32, 4, 35, 33, 7], where specific research goals have been set for different leagues.

In the simulation league all the constraints deriving from actual robot implementation are hidden from the designer, who can therefore concentrate on agent modeling; therefore, the relevant research issues are team work and multi-agent systems. In particular, the simulated environment is well suited for the application of learning techniques both on the single agent modeling and on the collaboative strategies.

Obviously, when real robotic players are considered, issues such as perception arise, that are not dealt with by the simulated environment. Particular emphasis is given to the problem of sensor fusion when information comes from different sensing devices. Two other main issues concerning physical agents are: the individual agent skills in performing soccer tasks such as ball control, obstacle avoidance when this conflicts with gaining ball possession; the multi-agent system behaviour. On the one side, the Small-size league seems more suitable for this purpose, because coordination can be based on reliable data concerning the position of the robots and of the ball. On the other hand, coordinating a multi-agent system, where there is a fully distribued processing of the sensory input and thus there are many possible sources of errors, appears to be a rather challenging problem.

3.2 Research work

The research work developed within Robocup has been described in the RoboCup Workshops held during RoboCup competitions [30, 6, 36]. In addition, research work originated from RoboCup has been published in many scientific venues. While we refer specifically to a few of the contributions that have appeared in the literature, mainly concerning the Middle-size league, there is no attempt to provide a complete coverage. For a more comprehensive list of references see [43].

- *Vision and Perception.*
  Vision and Perception are obviously of interest for real robot leagues. In the Small-size league the centralized vision system can provide fast and reliable information on the game.
  Vision in the Middle-size league is considered as the main source for acquiring information about the objects in the field. However, several kinds of sensors have been used to increase the performance in the tasks of object recognition, obstacle avoidance, localization.
  We recall that localization amounts to knowing the robot's pose (position and orientation) in the environment. This is a crucial feature for autonomous robots performing complex tasks over long periods of time and it is thus a main requirement for mobile robots involved in the Middle-size league.
  Vision work has been addressing the design of specialized settings, such as omnidirectional vision systems and multiple camera settings. The real time constraints of image processing can be successfully met both with specialized hardware and with processing on conventional machines [2, 9, 13]. Anyways, the amount of information that is extracted from the images ban be very different and context dependent special processing is sometimes performed.
  The use of other sensors such as those that are typically used for navigation, such as sonars, bumpers, infrared sensors, raises the problem of sensor fusion.
  On the other hand, the use of laser range finder combined with inter-robot communication has been shown extremely effective both for robot localization and for tracking opponents and teammates [20, 21].
- *Learning.*
  Learning approaches are being applied to many problems arising in all the leagues of RoboCup and using several techniques: genetic programming, reinforcement learning, neural networks.
  In the simulation league, we find proposals for learning basic skills, learning cooperative behaviour, learning opponents' behaviour among others. Such forms of learning can also be combined in a layered learning approach [50], according to a task decomposition structure.
  In the Middle-size league, learning collaborative behaviour has been attempted using genetic programming [52] and using a multiple reward criterion taking into account both individual and global factors, so to avoid the situations where individual behaviours are conflicting [51].
- *Control Architectures.*
  Robot soccer players embody different kind of sensing and acting devices. The flow of data from the sensors to the actuators is processed by several different modules and the description of the interaction among these modules is usually referred to as the architecture.
  The architecture issue spans over all RoboCup leagues. From the architecture viewpoint the RoboCup teams can be regarded as reactive and deliberative. We recall that the term ”reactive” denotes that the robot reacts directly to the stimuli coming from the external environment, often without embodying a model of the surrounding world, which, conversely, characterizes the deliberative robots.

While the RoboCup settings requires the development of systems that exhibit both reactive and deliberative capabilities, a reactive behaviour can have a very good pay-off [54], and certainly the effectiveness of the hardware significantly impacts on the robots' performance. On the other hand, the need for a deliberative component is shared by most of the approaches that can be characterised as hybrid, since they try to combine reactive and deliberative features [38, 14].
The design of the control system, which is typically accomplished using various specialized languages for real time control, happens to be an important issue in all leagues. Moreover, some of the techniques for implementing behaviour-based control may be difficult to apply, beacuse of the dynamics of the environment [24]. In this respect, both the cited machine learning techniques as well as novel approaches to behaviour engineering have been pursued [12].

