ARTIFICIAL INTELLIGENCE AND ROBOTICS

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1 Introduction

Artificial Intelligence and Robotics have a common root and a (relatively) long history of interaction and scientific discussion. The birth of Artificial Intelligence and Robotics takes place in the same period ('50), and initially there was no clear distinction between the two disciplines. The reason is that the notion of "intelligent machine" naturally leads to robots and Robotics. One might argue that not every machine is a robot, and certainly Artificial Intelligence is concerned also with virtual agents (i.e. agents that are not embodied in a physical machine). On the other hand, many of the technical problems and solutions that are needed in order to design robots are not dealt with by Artificial Intelligence research.

A clear separation between the fields can be seen in the '70, when Robotics becomes more focused on industrial automation, while Artificial Intelligence uses robots to demonstrate that machines can act also in everyday environments.

Later, the difficulties encountered in the design of robotic systems capable to act in unconstrained environments led AI researchers to dismiss Robotics as a preferred testbed for Artificial Intelligence. Conversely, the research in Robotics led to the development of more and more sophisticated industrial robots.

This state of affairs changed in the '90s, when robots begun to populate again AI laboratories and Robotics specifically addressed also less controlled environments. In particular, robot competitions[1] started: indeed they played a major role in rehestablishing a strict relationship between AI and Robotics, that is nowadays one of the most promising developments of research both in the national context and at the European level.

Summarizing, the borderline between the work in Artificial Intelligent and Robotics is certainly very difficult to establish; however, the problems to be addressed in order to build intelligent robots are clearly identified by the research community, and the developement of robots is again viewed as a prototypical case of AI system [29]. Following the title of the paper we shall refer to this body of research as AI Robotics.

We conclude this brief introduction with a disclaimer: the views presented in the paper are those of AI research, that use robots as a preferred model of intelligent agent and there is no attempt to provide a comprehensive survey. In the recent years, Robotics researchers have also tackled some of the issues that are dealt with in the present paper, but the view of Robotics research towards Artificial Intelligence may not be properly reflected in the paper.

The paper is organized as follows. In the next section we address the major scientific issues in the field. Then we look at the connections and relationships with other topics addressed in this collection, and with other disciplines. Afterwords, we present some application scenarios that have been developed by the research in Italy.

2 Research issues

In this section we analyse the recent work which can be characterised as AI Robotics, by arranging it into the two basic issues in robot design: Action and Perception.

2.1 Action

While there is nowadays a general agreement on the basic structure of the autonomous agent/robot, the question of how this structure can be implemented has been subject to a long debate and is still under investigation.

Agents and, specifically, robots, usually present various kinds 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 defines the *agentÕs architecture*.

The first, purely deliberative, architectures [12, 22] view the robot as an agent embedding a high-level representa-

[1] See, for example, AAAI robot competitions and challenges (www.aaai.org) and RoboCup competitions (www.robocup.org)

tion of the environment and of the actions that it can perform. Perceptual data are interpreted for creating a model of the world, a planner generates the actions to be performed, and the execution module takes care of executing these plans. In practice a sense-plan-act cycle is repeatedly executed. The problem is that building a high-level world model and generating a plan are time consuming activities and thus these systems have shown to be inadequate for agents embedded in dynamic worlds.

Reactive architectures focus on the basic functionalities of the robot, such as navigation or sensor interpretation, and propose a direct connection between stimuli and response. Brooks's *subsumption architecture* [4] is composed by levels of competence containing a class of *task-oriented behaviors*. Each level is in charge of accomplishing a specific task (such as obstacle avoidance, wandering, etc.) and the perceptual data are interpreted only for that specific task. Reactive architectures, while suitably addressing the dynamics of the environment, do not generally allow the designer to consider general aspects of perception (not related to a specific behavior), and to identify complex situations. In fact, the use of a symbolic high-level language is not possible, since it would necessarily require building a world model, and thus reasoning is usually compiled into the structures of the executing program. The lack of previsions about the future limits these systems in terms of efficiency and goal achievement.

The above considerations led to a renewed effort to combine a logic-based view of the robot as an intelligent agent, with its reactive functionalities. To this end a new research field is developing in the last years: *Cognitive Robotics*. The name was first introduced by the research group at the University of Toronto led by Ray Reiter [19]. The most recent view of cognitive robots, that has been accepted, for example in the EU framework, certainly keeps the original goal of embedding a reasoning agent into a real robot, but also takes a more general perspective, by looking at the perception/action cycle in a broader sense, in bio-inspired systems, as well as in the work on recognition and generation of emotional behaviours (see next section). Cognitive Robotics aims at designing and realizing actual agents (in particular mobile robots) that are able to accomplish complex tasks in real, and hence dynamic, unpredictable and incompletely known environments, without human assistance. Cognitive robots can be controlled at a high level, by providing them with a description of the world and expressing the tasks to be performed in the form of goals to be achieved.

