Research on Cognitive Robotics at the Institute of Cognitive Sciences and Technologies, National Research Council of Italy (ISTC-CNR)

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Introduction

The institute of Cognitive Sciences and Technologies of the National Research Council (ISTC-CNR) (http://www.istc.cnr.it/) is the most important Italian research institution on Cognitive Science. It includes more than 60 scientists involved in high interdisciplinary research ranging from cognitive science and robotics to linguistics, and primatology. The headquarters of the Institute are in Rome, but branches of the Institute are also in Padua and Trento.

ISTC-CNR is a "research hub" in Cognitive Robotics as this is the main research focus of several research labs working within it. Interdisciplinarity is one of the key characteristics of cognitive robotics studies at ISTC-CNR. This research involves over 30 people (among researchers, Post-Docs, and PhD students) having different backgrounds (ranging from engineering and computer science to psychology, neuroscience and philosophy) and pursuing research objectives as diverse as (a) the use of computational and robotic models to investigate psychological and neural phenomena, (b) the realization of novel paradigms for robot learning, control, planning, decision-making, team making, and human-robot interaction, and (c) the delivery of novel autonomous robotic technologies that act in real-world scenarios. This interdisciplinary has advantages, in that the broadness of methodologies that we employ, and our extensive networks of worldwide collaborations, allow for significant cross-fertilizations and hybridizations. This is making ISTC-CNR an ideal venue to develop novel ideas and paradigms that eschew the traditional disciplinary boundaries, and permits our research initiatives to have significant impact in several different fields: scientific, social, technological and industrial.

A second key characteristic of cognitive robotics studies at ISTC-CNR is its broad coverage of many interconnected research lines, all of which are at the interface of robotics and cognitive science, and address open problems within them. Hereby we summarize the main research lines that are currently active at ISTC-CNR.

Lines of research

Modeling and implementation of anticipatory, goal-directed, and proactive abilities

Current robotic systems are by far and large endowed with reactive controllers, which permit them to select quickly the most adequate responses for their current stimuli, and to achieve perceptually available goals. At the same time, they have limited abilities to predict the mid- or long-term effects of their actions, and the intrinsic dynamics of the external environment. This makes them less adaptive in open-ended (individual and social) scenarios, in which actions can have deleterious long-term effects, and task achievement can depend on factors that are not perceptually available.

A main research topic at ISTC-CNR concerns the realization of state-of-the-art anticipatory mechanisms for action-outcome and stimulus-stimulus prediction. Predictive abilities make robots more adaptive as they become able to forecast future dangers and opportunities, and to act proactively. In addition to that, anticipatory mechanisms provide the building blocks for the realization of more advanced decision-making, attention control, reasoning, goal-directed action planning and understanding algorithms. This research line links to recent ideas in computational motor control, cognitive neuroscience and psychology, which emphasize that the control, understanding, simulation and imitation of goal-directed actions are mediated by internal (forward and inverse) models (Jeannerod, 2006; Wolpert et al., 1995, 2003), or, almost equivalently, by bidirectional action-effect (ideomotor) codes (Hommel et al., 2001).

The main scientific objective of this research line is to develop theories and technologies for *proactive* and *goal-directed* robots, which can go beyond the here-and-now of current perception and ultimately behave as guided by internally generated goals rather than simply responding to external stimuli. To this aim, we have developed numerous mechanisms for prediction and mental simulations, and implemented them using multiple methodologies, which include connectionist networks, Bayesian networks, and distributed (schema-based) controllers that operate under bounded computational and attention resources (e.g., Pezzulo and Calvi 2007, in press; Pezzulo, 2009). We are adopting our schema-based design methodology in domains as diverse as visuomotor control, robot navigation, multimodal communication, action understanding, and joint action.

