Shaping Cognitive Control for HRI through the Dual Process Theory^{*}

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Abstract

Autonomous robots acting in working and social contexts require the development of cognitive capabilities necessary to realize adaptive, contextualized, and safe behaviors. Artificial Intelligence (AI) technologies well-support the implementation of relevant capabilities e.g., decision making, knowledge representation, problem-solving, or learning. The synergetic integration of heterogeneous AI technologies is crucial to endow robots with a "mind" and combine together the functions of cognition necessary to realize effective behaviors. This work discusses recent results concerning the design of a novel control architecture inspired by the Dual Process Theory. The distinction between fast and slow reasoning processes guides the integration of AI modules that reason at different levels of abstraction and "time scales". We show applications of the proposed concepts in healthcare assistance and collaborative manufacturing entailing continuous and adaptive interactions between a human and a robot.

Keywords

Cognitive Robotics, Dual Process Theory, Artificial Intelligence

1. Introduction

Robotics and Artificial Intelligence (AI) are two research areas that historically addressed the challenge (among others) of building embedded intelligent systems capable of acting in a real-world environment [1]. Recent technological advancements in Robotics and AI are pushing towards the design and deployment of *autonomous robots* in increasingly unstructured environments and complex scenarios. A tight integration of Robotics and AI is crucial to allow robots to safely and reliably *act* in the real-world [2, 3]. However, technology integration and deployment of *intelligent robots* in real-world scenarios is still an open research challenge.

Despite the increased reliability of developed technologies e.g., sensing, manipulation, and navigation skills of robots on the one hand, and increased solving and predictive capabilities of AI on the other, moving from structured in-laboratory environments to semi-

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structured/unstructured real-world environments still poses non-negligible research challenges. This is especially true when considering scenarios entailing the co-existence and/or continuous direct/indirect interactions with human users. The presence of a human introduces a significant source of *uncertainty* affecting robot control. The behavior of a human is uncontrollable as well as his/her intentions, desires and objectives. Robot controllers cannot reliably predict actions and behavior of humans and should therefore synthesize suitable *strategies* to carry out actions safely. Furthermore, robot controllers should take into account a number of "non-functional" *qualities* of the resulting behaviors when interacting with humans [4]. Indeed, doing the *right thing* is not always sufficient when robots act in "social contexts". It is seamlessly important to do the *thing right* and reason about *how* a robot should interact with humans [5, 6].

Robot controllers should evolve towards an advanced "Perception, Reason, Act" paradigm to achieve a higher level of *awareness* and *contextualization*. It is therefore necessary to endow robots with a number of cognitive capabilities to implement behaviors that are valid from both a technical and social point of view. In other words, robots *need a mind* to: (i) perceive and build abstractions about the state of the environment; (ii) contextualize their skills; (iii) reason about possible objectives; (iv) synthesize suitable actions and; (v) execute actions taking into account the observed state of the environment and interacting humans.

We propose an AI-based cognitive architecture which takes inspiration from the Dual Process Theory [7]. It organizes a number of AI modules into two reasoning layers (System 1 and System 2) that cooperate to realize flexible and contextualized robot behaviors [8]. These AI modules implement the reasoning processes of the *artificial mind* of a robot. The architecture is the result of research efforts concerning the development (and deployment) of AI-based robot controllers in several Human-Robot Interaction (HRI) scenarios ranging from healthcare and domestic assistance to collaborative manufacturing. The combination of a fast reasoning layer and a slow reasoning layer supports a flexible composition of the underlying AI-modules that realize the needed cognitive capabilities (e.g., decision making, knowledge representation, problem solving, abstraction).

This paper thus focuses on the integration of heterogeneous AI modules whose combination supports the synthesis of flexible robot behaviors. Interestingly, the same architecture would support different acting and interacting styles of a robot (reactive, proactive or deliberative), depending on the different features and needs of a HRI scenario.