- *Multi-agent systems.*
Coordination of robotic agents with distributed control is considered as one of the central research issues in RoboCup competitions. In a highly dynamic and uncertain environment such as the one provided by RoboCup games, the centralized coordination of activities underlying much of the work in Robotics does not seem to be adequate. In particular, the possible communication failures as well as the difficulty of constructing a global reliable view of the environment, require full autonomy on each robot.
Coordination in multi-agent systems and team work in the context of RoboCup have been faced in the simulation league [22, 40, 50, 39], it has a central role because of the high number of players. In the small size league coordination can take advantage of the availability of global information on the game status, because a centralized vision system and computation is used [49]. In the Middle-size league, although the number of players is smaller, coordination among the players is still a critical issue [55], because the dynamics of the game make it necessary to avoid interferences among players' actions and because of the difficulty of reconstructing global information about the environment. In addition, learning methods have been proposed [5], in order to achieve coordination without communication, which is also viewed as implicit communication.

4 ART: AZZURRA ROBOT TEAM

At the beginning of 1998, based on an actual project proposal, Consorzio Padova Ricerche decided to provide the funding to build a national Italian team for RoboCup mid-size league.

The project was called Azzurra Robot Team. In this paper we shall refer to the work done in 1998-1999 [42]. Besides the realization of a competitive team to partecipate to Middle-size RoboCup league, ART aims at developing research activities that qualify from a scientific viewpoint the Italian partecipation in RoboCup and to set up education activities to foster student involvement in research and experimental activities in the field of mobile robotics.

ART qualified for the quarter finals in RoboCup 1998 and obtained the second place in Stockholm (1999). The project was actually developed in two stages, corresponding to the partecipation in the competitions held in July 1998 [45] and August 1999 [44].

ART is formed by players that have been developed by 6 research groups, operating in various Italian universities, and therefore constitute a multiagent robotic system that is heterogeneous both from the hardware and from the software viewpoint.

ART has been realized after the design of a Robot Player implemented in the first phase of the project and made by the following components: a mobile basis equipped with wheels; a conventional PC for onboard computation; an image acquisition system with a color camera positioned in different ways in diffrent players; a wireless communication system; a pneumatic kicking device with different kinds of actuators; in addition, other sensing devices have been added which vary in typology and configuration. The features of this basic player represent a fundamental stone for the success of the team. The technical solutions implemented in the basic player proved to be extremely effective in comparison with those taken by other competing teams.

Starting from the basic player, in the second phase of the project, several prototypes have been implemented that have different features both from a hardware and from a software point of view. ART partecipated in the competition held in Stockholm with a robot goalkeeper TinoZoff (Parma), fully renewed with respect to the one used in RoboCup98 and 6 middelfield players, Bart, Homer (Padova), Rele' (Genova), RonalTino, TotTino (Roma "La Sapienza") and Rullit (Politecnico Milano). ART thus forms a multi-agent, heterogeneous robotic system, in which the robots coordinate their behaviour through a distributed coordination protocol. In Stockholm ART was the only team to adopt this kind of architecture.

5 OUR RESEARCH EXPERIENCE IN ROBOCUP

In this section we look more closely at the issues that we have directly addressed in our experience in RoboCup within the ART team and, more specifically, within the research group at "La Sapienza".

In particular, here we focus the following topics:

- *Architecture.* We developed our robot soccer players by relying on a hybrid architecture including a cognitive, deliberative level and a reactive, operative level.
- *Localization.* We proposed a robust and efficient method for the player self-localization based on the Hough-transform representation of data coming from vision.
- *Cognitive Players.* We regard our robot players as cognitive robots. We have developed a formalism for characterizing the actions of the robots and generate plans that can lead to the achievement of a given goal.
- *Coordination.* In RoboCup-99 the ART team provided a concrete, successful running example of cooperation among heterogeneous robots, which have a fully distributed control.

Other scientific contributions developed within the ART team, that we will not specifically address here, are concerned with the acquisition of information through vision [1, 3, 11], the perception/action cycle [10], the implementation of programming environments for robot control [48, 41].