A second, broader objective of this research line is extending further the study of predictive mechanisms from sensorimotor to cognitive domains, by pursuing an independent research hypothesis, which can be summarized as: *prediction bootstrapped cognition*. Put in simple terms, we argue that predictive abilities, which originally developed for accurate motor control, have been exapted during evolution and bootstrapped increasingly sophisticated cognitive abilities in individual and social domains, such as prospection, thinking, and action understanding (Grush, 2004;

Pezzulo, 2008; Pezzulo and Castelfranchi, 2007; 2009). The idea that primitive action control architectures of early living organisms provided the foundations for advanced cognitive abilities is of paramount importance for recent theories of grounded and embodied cognition (Barsalou, 1999; 2008; Glenberg, 1997), and indeed there is a strong push in this direction in current neuroscientific and psychological research. It is increasingly recognized that the combined theoretical and cognitive robotic methodology that we adopt is highly complementary to empirical studies. This permitted us to establish strong connections with leading researchers in psychology and neuroscience, with which we are collaborating for the foundations of a novel "embodied cognitive modeling" paradigm for the study and synthesis of higher-level cognitive skills on the top of earlier architectures for sensorimotor prediction and control (Pezzulo, 2011; Pezzulo et al., 2011; see also the special issues on "Anticipation and Anticipatory Behavior" in *Cognitive Processing* in 2007, and on "Intentional Action" in *Psychological Research* in 2009). Our initiatives include also the co-organization of the ABiALS international workshop series on "Anticipatory Behavior in Adaptive Learning Systems", and the realization of a webportal devoted to the study of anticipation and anticipatory behavior (www.anticipatorybehavior.org), all of which are venues for discussion and cross-fertilization between researches of different disciplines.

Evolution of communication and language in populations of robots

Understanding the evolution of communication and human language is one of the hardest problems in science (Christiansen and Kirby, 2003). Of significant research and practical interest is the related artificial perspective: How can populations of robots develop forms of communication of varying complexity, analogous to animal and human communication? This represents a new field of research (Steels, 2003; Nolfi & Mirolli, 2010) that can advance our knowledge about how communication skills originate and evolve in natural organisms and how we can develop autonomous artifacts able to cooperate to solve real-life problems.

Our institute played and still plays a significant role in this area. More specifically: (a) together with other researchers (Steels, 1997; Kirby, 2002) we contributed to elaboration of the theoretical basis of this research area (Cangelosi & Parisi, 2002; Nolfi, 2005), (b) we carried out a large number of experimental studies, (c) we edited the first comprehensive book on the area (Nolfi & Mirolli, 2010).

More specifically, we provided one of the first experimental demonstration of how a stable and reliable communication system can emerge despite the problems caused by the conflict of interest between individuals and the need to develop two interdependent skills that are adaptively neutral in isolation: an ability to produce useful signals and an ability to react to signals appropriately (Cangelosi & Parisi, 1998). We studied the role that different factors (e.g. kin selection and genetic relatedness) have in the emergence of stable communication systems, and we identified a new factor --- the producer bias --- that results as a by-product of the need of the robots to internally categorize their sensory-motor experiences in adaptive ways (Mirolli & Parisi, 2008). We studied how communication systems can progressively complexify during the evolutionary process, how 'signals' and 'meaning' originate and vary (De Greef and Nolfi, 2010). Finally, we studied the role of the co-adaptation of behavioral and communication skills and how embodied concepts are grounded in robots' sensory-motor experiences (De Greef and Nolfi, 2010). We demonstrated the possibility to co-evolve behavioral and communicative skills allowing a team of robots to solve problems which require sophisticated cooperative and/or collaborative skills (Baldassarre et. al., 2007; Trianni et al. 2007; Trianni & Nolfi, 2009, Sperati, Trianni and Nolfi, 2010).

Co-development and integration of linguistic and behavioral skills

Recent theoretical and experimental research on action and language processing in humans and animals clearly demonstrates the strict interaction and co-dependence between language and action (e.g. Rizzolatti & Arbib, 1998; Cappa and Perani, 2003; Glenberg and Kaschak, 2002; Pulvermuller, 2003; Gallese, 2008).

Developmental psychology studies based on emergentist and constructivist approaches also support a view of cognitive development strongly dependent on the contribution of various cognitive capabilities (e.g., Bowerman and Levinson, 2001; MacWhinney, 2005; Tomasello, 2003). They demonstrate the gradual emergence of linguistic constructs built through the child's experience with her social and physical environment. This is consistent with cognitive linguistics approaches (cf. Lackoff, 1987; Langacker, 1987) where syntactic structures and functions, that is, symbolic structures in both lexicon and grammar, are constructed in reference to other cognitive representations.