2. Towards a Mind for Autonomous Robots

Artificial Intelligence, Cognitive Sciences, Neuroscience and Robotics have all contributed to the understanding of minds by focusing at different levels of abstraction. While Cognitive Sciences mostly focus on understanding cognitive processes and Neuroscience focus on the structure and physiology of the brain (i.e., the physiological and physical correlates of mental processes), Robotics and AI focus on understanding how minds work in order to provide software or physical agents with intelligent behaviors. Although with different perspectives and levels of abstraction, the common objective is to understand and simulate the functioning of a *mind* and the related cognitive functions [9, 10].

According to [11], a mind is a functional entity that can think and thus support intelligent

behaviors. The work [11] indeed represents a first effort aiming at developing a *standard model* of the mind, taking into account a cognitive perspective. From a structural point of view the proposed model is made of a number of independent modules "encapsulating" different (cognitive) functionalities. This section briefly discusses some related works that have addressed the problem of endowing robots with advanced cognitive capabilities. Although from different perspectives, these works show the importance of integrating hybrid reasoning technologies to realize effective, safe, and acceptable behaviors.

2.1. Context Aware Robots

To enhance the level of awareness, robots should be endowed with proper perception and abstraction capabilities in order to *understand* observed situations. To this aim the integration of ontology with AI and robot architectures seems promising. Researchers have investigated different aspects of the reasoning and interaction capabilities of robots and used ontologies to enhance them from different perspectives. The integration of semantic technologies with robot controllers indeed has been widely studied in the literature [12].

Some works for examples have focused on providing robots with knowledge about the objects of the environment in order to enhance manipulation skills or reason about possible use of such object to perform complex tasks [13]. KnowRob [14, 15] is a well-known framework supporting advanced perception, reasoning and control. The framework provides robots with a logical representation of a number of entities ranging from robotic parts and objects (with their composition and functionalities) to tasks and actions. This framework focuses on manipulation tasks and allows robots to perceive objects of the environment, reason about their *affordances* [16], and decide how to use them by synthesizing a suitable sequence of (STRIPS/PDDL) actions [17].

An ontological model characterizing object manipulation tasks of robots has been also considered within the PMK framework [18]. Similar to KnowRob [14, 15], PMK supports a "standardized" representation of the environment defining a "common language" to exchange information between a human and a robot. It also models sensory capabilities to perceive objects in the environment, linking perception outcomes to the ontological models of related objects.

Other works have focused on the "social dimension" of the interactions between humans and robots to realize behaviors that are compliant with *social norms*. The ORO framework [19] develops a knowledge reasoning framework endowing robots with common sense reasoning capabilities to autonomously operate in semantically-rich human environments. ORO addresses the control problem from a cognitive perspective and realizes a general cognitive architecture deployed on different robotic platforms and assessed on different cognitive scenarios [19]. This architecture has been specifically developed to support advanced cognitive skills (e.g., *theory of mind* capabilities) and supports flexible and adaptive human-robot interactions [20].

The work [21] uses knowledge reasoning to represent *social norms* and allow a social robot to implement acceptable behaviors for social tasks. More specifically, the work proposes a formal description of the functional affordances of objects to reason about their possible use and thus infer those that are "socially acceptable" to accomplish the requested social task (i.e., serving coffee to guests using the right object). The work [6] proposes the use of knowledge

reasoning to adapt human-robot interactions to the cultural knowledge of different contexts and people. This is another example of how ontology-based reasoning can enhance awareness of robots by implementing suitable cognitive capabilities. In this case, such capabilities are used to reason about non-functional qualitative aspects of human-robot interactions and synthesize socially-compliant and acceptable behaviors.

2.2. Cognitive Design of Robot Controllers

Several researchers have investigated the development of cognitive architectures based on a *functional model* of the human mind. Following the review [22], a common agreement among AI researchers sees cognitive architectures classified in *symbolic, connectionist,* or *hybrid* ones. *Symbolic architectures* use production rules and represent concepts using symbols that can be manipulated using a predefined instruction set. Although they excel at planning and reasoning, these architectures do not sufficiently support robustness which is necessary to deal with a changing environment and perceptual processing. *Connectionist architectures* address adaptability and learning aspects by building parallel models that are organized in networks. Although effective, the resulting system loses transparency, since knowledge is no longer a set of symbolic entities and is distributed throughout the network. *Hybrid architectures* attempt to combine elements of both symbolic and connectionist approaches, by including both symbolic and sub-symbolic components with the aim to match human cognition.