5.1 Architecture

In our robots we adopt a heterogeneous layered hybrid architecture [27], with two levels: the *deliberative* (cognitive) level, in which a high-level state of the agent is maintained and decisions on which actions are to be performed are taken, and the *operative* (reactive) level, in which low-level conditions on the world are verified and actions are actually executed. The central issue in devising hybrid architectures is to provide an effective integration of reasoning and reactivity.

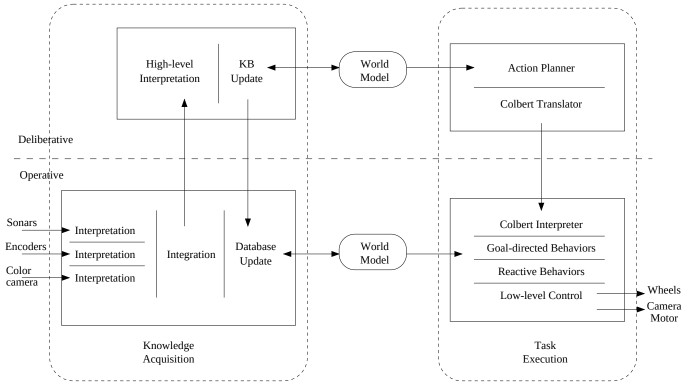

Figure 1. Layered architecture for the robot soccer player

The software architecture of the robot soccer player is shown in Fig. (1). The deliberative level is constituted by a knowledge base containing a description of the dynamic system, together with information about the state of both the robot and the environment. The operative level is based on a geometrical representation of the environment and a set of values characterizing the internal data of the robot, and is represented as a data base of objects properties.

The main features of the architecture we adopt for the implementation of reasoning and reactivity are *heterogeneity* and *asynchronism*. Heterogeneity refers to the use of many different techniques, for example a fuzzy reactive controller, together with a knowledge representation system and low-level image processing routines. Asynchronism is essential for an effective integration of reasoning and reactivity. Indeed, asynchronous architectures, allow time-critical modules to have processing time available when needed. In our case this has been obtained by forcing the system to give control to low-level modules every 100 ms.

The different levels of the representation are characterized by the degree of abstraction of data representation. Thus, Knowledge Acquisition and Task Execution are performed over the two levels. Two kinds of data run across these levels: the first one, representing *perceptual data*, goes from the sensing devices to the deliberative level through a high-level interpretation process, and the second one, representing *action data*, goes from the deliberative level to the actuators. In addition, conclusions drawn at the deliberative level may require the update of the world model of the operative level.

The actions in the operative level are expressed as control programs in the Colbert language, that can be directly executed by the Saphira system [37], which controls the mobile base. Such programs are generated by the planner (possibly off-line) and turned by the Colbert translator into sequences of actions, or, more generally, into execution structures (including behaviours and low level control actions), that are handled by the Colbert interpreter. In subsection 5.3 we consider more closely the techniques used for the cognitive level.

The basic feature of this architecture is thus the presence of different representations (at different degree of abstraction) of the same information on the environments. We consider the relationships between the two world models to be a critical element for the development of cognitive agents, since updating a logic-based knowledge base can require high computational time and affect reactive abilities.

5.2 Localization

In the Middle-size league, localization is a critical problem, since global positioning sensors are not allowed. This is especially true for those approaches that attempt to build an explicit model of the state of the robot (i.e. excluding the purely reactive ones).

The Middle-size RoboCup environment assumes the following characteristics that must be considered for the choice of localization methods: (i) the geometry of the walls delimiting the field and of the lines drawn on the field are known, (ii) the environment is highly dynamic (there are many robots and the ball moving in the field); (iii) the task must be performed continuously for a "long" time (the length of each period is 10 minutes); (iv) the environment cannot be modified; (v) crashes among robots are possible. All these factors determine a difficult scenario for localization methods. Indeed, dead reckoning methods are not effective for localization, since they accumulate errors over time and they cannot deal with crashes among players. On the other hand, absolute positioning methods must consider the high noise in acquiring information from the environment due to varying conditions during data acquisition (e.g. other robots moving around).