In recent years, a fruitful exchange of ideas between roboticists and cognitive linguists has begun to develop. On the one hand, more and more language-related research in robotics embraces key ideas of the usage-based language model developed in cognitive linguistics (Goldberg, 2006, Langacker, 2008). Several roboticists explicitly acknowledge this framework as their main theoretical inspiration on the language side (e.g., Dominey, 2006; Hutchins and Johnson, 2009; Wermter et al, 2009). On the other hand, it is becoming more and more common for cognitive linguists to draw on insights and suggestions from work on computational modelling (see e.g., Langacker, 2000; Goldberg, 2009). This is especially evident in the field of language acquisition, where computational modelling has become an ever more prominent aspect of the research agenda of various scientists (see Elman, 2006; Kaplan, Oudeyer, and Bergen, 2008; MacWhinney, 2010, for recent reviews).

During the last few years, we carried out research on the co-development and integration between behavioral and linguistic/categorization skills (Cangelosi et al., 2010). More specifically, in a first series of experiments we studied how an humanoid iCub robot can develop an ability to perceptually categorize functionally different contexts by exploiting sensory-motor coordination (e.g. by exploiting the possibility to actively manipulate the objects to be discriminated (Tuci, Massera, and Nolfi, 2010) or by visually exploring the image to be discriminated (Mirolli, Ferrauto, and Nolfi, 2010). The obtained results demonstrate how these problems are solved by coordinating the sensory-motor process so to experience discriminative stimuli and by integrating the partially conflicting cues provided by such stimuli over time (fundamentally through a simple process of accumulation of evidences). In a second series of studies (Massera, Tuci, Ferrauto, Nolfi, 2010) we investigated how the possibility to access linguistic input that describes the current categorical context facilitate the development of complex manipulation skills (e.g. reaching, grasping, and moving an object) as well as an ability to concatenate such behavioral skills in sequence. Finally, in a third series of experiments (Tuci, Ferrauto, Massera, and Nolfi, 2010a, 2010b, Tuci et al., in press) we studied how an iCub robot can be trained to react to linguistic instructions formed by simple sentences such us "Touch the green object" or "Move the blue object" by producing the corresponding behavior. Moreover, we showed how in certain conditions the robots display an ability to understand the meaning of sentences never experienced before by producing the appropriate behaviors (thus displaying a form of compositional language) by display new behaviors for which they have not been trained (thus displaying the ability to generalize at the level of behavior).

Using robots as models of the brain and behavior, and to design novel architectures and algorithms

Two lines of research use robots as a means to understand organisms' brain and behaviour, and, at the same time, to exploit the knowledge so gathered to design innovative architectures and learning paradigms for autonomous robots. The method used (''computational embodied neuroscience'', see Caligiore et al., in press; Mannella et al., 2010) aims to build models that are strongly constrained by anatomical and physiological data on brain, and by requesting the models to reproduce the detailed results of psychological experiments while acting in an embodied system (robot). This approach has the potential to lead to: (a) a deeper understanding of brain and behavior of organisms; (b) the development of radically novel architectures and learning algorithms for controlling autonomous robots.

A first research thread using this approach aims to understanding the basic principles underlying the autonomy of organisms based on the emotional regulations of behaviour. A major basis of the flexibility of organisms' behaviour relies upon the sophisticated emotional/motivational systems that on one side allow the body to inform the brain on the homeostatic needs of the organism (e.g., level of water and glucose in blood, temperature, etc.), and on the other side allow the brain to regulate various aspects of body (e.g., heart beat, energy expenditure, etc.). These systems play at least two functions for behaviour: (a) they allow the selection of different courses of actions with different internal contexts (body states) and external contexts; (b) they generate learning signals that allow organisms to adapt their behaviours so to improve their survival and reproduction chances. These issues have been investigated with "rat robots" by building computational embodied models of the behaviours exibited by real rats in behaviourist experiments. The studies have led to develop sophisticated models of the amygdala (see Mirolli et al., 2010, for a review) and the way it contributes to produces flexible goal-directed behaviour (e.g. produced by basal ganglia and prefrontal cortex, Mannela et al., 2010), on the basis of internal states and needs. The models so produced allow to understand the brain mechanisms underlying the flexibility of behavior in organisms. Such mechanisms can be also exploited in robots to allow them to adapt their behaviours to the current needs (e.g., energy management, own and user's safety, etc.) and goals (e.g. from the users). They are also important to build devices that guide learning algorithms, for example reinforcement learning algorithms: the autonomous generation of learning signals is indeed a key issue to develop learning intelligent systems with high autonomy.