Within the hybrid architectures category some research efforts have been inspired by the dual process theory and combined symbolic and sub-symbolic components in the attempt to simulate the System 1 and the System 2. The work [23] endows a social robot with a computational explanation module based on two components: a System 1 component (S1) responsible for the fast categorization and for the perceptual based recognition of gestures in a social context, based on deep neural network architecture; a System 2 component (S2) responsible for providing a high level model that can be exploited to extract an explanation about the high level features that characterize the categorized output provided by S1 exploiting an ontology.

Differently, [24] developed a model able to handle both symbolic and sub-symbolic reasoning, by means of an architecture based on two memory systems: (i) a long-term memory, an autonomous system that develops automatically through interactions with the environment, and (ii) a working memory, a memory system used to define the notion of (resource-bounded) computation. The long-term memory is modeled as a transparent neural network that develops autonomously by interacting with the environment, while the working memory is modeled as a buffer containing nodes of the long-term memory. The Clarton architecture instead is a hybrid cognitive architecture with both connectionist and symbolic representations, that combines implicit and explicit psychological processes, and integrates cognition (in the narrow sense) and other psychological processes. Overall, Clarton is a modular cognitive architecture consisting of a number of distinct subsystems, with a dual representational structure in each subsystem [25].

3. Integrated AI for Fast and Slow Reasoning

A key point in the design of cognitive architectures is the management of different source of knowledge and the basic capabilities needed to access and process such knowledge. The work by [9] systematizes a number of cognitive capabilities that are relevant to an autonomous system: (i) recognition and categorization; (ii) reasoning and belief maintenance; (iii) prediction and monitoring; (iv) problem solving and planning; (v) decision making and choices; (vi) execution and action.

Robots need a suitable integration of these capabilities to effectively act in HRI scenarios. Well established AI technologies like *Machine learning*, *knowledge representation and reasoning*, *automated planning and execution* can play an important role in this context. We here propose a *hybrid cognitive architecture* which integrates heterogeneous AI modules following the Dual Process Theory. Figure 1 shows the structure of this architecture, initially introduced in [26].

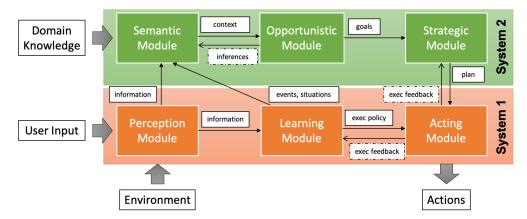


Figure 1: Integration of Fast and Slow AI reasoning modules to support flexible and adaptive cognitive control.

The architecture is articulated into a fast and slow reasoning layers emulating the functioning of System 1 and System 2 of the Dual Process Theory. Both layers consist of a pipeline of AI modules implementing reasoning processes at two different levels of abstraction. Broadly speaking, the System 1 layer supports fast reasoning capabilities that are directly linked to the perception and acting skills of a robot. This layer deals with a high level of *uncertainty* generally given by a non-perfect knowledge of the environment and unpredictable (and uncontrollable) behaviors of humans. Implemented cognitive processes therefore reason on a short time horizon in order to realize (fast) reactive behaviors.

The System 2 layer supports slow reasoning capabilities that are directly linked to domain knowledge and the objectives of a scenario. This layer relies on semantic abstractions and models of the dynamics (either physical or social) of a HRI domain. It generally pursues an optimization perspective aiming at synthesizing interaction strategies (or plans) to achieve complex goals. Goals can be "manually" set by domain experts or opportunistically inferred by System 2 taking into account observed situations.

The reasoning processes implemented by System 1 and System 2 work in parallel and both contribute to the synthesis of robot behaviors. Depending on the domain and observed situations one can see a particular System "dominating" the other leading to behaviors with different features. In general, a robot follows a *deliberative behavior* when the System 2 predominates on System 1. Vice versa, a robot would follow a *reactive behavior* when the System 1 predomi-

nates on System 2. This structure supports a flexible synthesis of robot behaviors that can be dynamically adapted to the evolving state of the environment.