We proposed a localization method [25], that is based on matching a geometric reference map with a representation of range information acquired by the robot's sensors. The method exploits the properties of the Hough Transform for recognizing lines from a set of points, as well as for calculating the displacement between the estimated and the actual pose of the robot. The Hough Transfom enables for a representation of lines that makes the matching process computationally fast and robust to noise.

The proposed technique applies to any robot equipped with sensors that can give range information about the environment (ultrasonic sonars, laser range finders, vision and stereo vision systems, ecc.), and it can be effectively applied in indoor office-like environments, and specifically in those environments that can be represented by a set of segments.

In the RoboCup environment we have used vision-based line extraction procedures as a range data sensor and the implementation of our localization method in the robot soccer players, properly integrated with other classical positioning methods, has been sufficiently fast and accurate [28]. Moreover, the use of a vision-based range sensor allows for the application of method even if current boards in the field are substituted by lines on the ground (that will be eventually done in the RoboCup competitions).

5.3 Cognitive players

In the past years we developed a formal framework for representing the actions of a robot and reasoning to derive an executable plan to achieve a given goal and applied it on top of a cognitive mobile robot [19]. The framework originates from Propositional Dynamic Logics and exploits their formal correspondence with Description Logics. In [26] an extension of such a framework is presented including both concurrency on primitive actions and autoepistemic operators for explicitly representing the robot's epistemic state. The resulting formal setting allows for the representation of actions with context-dependent effects, sensing actions, and concurrent actions, and properly addresses both the presence of exogenous events and the characterization of the notion of executable plan in such a complex setting.

The proposed framework has been implemented in a system which is capable of generating plans that are actually executed on mobile robots operating in office-like environments. The system has also been used to describe the knowledge of robotic soccer players. In the implementation, the output of the planner is used to generate Colbert activities (control programs), that can be directly executed on the mobile base.

Spcifically, we have been able to formalize at the logical level several situations arising in the RoboCup scenario and to generate, through the planner, a significant portion of the control programs that were executed on our soccer players.

The introduction of a system that generates plans with concurrent actions requires the robotic architecture to be able to schedule and manage concurrent behaviors and to provide synchronization among such behaviors. Concurrent plans are actually executed on a single player by making use of the Saphira built-in mechanisms for activating concurrent behaviors and for monitoring their end before starting the next action in the plan. The execution of global concurrent plans (that concern more than one robot) is instead realized by means of explicit communication among players. Observe that in this case all the players share the same plan, and each player is able to identify the actions that must be executed. For example, the execution of the action $A_1||B_2$ is obtained by performing A on $P1$ and B on $P2$ and by a broadcast notification when actions terminate. In this way, all the robots involved in the global plan can detect when it is possible to start the next action in the plan.

5.4 Coordination of heterogeneous multi-robot systems

We have already pointed out that the idea of the Middle-size league is that robots are autonomous, since each robot acquires the information about the game only through on board devices. While a centralized approach is possible, in most cases each robot control is fully distributed. Moreover, due to the difficulties of reconstructing precise and reliable information about the environment (with the exception of [20]) coordination in the Middle-size league needs to be achieved without laying down drastic prerequisites on the knowledge of the single players, but typically relying on explicit communication to exchange information among the players. However, due to the frequent communication failures the robots must depend neither on communication, nor on information provided by other robots.

ART is composed of different elements developed in various Italian universities. Because of this kind of organization, the players differ both in the hardware and in the software. Consequently, coordination among the ART players requires not only a distributed coordination protocol, but also a very flexible one, that allows the coach to accommodate the various configurations that can arise by forming teams with different basic features.

Consequently, the hypotheses underlying the coordination problem that we have faced are:

1. *Communication-based coordination:* exploit the use of communication among the players to improve team performance.
2. *Autonomy in coordination:* the players are capable to perform their task, possibly in a degraded way, even in case of lack of communication.
3. *Heterogeneity in the multi-agent system:* the players are heterogeneous both from hardware and software viewpoints.

Besides the above constraints, coordination in ART has been designed to deal both with roles (defender, attacker etc.) and with strategy (defensive, offensive). While the strategic level is currently demanded to an external selection (the human coach), roles are dynamically assigned (see [50]) to the various team elements during the game, depending on the configuration present on the field.