A second research thread aims to understand how organisms, and especially human and non-human primates, can exploit their motivational systems to undergo an open-ended cumulative learning process, which allows them to acquire increasingly complex skills on the basis of already acquired skills. The long-term goal of this research is to build a new generation of humanoid robots with unprecedented autonomy and learning capabilities capable of autonomously develop complex repertoire of skills and actions. These robots should be capable of learning new tasks, for example tasks useful for the user, very fast thanks to the re-use of the skills previously acquired through the direct interaction with the environment. The working hypothesis is that cumulative learning relies upon three pillars (Baldassarre et al., 2009): (a) the capability of sensory and motor abstraction; (b) the capacity to self-generate learning signals on the basis of intrinsic motivations, such as curiosity and novelty detection; (c) the capacity to build new skills based on previous ones in a compositional way thanks to sophisticated hierarchical and soft-modular architectures. The investigation also involves the primatology group of ISTC to study intrinsic motivations and action learning in monkeys so to inform the models with data and ideas from the study of real organisms. The research uses a humanoid iCub robot to test the designed models in noisy and complex realistic experimental setups. The research is developing novel hierarchical cognitive architectures based on the broad organization of brain (Caligiore et al., 2010, Caligiore et al., in press), a new reinforcement learning paradigm based on a partially abstract encoding of actions (Caligiore et al., 2010a), and new learning algorithms based on intrinsic motivations (e.g., Santucci et al., 2010).

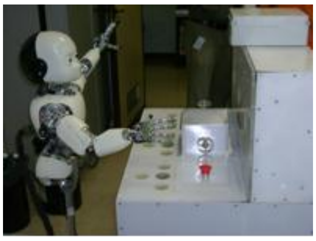

Figure 1: One of the iCub robots available at ISTC-CNR.

Mixed-Initiative between Human and Artificial Intelligent Systems

The laboratory on Intelligent Problem Solving Systems (also called Planning and Scheduling Team) comes from a strong tradition in AI techniques for problem solving with a constant attention to injecting such techniques in software artifact that interact with people to help them solving real life problems. We have a tradition in addressing problem solving not only in abstract very complex scheduling problems but also real cases in medicine, space, etc. This injection effort initially motivated by technology transfer has become a parallel line of research dedicated to the study of Mixed-Initiative Systems (Haller et al., 1999). These systems explicitly consider the pair Human-Artificial System in performing a joint task. A number of interesting issues appear when considering such a pair explicitly, like for example, the need for a shared representation or at least a user-oriented representation, the difference in contributing roles when participating to a joint task, the need to understand rules for the change of initiative, the relevance for producing explanations and rationale for the automated problem solving task to allow the human to insert his own information/decision in his dedicated choice points, etc. Specific contributions are given on the role of personalization (Cesta and D'Aloisi, 1999), the "understandable" problem solving (Oddi and Cesta, 2000), the robust experimentation methodology with real users (Cortellessa and Cesta, 2006). A specific line of work consisted in a collaboration with the European Space Agency to deploy different complete interactive systems to help users in their daily work, for example (Cesta et al., 2007). Out of this experience quite an amout of know-how has been elicited, tested, elaborated and definitely accumulated on the pair Human-Artificial System at work.

Robotic Companions. The experience on "Artificial System" has started to include "Interactive Robots" during the RoboCare Project [2002-2006]. This has been a pioneriing work on the sinthesis of a robotic companion for old people at home (robocare.istc.cnr.it) which represented a new challenge for the interests in *interaction* given the enbodiment of the *artificial artifact*. An interesting set of challenges on the Human-Robot interaction are fostered by this scenario: How the monitoring of person behavior can intersect with the internal representation maintainable by a robot? how to create a common context between human and robot to generate meaningful interactions? How to modulate the level of invasiveness of the technology and where is the boundary acceptable by humans which are not designers of such technology? Which ethical issues are generated by artifacts that are potentially able to move autonomously and register facts in the private environment of a person. Some challenging aspects have been touched upon within RoboCare are both technological, like the continuous monitoring and the generation of simple contextualized speech act (Cesta et al., 2007), and more related to understanding impact of technology on human users, see for example the user evaluation methodology and the results described in (Cesta et al., 2007b).