3.1. Deliberative Behavior

The System 2 is composed by AI modules mainly relying on symbolic technologies ranging from *knowledge representation & reasoning* and *automated planning*. The integration of these technologies according to the pipeline of AI modules in Figure 1 (System 2) implements deliberative reasoning suitable to contextualize robot acting skills and synthesize plans that achieve complex goals in the "long term". The *Semantic Module* encapsulates domain knowledge and contextualize information, events and situations collected by data streams processed by the System 1. This module thus builds and continuously refines an abstraction of the scenario integrating knowledge about the social context, robot capabilities, features and needs of human users and operational requirements. The *Opportunistic Module* implements goal reasoning capabilities to dynamically evaluate *affordances* and opportunities of action that may lead to the achievement of new or additional goals. This module enriches knowledge reasoning by integrating contextual knowledge about the (sub)set of goals that can be actually achieved by the robot in a *known* scenario.

The reasoning processes carried out in conjunction by the *Semantic Module* and the *Opportunistic Module* support personalization and contextualization of robot behaviors. From a HRI perspective, they allow a robot to autonomously reason about *who* is the target of the interactions (e.g., human user), *which* objectives are suitable in a given scenario and *how* such objectives should be achieved by the robot, taking into account social, human and technical perspectives. Inferred (and selected) goals are then passed to the *Strategic Module* which is in charge of deciding *which* actions are necessary and *when* they should be executed. This module relies on automated planning technologies in order to optimize strategies/plans according to a number of metrics (either general or domain specific). The reasoning processes of this layer are slow since they process symbolic information and generally span over a long time horizon.

The outcome of the reasoning processes implemented at System 2 level are passed to the System 1 in shape of plans characterizing desired robot behaviors from a high abstraction level. The System 1 is then in charge of physically implementing this behavior by synthesizing planned actions in physical operations/interactions performed by the robot in the real-world. System 2 thus provides System 1 with a general description of the behaviors that should be implemented to achieve complex (domain relevant) objectives.

3.2. Reactive Behavior

The System 1 is composed by AI modules mainly relying on sub-symbolic technologies ranging from *machine learning*, *natural language processing*, *computer vision* and other control-related technologies e.g., *motion/path planning* or *autonomous navigation*. The integration of these technologies according to the pipeline of AI modules in Figure 1 (System 1) implements reactive reasoning suitable to allow a robot to perceive the environment, receive input and physical interact with objects, humans and other domain entities. These modules support the interacting skills of the robot controller. They should therefore realize fast reasoning processes to quickly

adapt physical behaviors of robots to exogenous events and unknown/unexpected states of the environment. These capabilities are crucial to safely interact with humans and carry out long-term deliberated plans in a reliable way. Examples are reasoning and data processing capabilities necessary to avoid obstacles during robot navigation or avoid collisions with humans during the execution of robot motions.

The *Perception Module* elaborate inputs from users and streams of data gathered from sensing devices to produce clean and useful information. Depending on the specific needs of a HRI scenario, this module would thus encapsulates data fusion techniques to process data from multiple input channels e.g., robot camera, input voice or text, environmental sensors etc. Produced information would be used by System 2 for knowledge abstraction and by the *Learning Module* to infer patterns and similar situations. Namely, this module would thus enrich perception capabilities of the robot with an *associative network* suitable to incrementally build "experience" and autonomously recognize recurrent events or situations.

Learned experience is useful at both System 2 and System 1 level. System 2 would consider *learned patterns* in the deliberative process and thus synthesize in advance plans that are reliable with respect to possible (known) situations. System 1 would consider such patterns to enhance the adaptation of robot behaviors and thus generate more accurate polices leading to more efficient and robust behaviors. These policies are indeed used by the *Acting Module* which is in charge of dealing with the physical implementation and actual execution of the actions composing the plans synthesized by System 2. The reasoning processes implemented at System 1 level thus decide the best way of execution actions according to the observed state of the environment (included the observed behavior of human users).