The characterizing feature of a *cognitive robot* is the presence of cognitive capabilities for reasoning about the information sensed from the environment and about the actions it can perform. The design and realization of cognitive robots has been addressed from different perspectives, that can be classified into two groups: action theories and system architectures.

Action theories A number of theories of actions have been developed in order to represent the agent's knowledge. They are characterized by the expressive power, that is the ability of representing complex situations, by the deductive services allowed, and by the implementation of automatic reasoning procedures. Several formalisms have been investigated starting from Reiter's Situation Calculus [27, 13]: A-Languages (e.g., [14]), Dynamic Logics (e.g., [11]), Fluent and Event Calculi (e.g., [8]).

The proposed formalisms address several aspects of action representation including sensing, persistence, nondeterminism, concurrency. Moreover, they have been further extended with probabistic representations, representations of time etc. However, much of the work carried out on action theories has been disconnected from applications on real robots, with some notable exceptions. (see for example [5, 3, 7, 11]). A more popular approach to action representation on robots is based on decision making techniques, which maximise the utility of the actions selected by the robot, depending on the operational context [29]. However, this approach does not provide an explicit representation of the properties that characterize the dynamic system, while focussing on the action selection mechanism.

Architectures There are many features that are considered important in the design of agents' architectures and each proposal describes a solution that provides for some of these features. Approaches to architectures that try to combine symbolic and reactive reasoning are presented for example in [1, 26] as so called *Hybrid Architectures*. We can roughly describe a layered hybrid architecture of an agent with two levels: the deliberative 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 level, in which conditions on the world are verified and actions are actually executed.

The *embodied intelligence* approach generalizes Brooks's ideas (see e.g., [32], [25]). The robot is a real physical agent tightly interacting with the environment and the robot behavior is generated not by the robot controller alone, but it emerges by means of the interactions between the robot with its body and the environment.

Other contributions to the realization of robot architectures come from evolutionary computing, where *evolutionary robotics* is a research field aiming at developing robots through evolutionary processes inspired by biological systems [23]. For example, neuro-fuzzy systems have been successfully used in the design of robot architectures.

Often, the work on architectures is developed in the context of robot programming environments, including ad-hoc specialised control languages. Most of this work is more concerned with engineering aspects and will not be addressed here.

2.2 Perception

Robot perception is a prominent research field in AI and Robotics. Current robotic systems have been limited by visual perception systems. In fact, robots have to use other kinds of sensors such as laser range finder, sonar, and so on in order to bypass the difficulties of vision in dynamic and unstructured environments.

A robotic agent acting in the real world has to deal with rich and unstructured environments that are populated by moving and interacting objects, by other agents (either robots or people), and so on. To appropriately move and act, a robot must be able to *understand* the perceptions of the environment. Understanding, from an AI perspective, involves the generation of a high-level, declarative description of the perceived world. Developing such a description requires both *bottom-up*, data driven processes that associate symbolic knowledge representation structures with the data coming out of a vision system, and *top-down* processes in which high-level, symbolic information is employed to drive and further refine the interpretation of the scene.

To accomplish its tasks, a robot must be endowed with selective reasoning capabilities, in order to interpret, classify, track and anticipate the behavior of the surrounding objects and agents. Such capabilities require rich inner representations of the environment firmly anchored to the input signals coming from the sensors. In other words, the meaning of the symbols of the robot reasoning system must be anchored in sensorimotor mechanisms.

On the one side, the robot vision community approached the problem of the representation of scenes mainly in terms of 2D/3D reconstruction of shapes and of recovery of their motion parameters, possibly in the presence of noise and occlusions, in order to control the motion of the robot. This approach is known as *visual servoing* of robot system [10]. On the other side, the AI community developed rich and expressive formalisms for image interpretation and for representation of processes, events, actions and, in general, of dynamic situations, as mentioned in the previous section.

However, the research on robot vision and on AI knowledge representation evolved separately, and concentrated on different kinds of problems. On the one hand, the robot vision researchers implicitly assumed that the problem of visual representation ends with the 2D/3D reconstruction of moving scenes and of their motion parameters. On the other hand, the AI community usually did not face the problem of anchoring the representations on the data coming from sensors.