Current work on Cognitive Robots. We are currently pursuing two separate set of activities with respect to robotics. In the same line of the robot companion we are using more "simple" robotic technology for remote presence (or telepresence) in the ExCITE project (within a Ambient Assisted Living EU initiative). The basic idea is to help developing a technology able to facilitate social interaction of people potentially isolated (in their home or in a health institution) in order to increase their level of social participation thus diminishing the sense of loneliness. Specifically, the project aims at addressing social isolation and reduction of loneliness by bridging distances, facilitating interaction and communication through the use of selected ICT technologies on top of the robotic platform. Specifically, we plan to use a remote-controlled robot, called Giraff, able to move within the home environment and endowed with a teleconferencing system. The robot is operated by a person (relative, caregivers, friends), the client, who wants to contact the old person (user) in his/her living environment (e.g., home, health care institution, etc.) (Cesta et al., 2010). It is worth highlighting how one of the most important aspect within ExCITE project is the idea of using telepresence based on a robotic platform to diminish the sense of loneliness of elderly people and foster their social participation.

Finally we are doing quite an amount of work on developing a robust platform for planning and executing with a explicit representation (in line with a more AI model based representation of a cognitive agent). This is an ongoing work for the European Space Agency in the GOAC project. The Goal Oriented Autonomous Controller (GOAC) is an autonomous controller using a sense-plan-act paradigm to provide increasing levels of autonomy for robotic task achievement. GOAC will generate plans in-situ, will deterministically dispatch activities for execution and will recover from off-nominal conditions. Underlying GOAC is a rich representation that deals with metric time and resources (Cesta et al., 2008; 2010; McGann et al., 2008) necessary for dealing with planning and execution time uncertainty in dynamic environments. It comes with a lower-level functional layer that is tightly integrated with an abstract decisional level all of which have a rich operational legacy with deployments in real-world environments. The system's higher levels of abstraction deal with long-term mission plans that are deliberative; lower levels of abstraction are increasingly reactive. The functional layer is purely reactive with fast reaction times necessary for failure recovery and command dispatch. Additionally a Verification and Validation system ensures compositional correctness by guaranteeing global system properties of system components.

This second activity may seem completely detached from cognitive systems aims. Indeed, independently on the needs of the sponsoring entity the final GOAC architecture, project ends 3rd quarter of 2011, will put available a robust architecture for continuous goal based behavior used as the seed of a more complex goal based architecture for simulating complex agents.

Facilities

To conduct its research, ISTC-CNR has many robotic platforms: 2 i-Cub humanoid robots (see fig. 1); 8 s-bot/foot-bot robots; 20 e-puck robots (provided with ground sensors extensions, omnidirectional vision turret, and color led turret); 2 Pioneer robots; a customized robot hand (with 4DoF). ISTC-CNR has developed numerous open-source software platforms for research, which include an i-Cub simulator, the Evorobot software for running evolutionary robotics experiments (http://laral.istc.cnr.it/evorobot/simulator.html, and http://laral.istc.cnr.it/evorobotstar/), the AKIRA framework for developing distributed architectures (see the Institute webpages for more details). Finally, the facilities at ISTC-CNR include two computer clusters for running simulations.

Current projects at ISTC-CNR

To conduct research on Cognitive Robotics, ISTC-CNR has attracted funds from the EU within the ICT initiatives "Cognitive Systems and Robotics", "Future Emerging Technologies", and "Ambient Assisted Living", from the European Space Agency, Department of Automation and Robotics, and from the Italian Ministry for Education, University and Research, all of which we gratefully acknowledge. Research on anticipatory and goal-directed behavior is funded by the EU through the ICT projects MindRACES (IST-511931; www.mindraces.org), HUMANOBS (ICT-231453; www.humanobs.org), and Goal-Leaders (ICT-270108; www.goal-leaders.eu). Research on language-action integration and evolution of communication is funded by the EU through the ICT projects ECAgents (www.ecagents.org), ITALK (ICT-214668; www.italkproject.org), Swarmbot (http://www.swarm-bots.org/) and Swarmanoid (www.swarmanoid.org). Research on the emotional regulations of behaviour and learning is funded by the EU through the ICT project ICEA (www.iceaproject.eu). Research on cumulative learning is funded by the EU through the ICT project IM-CLeVeR (www.im-clever.eu).

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