4. Enhancing Human-Robot Interactions

The architecture of Figure 1 is the result of research efforts concerning the development (and deployment) of AI-based robot controllers in HRI scenarios ranging from healthcare [27, 28, 29] to manufacturing [30, 31, 32]. We made a first attempt of integrating the developed reasoning capabilities within a "Dual Process" inspired architecture with the work [26].

We first investigated cognitive control for reconfigurable manufacturing systems to endow a number of transportation modules with a level of *self-awareness* suitable to autonomously adapt their capabilities to the evolving state of a production context [32]. Although not in HRI, this work gave us the possibility of investigating the integration of perception, knowledge reasoning and planning for the synthesis of flexible robot behaviors in a multi-agent setting [33]. Perception data from transportation modules were interpreted and contextualized into a knowledge base following a formal ontological model of agents' capabilities. Each transportation module (i.e., agent) was thus capable of autonomously infer the set of transportation capabilities supported according to its configuration and local topology (i.e., local connections with other transportation modules). This knowledge was automatically synthesized in a planning model to support dynamic reconfiguration of each agent and reliable functioning of the whole system.

We have then further investigated this first result evolving towards a cognitive approach for the synthesis of flexible behaviors. In collaborative manufacturing, we have investigated the integration of knowledge reasoning, perception, task and motion planning to realize optimal, safe and human-aware collaborative processes [34, 31, 30]. In healthcare assistance, we have investigated the integration of knowledge reasoning, planning, learning and natural language processing to realize personalized, proactive and adaptive assistance to human users [27, 35, 29]. These results all rely on the integration of heterogeneous AI modules based on a two-layered structured as the one proposed in Figure 1. Next subsections discuss with more details the different features of the robot behaviors implemented in the cited works and show how the proposed architecture (and the underlying AI modules) realizes the needed cognitive capabilities.

4.1. Human-Awareness and Personalization

Human-aware and personalization are two *qualities* crucial for the effective interactions between the human and the robot. Cognitive processes supporting these qualities mainly work at System 2 level of the designed architecture. The *Semantic Module* of Figure 1 should be enriched with domain knowledge suitable to characterize the relevant features of humans, interaction capabilities of robots and the way they affect these features.

Depending on the application scenario we have developed ontological models suitable to completely characterize relevant knowledge. In manufacturing for example we have integrated a domain ontology into the *Semantic Module*. The ontology characterizes production dynamics of collaborative scenarios and working skills of robots and human works [36]. The integration of this knowledge with the *Strategic Module* and underlying planning technologies allows a robot to reason about: (i) production operations necessary for accomplishing collaborative tasks; (ii) the set of operations the human and the robot could perform according to their skills; (iii) most suitable allocation of tasks/operations taking into account expected *qualities* concerning the execution of assigned operations (e.g., average execution time, time variance etc.). Resulting collaborative plans are then executed through the *Acting Module* to physically control robot motions and coordinate them according to the observed behavior of the human. The integration of these two modules thus allows a robot to adapt the synthesis of collaborative processes according to the *known* skills and qualities of their human working fellow [34].

In healthcare assistance we have developed a *Semantic Module* integrating a domain ontology of cognitive impairments of persons in order to personalize cognitive stimulation therapy [35, 28]. The ontology encapsulates a formal description of the ICF classification ¹ and allows a robot to characterize the *functioning* of human users and automatically infer *impairments*.

The *Opportunistic Module* then matches health impairments of users with stimulation capabilities of robots (e.g., known cognitive stimulation exercises) to generate recommendations about the (sub)set of exercises that best fit the stimulation needs of a user. This module in particular introduces the concept of *affordances* to reason about *opportunities of stimulation* resulting by matching assistive capabilities of robots and health needs of users [28]. The *Strategy Module* then further elaborates this knowledge and generated recommendations to synthesize personalized interventions. Intervention plans consist of stimulation exercises that are administrated to a user through the *Acting Module* of System 1 layer. The administration of such exercises indeed requires fast adaptation capabilities in order to deal with user feedback [29].