Starting from the seminal paper of Reiter and Mackworth [28], some proposal have been made in this research field, a few of them briefly described below.

The main steps toward an effective cognitive vision system for dynamic scene interpretation have been recently discussed [20] by adopting a fuzzy metric temporal Horn logic in order to provide an intermediate formalism that represents schematic and instantiated knowledge about dynamic scenes. This conceptual formalism mediates between the spatiotemporal geometric descriptions extracted by video cameras and the high-level system for the generation of natural language text.

A related system [6] is based on three level of representations: the subconceptual, the conceptual and the symbolic level. In particular, the main assumption is that an intermediate representation level is missing between the two classes of representations mentioned above. In order to fill this gap, the notion of *conceptual space* is adopted, a representation where information is characterized in terms of a metric space. A conceptual space acts as an intermediate representation between subconceptual (i.e., not yet conceptually categorized) information, and symbolically organized knowledge.

Some basic primitives (*Find*, *Track*, *Reacquire*) that define the anchoring of symbols in sensory data as a problem *per se* and independent of any specific implementation have been proposed and discussed [9].

In order to define a more general logical account of robot perception linking sensory data to high-level representation, recently an *abductive* theory of perception has been proposed [31]. In this theory, the task of robot perception is to find and explanation of sensory data according to a background theory describing the robot interactions with the environment.

3 Interaction with other AI fields

As already mentioned, the research on AI Robotics intersects a number of subfields of AI. Indeed, the robotic agent can be seen as a main target for the grand goal of Artificial Intelligence, and thus for all the aspects of AI somewhat related to Robotics. Below, we address the main connections with the other AI research topics included in this collection.

Machine Learning Learning approaches are being applied to many problems arising in the design of robots. According to the structure adopted above, both action and perception can be supported by learning approaches. Moreover, several approaches that include a training step are pursued ranging from machine learning approaches to genetic programming, and neural networks.

From the standpoint of action, learning approaches can be used for the basic action skills, specifically locomotion, but also learning cooperative behaviours, adaptation to the environment, and learning opponents' behavior, among others.

Obviously, the learning process must face the challenges of the experiments with real robots. Nevertheless, in several experimental settings (e.g. RoboCup), learning and adaptation of the basic skill, such as walking, vision calibration, have shown to be much more effective than parameter tuning by hand.

Edutainment Toy robots are very promising to be used both for research purposes and for education, because of low costs and high attraction for students. Even though, at this moment, the available educational kits seem to provide too limited capabilities, toy robots are certainly an interesting commercial market. Consequently, the design of intelligent toy robots is an interesting opportunity for AI researchers.

The experience with Aibo robots [33] shows this potential: they have been successfully used by many research groups in the world not only in the RoboCup competitions (Four-Legged League), but also for demonstrating other AI and Robotics research issues.

Multi agent systems A multi-robot system (MRS) can be considered as a multi-agent system (MAS), but the techniques for achieving coordination and cooperation in MAS are often not well suited to deal with the uncertainty and model incompleteness that are typical of Robotics. Multiple robots may achieve more robust and more effective behavior by accomplishing coordinated tasks that are not possible for single robots. Groups of homogeneous and heterogeneous robots have a great potential for application in complex domains that may require the intelligent use and merge of diverse capabilities. The design, implementation, and evaluation of robots organized as teams pose a variety of scientific and technical challenges.

Natural Language Processing It is an obvious requirement of home and service robotics the ability to interact with people in natural language; therefore, natural language processing techniques find an interesting application domain on robots (see for example the RoboCare project below).

Logics for AI and Automated Reasoning The connection to the Logics for AI and Automated Reasoning is central to the work on Cognitive Robotics, but we do not further expand it here, as it is discussed in the previous section.

Evolutionary Computation and Genetic Programming Evolutionary Robotics is a new approach that looks at robots as autonomous artificial organisms that develop their own skills in close interaction with the environment without human intervention. Evolutionary robotics thus applies techniques coming from evolutionary computation.

4 Interaction with other disciplines

Robotics is a multidisciplinary field: to make an operational robot, several contributions from many disciplines are needed: physics, electrical engineering, electronic engineering, mechanical engineering, computer science, AI, and so on. It is therefore difficult also to have a common background of terms, notations and methodologies. In this sense, the efforts to define a common ontology of terms for a robotics science [15] are noteworthy.

In particular, AI Robotics interacts with several research disciplines outside AI.