In the design of the coordination system, it is necessary that each team member relies on information received from other members. However, in this way, it is unavoidable that measurement errors, sensor noise, network failures, and other possible malfunctionings of one element in the system cause the deterioration of the overall performance of the team. One of the most difficult issues to face in the design of the coordination system was to determine, experimentally, a suitable solution for the interpretation and usage of the information coming through the net.

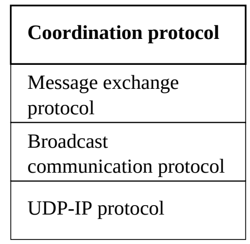

Figure 2. Protocol levels in coordination

The communication among players is built on top of a layered communication structure shown in Figure 2. Accordingly, the requirements a robot of the ART team must fulfill to be able to coordinate itself with the teammates are to have the same communication apparatus (net card) and the ability to handle correctly the set of protocols.

The distributed coordination method has been successfully employed by all the members of the ART team during the 1999 RoboCup competition [47, 15, 16]. The effectiveness of the method has been proved by the fact that we were always ready to substitute any robot with another one, without endangering the coordinate behaviour of the overall team.

Therefore, the goal of coordinating through a distributed protocol a multi-agent system, formed by heterogeneous components, not only has been achieved, but actually provided a substantial contribution to the overall performance of the ART team. A key step that made coordination successful was the experimental work carried out in order to attain the desired coordinated behaviour. Performing the experimental activities that support the realization of a coordination protocol is practically very demanding, but necessary to accommodate the diversities arising from players developed by different groups.

From a technical viewpoint, the proposed protocol is based on the explicit exchange of data about the status of the environment and is based on simple forms of negotiations. Simplicity in the protocol stems from the need to make rather weak assumptions on each robot's capabilities. An increase of such capabilities would lead to more complex protocols. However, we believe that a major issue in coordination is to find a suitable balance between the robot individual capabilities and the form of cooperation realized.

6 CONCLUSION

In this paper we have addressed research in Artificial Intelligence carried out within the RoboCup initiative, focussing in particular on the Middle-size league of autonomous robots and on the experience gained through the development of the national Italian team ART. We have discussed some of the challenges and briefly addressed some of the research results. Overall, we believe that the RoboCup framework is well suited for developing interesting research work in Artificial Intelligence and it will be even more so in the future.

Besides research, there are a few other issues that are worth to be mentioned, that are related to our partecipation in RoboCup and we address them below.

From the standpoint of RoboCup, ART has proposed a ”national” team model with contributions from various university sites. This model has led to scientific and technical success: ART showed the ability to realize competitive robotic football players, but foremost the ability to blend in a single national team methodologies and implementation techniques individually developed by the research groups. In this respect, the work done on the issue of coordination, leading to the definition of communication and coordination protocols used by the ART players, has been both very challenging and very successful. Finally, collaboration/competition achieved in the project has been essential to the final results, since it allowed for a project development with a tight interaction and exchange of results, compared to conventional research projects.

The realization of the robots of the ART team has involved about 40 students from the universities belonging to the project. They have been a major resource of the project and the main investments have been dedicated to them, through schools (“Scuola di Progettazione di Robot Calciatori”, Roma, February 1999, RoboCup CAMP 2000, Padova February 2000), through several preparation meetings at the national level, where the technical solutions developed within the projects were presented and carefully evaluated, and, finally, through the partecipation in the competitions held in a scientifically qualified international environment. In addition to the conventional lectures, such activities allowed the students to interact with colleagues and teachers of other academic institutions and discuss their own ideas in a very stimulating and competitive framework. The overall training experience for the ART students has no counterpart in the Italian university curricula.

The costs of developing a Middle-size team are not negligible as compared to the funding that Universities and other agencies can provide for education and research. In our case, the Consorzio Padova Ricerche made ART possible, buying a large portion of the equipment used in the project.

We believe that the appreciation of the RoboCup initiative, that combines, in a very attractive fashion, education with the development of basic research in Artificial Intelligence, can bring in the field new ideas, new resources and new funding.

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