As shown in [35], these reasoning capabilities in particular allow a robot to support decision making of clinicians. On the one hand, the developed *Semantic Module* allows a robot to

¹https://www.who.int/standards/classifications/international-classification-of-functioning-disability-and-health



Figure 2: Administration of personalized cognitive stimulation through a social robot

understand user knowledge obtained through standard screening procedures like the Mini-Mental State Examination (MMSE) and build suitable *user profiles*. On the other hand, the resulting reasoning mechanisms allow a robot to effectively support therapists in making decisions about how to "shape" interventions.

4.2. Proactivity and Adaptation

The integration the *Perception Module*, *Learning Module* and *Semantic Module* within System 1 and System 2 layers allows a robot to continuously "monitor" the state of the environment and (autonomously) evaluate the opportunity of performing actions and thus achieve goals. This integration supports qualities like *proactivity* and *adaptation* that are crucial to reliably and effectively act in real-world scenarios.

In the context of domestic assistance to seniors through social robots for example we have developed a *Perception Module* to integrate data streams gathered from environmental sensing devices [27]. Obtained information (*observations*) are then collected, interpreted and contextualized by the *Semantic Module* which maintains a semantic module of the house and state of both the user and the robot. The *Opportunistic Module* further reasons about this knowledge in order to identify situations or conditions requiring the proactive execution of some actions or assistive routine by the robot. Examples are situations concerning the health state of the user (e.g., anomalous heart rate) that would trigger warnings and procedures to assist the user through the robot. This triggers would thus generate goals that are give to the *Strategic Module* which generates suitable assistive plans executed through the *Acting Module*.

Considering again a scenario of cognitive stimulation, the reactive capabilities of System 1 are crucial to adapt robot behaviors to the evolving state of human supporting effective (and engaging) interactions [29]. Given a personalized stimulation plan generated by the System 2 indeed the integration of *Perception Module*, *Learning Module* and *Acting Module* at System 1 level is crucial to effectively carry out the execution of such a plan, dealing with the evolving state of a human user. The administration of cognitive exercises and the adaptation of the way a robot interact and stimulate a person would be dynamically adapted to the feedback and to the perceived state of the user (e.g., mood, personality traits, etc.). This level of adaptation is



Figure 3: Contextual interpretation of environmental sensors for proactive domestic assistance

crucial to achieve engaging and effective interactions between the human and the robot.

4.3. Cooperation and Optimization

Discussed HRI scenario see the robot and the human interacting together while playing two distinct and different roles. In scenarios like collaborative manufacturing instead the human and the robot can be seen as two peer agents working together to achieve a common objective. In this context the proposed architecture supports a flexible and adaptive coordination between the human and the robot [31, 30]. The distinction between the two reasoning levels well support the design of advanced task and motion planning capabilities suitable to reason about working skills of the two working fellows, optimize collaborative process and safely execute planned actions. Reasoning processes at System 2 level mainly deal with domain knowledge concerning production procedures and known skills of the human and the robot. According to this knowledge the integrated *Semantic Module* and *Strategic Module* optimize the resulting collaborative process. The *Strategic Module* in particular reasons about possible assignments of tasks/operations to the human and the robot following a multi-objective optimization of the whole process taking into account both cycle time and risk of collision.



Figure 4: Coordination of human and robot skills within collaborative processes in manufacturing

The *Acting Module* then in combination with the *Perception Module* executes planned actions taking into account feedback and the observed behavior of the worker. In particular, the *Acting*

Module implements safe procedures to control robot motions avoiding collisions with the human.

5. Conclusions

This work proposes an AI-based cognitive architecture inspired by the Dual Process Theory. The architecture is the result of research efforts concerning the development (and deployment) of AI-based robot controllers in different HRI scenarios. The combination of a fast reasoning layer and a slow reasoning layer supports a flexible composition of the underlying AI-modules that realize the needed cognitive capabilities. The proposed architecture systematizes the integration of AI modules developed to support flexible and adaptive interactions and collaborations between humans and robots. We show how the proposed composition supports both deliberative and reactive behaviors of the robot that can be dynamically adapted and "interleaved" according to the specific application needs. Future works will further investigate the design and integration of AI modules leading to a modular robotic architecture evaluated on different robotic platforms and working scenarios.

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