Industrial Robotics Many contact points may be found between AI, Robotics and Industrial Robotics. In early days there were not clear and cut distinctions between the two fields, as already mentioned. Today, research in Industrial Robotics is oriented towards the safe and intelligent control of industrial manipulators and in the field of service robotics. The methodologies in Industrial Robotics are grounded in Automatic Control Theory [30]. The relationship between the robot and the environment is generally modeled by means of several types of feedback systems. Moreover, methodologies are typically based on numerical methods and optimization theory.

Computer Vision Robot Vision is specific with respect to computer vision, because Robot Vision is intrinsically active, in the sense that the robot may actively find its information sources and it can also reach the best view position to maximize the visual information. Moreover, Robot Vision must be performed in *real-time*, because the robot must immediately react to visual stimuli. In general, the robot cannot process for a long time the same image because the environmental conditions may vary, so the robot has to deal with approximate, but just in time information. Several research topics and debates in this field have strong correlations with AI and Robotics, for example, if a Computer Vision system may be based on inner representation of the environment or it should be purely reactive.

Mechatronics Mechatronics encompasses competencies from electrical engineering, electronic engineering, mechanical engineering. All of these competencies are strictly related to AI and Robotics: the research field of electrical engineering concerns motors and actuators, while electronic engineering mainly concerns boards for robot control, for data acquisition and in general for the hardware that makes the robot operational. Mechanical engineering concerns of course the mechanical apparatus of the robot itself. From this point of view, Mechatronics, AI and Robotics have tight relations: Mechatronics mainly focuses on the robot hardware at all levels, while AI and Robotics take care of the software that makes the robot operative and autonomous.

Embedded Systems The AI software architecture of a robot is naturally embedded into the physical apparatus of the robot. Therefore, the robot software system needs to work in real time in order to guarantee that the robot correctly copes with the changing environment; it must be fail safe with graceful degradation in order to ensure that the robot may operate also in case of damages; the hardware system of the robot must be low power designed to optimize the batteries, and so on. From this point of view, several of the typical challenges of embedded systems are also challenges for robotics systems.

Human Robot Interface The field of Human Robot Interface (HRI) is related to the interaction modalities between the user and the robot. This field may be subdivided into two subfields: the cognitive HRI (cHRI) and the physical HRI (pHRI) [2]. Cognitive HRI analyzes the flow of information between the user and the robot and it mainly focuses on interaction modalities, which may span from textual interfaces to voice and gestures. The interface may be more or less intelligent in the sense that the robot may be constrained by a fixed set of commands or it may interpret a string written in natural language or a sequence of gestures performed by the operator. The interface may also be adaptive in the sense that the robot may adapt to the operator through a suitable training phase. Physical HRI instead concerns the design of *intrinsically safe* robots. The main idea is to interpose compliant elements between motors and moving parts of the robot in order to prevent damages in case of impact, and without performance loss. Hence, cHRI research is closely related to the research of AI and Robotics, while pHRI research is more linked with research in Industrial Robotics.

5 Applications

In this section, we report on a few application scenarios, where the research on Artificial Intelligence and Robotics has been developed in Italy.

5.1 Robotic Soccer

RoboCup started its activity about ten years ago by taking soccer games (football for Europeans), as a scientific testbed for the research in AI and Robotics. Italian researchers gave a significant contribution to RoboCup over the years, both at the organization level and in terms of participating teams. RoboCup 2003 was held in Padova [24], and it attracted more than a thousand participants from all over the world. Below we focus on the leagues, where the Italian participation has been more relevant.

The *Middle-Size* league is played within a 5x9 meters field by 4 wheeled robots per team and the body of the robot must be within a cylinder of 50 cm diameter and 80 cm height. All sensing devices must be onboard the robots, in particular global vision as well as other external sensing devices are not available. The Italian participation in RoboCup was boosted by the creation of a national team, called ART (Azzurra Robot Team) [21], formed by several universities and the Consorzio Padova Ricerche. ART obtained the 2nd place in 1999 and subsequently it was split into several local teams: Golem, Artisti Veneti and Milan RoboCup team.

The *Four Legged Robot* league is played in 4x6 meters field by 4 four-legged Aibo robots. The Aibo have on board a color camera and their mechanical structure provides 18 degrees of freedom. The availability of a standard platform has significantly contributed to the scientific evaluation of the solutions proposed. The SPQR team participated in the competition since 2000 obtaining the 4th place and accessing the quarter finals several times.

Recently, a *Humanoid Robot* league started to approach the ultimate goal of RoboCup to build a humanoid team to play with humans [17]. Humanoid Robotics is currently one of the main challenges for many researchers, mostly focussing on mechanics and locomotion. Politecnico of Torino developed the humanoid robot Isaac that has participated to RoboCup Humanoid League since 2003. IAS-Lab of University of Padova later joined the Humanoid League, with a fully autonomous humanoid robot that uses an omnidirectional visor.

It is worth emphasizing that the ART national model 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 [16], 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.

5.2 Rescue Robotics

Besides soccer, RoboCup promotes other leagues, aiming at the transfer of the research results into socially and industrially relevant contexts. Specifically, RoboCup Rescue [18] aims at the design of systems to search and rescue for large scale disasters. Here we focus on the *rescue robot* league, that aims at the design of robots searching victims in an unknown environment representing a disaster scenario. This kind of application brings in scientific challenges, related to the uncertainty about the environment, that are not present in the soccer leagues. The experimental set up, called *arena*, is being developed in close cooperation with USAR [2]. The arenas have already been used in various experiments (including RoboCup and AAAI rescue competions) and nowadays represent a reference for experimental evaluation of the performance of rescue robots. The current aim of the competition is twofold: mobility and autonomy. As for the former, the research is focussed on the mechanical design that allows the robot to overcome the obstacles present in the environment; the latter is concerned with the design of robots that can autonomously explore the environment, possibly working in a team, build the map, find the victims and locate them in the map.

Two Italian teams participate in these competitions since 2004: the first one from SIED Lab, within a collaboration between "Istituto Superiore Antincendi" and the University of Rome "La Sapienza"; the second one from the ALCOR lab of the University of Rome "La Sapienza", which developed a model-based approach to the executive control of a rescue rover, winning the third award in 2004. The RoboCup activity contributed and benefitted from the results of the research project Simulation and Robotics Systems for Operations in Emergency Scenarios (SRSOES 2003-2005), funded by Italian MIUR [3].

5.3 Space Robotics

The aim of the project *An Intelligent System for the Supervision of Autonomous Robots in Space*, funded by the Italian Space Agency (ASI) during years 1997-2000, is the application of AI techniques to the design and realization of space robotics systems for planetary exploration missions, that require an increasing autonomy. In particular, the aim of this project has been the application of AI techniques to the design and realization of an effective and flexible system for the supervision of the ASI robotic arm SPIDER.

The project was coordinated by the unit at the University of Palermo. Subproject units were the Universities of Roma "La Sapienza", Torino, Genova, Parma, and the research centers ISTC-CNR Roma and IRST-ITC Trento.

The scientific objective of the project is the design and development of an intelligent system able to supervise autonomous robots in space. The system is based on a multi-agent architecture in which each block is a software agent interfaced with the rest of the system. This design choice is motivated by high flexibility, agent interchangeability with consequent easy improvement of the architecture, reuse of all the agents or part of them, or of the architecture itself. The architecture has been designed by keeping in mind the ASI missions; but it is fully general and the single modules and the whole architecture may be easily reconfigured for the supervision of other robotic systems. The project aimed at realizing an innovative research product, and it is complementary to ASI activities.

[2]Performance Metrics and Test Arenas for Autonomous Mobile Robots. www.isd.mel.nist.gov/projects/USAR/

[3]sied.dis.uniroma1.it

5.4 Robotics for Elderly and Impaired People

The goal of the project *RoboCare*[4] sponsored by Italian Ministry of Education, University and Research (MIUR) from 2002 to 2006 is to build a multi-agent system which generates user services for human assistance. The system is implemented on a distributed and heterogeneous platform, consisting of a hardware and software prototype.

The project, currently running, is coordinated by the ISTC-CNR Roma, subproject units are at the Universities of Genova, Torino, Bologna, Parma, Roma "La Sapienza", and at the CNR research centers of Genova, Palermo, and Milano.

The use of autonomous robotics and distributed computing technologies constitutes the basis for the implementation of a number of services in an environment with elderly people, such as a health-care institution or a home environment. The fact that robotic components, intelligent systems and human beings are to act in a cooperative setting is what makes the study of such a system challenging, for research and also from the technology integration point of view.

The project is organized in 3 tasks: the development of a HW/SW framework to support the system; the study and implementation of a supervisor agent; realization of robotic agents and technology integration. Alongside the above research tasks, common usability and acceptability issues are analyzed, contributing to the implementation of SW development, visualization and simulation tools for multi-robot systems.

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