Artificial Mental Imagery in Cognitive Robots Interaction

A review and future research directions

Alessandro Di Nuovo [a,b] and Angelo Cangelosi [a]
[a]School of Computing, Electronics and Mathematics, Plymouth University, Plymouth, UK
[b]Faculty of Engineering and Architecture, University of Enna "Kore", Enna, Italy
alessandro.dinuovo@plymouth.ac.uk; a.cangelosi@plymouth.ac.uk

***Abstract*— Cognitive Robotics is a new and effective approach for the modelling and better understanding of human cognitive functions and to create effective human-robot interaction. This article reviews the recent literature that exploit of the concept of mental imagery as a fundamental cognitive capability to enhance the robot's ability to interact with the physical and social environment. Then, three future interdisciplinary research directions are identified and discussed, highlighting the new collaborative research themes for the definition of a new class of imagery enabled robots that can overcome some limitation of the current technology, especially in its application in social contexts.**

I. INTRODUCTION

While Artificial Intelligence was moving its first steps, Alan Turing argued that "it is best to provide the machine with the best sense organs that money can buy, and then teach it to understand and speak English. That process could follow the normal teaching of a child. Things would be pointed out and named, etc." [1]. This is strictly related to the embodied cognition theory, which affirms that all aspects of human cognition are shaped by aspects of the body [2].

Computer simulations of humanoid robotic platforms can complement standard robotic experiments by testing the embodied cognition hypotheses [3]. Computational models allow experimenters to make explicit assumptions and hypotheses, and to implement their details. Moreover, the analysis of results can be conducted at a level of detail that would be difficult to achieve in other domains of cognitive neuroscience. This "ecological", or Artificial Life approach adds further power to the connectionist modelling by means of simulating not only the brain and the nervous system, but also the body and the environment of artificial organisms [4], [5].

In this view, Cognitive Robotics targets to provide robots with cognitive capabilities like perception processing, attention allocation, anticipation, planning, complex motor coordination, reasoning about other agents and perhaps even about their own mental states (see [6]–[9] for details and examples). Here the behavior of intelligent agents in the physical world is embodied in a cognitive robot. In the case of simulated cognitive robotics, the platform will operate in a virtual world that resembles the real world, e.g. [10].

The embodied cognitive approach is the motivation behind a strongly humanoid design of the some of the recent and most advanced robotic platforms, e.g. iCub [11], NAO [12], and ASIMO [13]. These platforms are equipped with sophisticated motors and sensors, which replicate animal or human sensorimotor input/output streams. The sensors and actuators arrangement determine a highly redundant morphological structure of humanoid robots, which are traditionally difficult to control and, thus, require complex models implementing more sophisticated and efficient mechanisms that resemble the human cognition [14].

In this multidisciplinary context, improving the skill of a robot in terms of motor control and interaction capabilities (with the environment and/or human beings) is a timely and important issue in current robotics research especially in the case of a complex robot with many degrees of freedom. Among the many bio-inspired mechanisms and models already tested in the fields of robot interaction behavior and navigation, the use of mental imagery principles is of interest in modelling mental imagery as a complex, goal-directed and flexible motor planning strategy and to go further in the development of artificial cognitive systems capable to better interact with the environment and refine their cognitive motor skill in an open-ended process.

The present article especially reviews models and robotic applications of the *motor imagery*, which is considered a multimodal simulation that activates the same, or very similar, sensory and motor modalities that are activated when human beings interact with the environment in real time.

II. SIMULATED MENTAL IMAGERY IN ROBOT INTERACTION: A BRIEF REVIEW

In the multidisciplinary context in which cognitive robotics operates, improving the interaction skills of a robot in terms of motor control and navigation capabilities, especially in the case of a complex robot with many degrees of freedom, is a timely and important issue in current robotics research. Among the many bio-inspired mechanisms and models already tested in the field of robot control and navigation, the use of mental imagery principles is of interest in modelling mental imagery as a complex, goal-directed and flexible motor planning strategy and to go further in the development of artificial cognitive systems capable to better interact with the environment and refine their cognitive motor skill in an open-ended process.

This section reports some of the recent work in the field of simulating mental imagery to improve the interaction capabilities of robots. Examples are given in four areas and more details can be found in a dedicated special issue [15].

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A. Neuro-cognitive inspired models of mental imagery in robots

A model-based learning approach for mobile robot navigation was presented in [16], where it is discussed how a behaviour-based robot can construct a *symbolic process* that accounts for its deliberative thinking processes using internal models of the environment. The approach is based on a forward modelling scheme using recurrent neural learning, and results show that the robot is capable of learning grammatical structure hidden in the geometry of the workspace from the local sensory inputs through its navigational experiences.

Lallee and Dominey, [17], suggest the idea that mental imagery can be seen as a way for an autonomous system of generating internal representation and exploiting the convergence of different multimodal contingencies. That is, given a set of sensory-motor contingencies specific to many different modalities, learned by an autonomous agent in interaction with the environment, mental imagery constitutes the bridge toward even more complex multimodal convergence. The model proposed by the authors is based on the hierarchical organization of the cortex and it is based on a set of interconnected artificial neural networks that control the humanoid robot iCub in tasks that involve coordination between vision, hand-arm control, and language. The paper also highlights interesting relations between the model and neurophysiological and neuropsychological findings that the model can account for.

Fascinatingly, in [18], authors explore the idea of dreams as a form of mental imagery and the possible role they might play in mental simulations and in the emergence and refinement of the ability to generate predictions on the possible outcomes of actions. What the authors propose is that robots might first need to possess some of the characteristics related to the ability to dream (particularly those found in infants and children) before they can acquire a robust ability to use mental imagery. This ability to dream, according to them, would assist robots in the generation of predictions of future sensory states and of situations in the world.

Starting from the fact that some evidence in experimental psychology has suggested that imagery ability is crucial for the correct understanding of social intention, an interesting study to investigate intention-from-movement understanding is presented in [19]. Authors' aim is to show the importance of including the more cognitive aspects of social context for further development of the optimal theories of motor control, with positive effects on robot companions that afford true interaction with human users. In the paper, the authors present a simple but thoroughly executed experiment, first to confirm that the nature of the motor intention leads to early modulations of movement kinematics. Secondly, they tested whether humans use imagery to read an agent's intention when observing the very first element of a complex action sequence.

B. Simulated imagery in Human-Robot Interaction

An example of the essential role mental imagery can play in human-robot interaction was recognized by [20], where authors presented a robot, called Ripley, which is able to translate spoken language into actions for object manipulation guided by visual and haptic perception. The robot maintained a dynamic *mental model*, a three-dimensional model of its immediate physical environment that it used to mediate perception, manipulation planning and language. The contents of the robot's mental model could be updated based on linguistic, visual, or haptic input. The mental model endowed Ripley with object permanence, remembering the position of objects when they were out of its sensory field.

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The use of a primate's spatial ability of mental rotation to serve as a basis for robotic navigation has been almost entirely overlooked by the robotics community to date. In [21], the role of this cognitive capacity is presented as an adjunct to existing robotic control systems, with the underlying approach being derived from studies of primate spatial cognition. Specifically, in this work, the optical flow is used as a basis for transitory representations (snapshots) that are compared to an a priori visual goal to provide corrective course action for a robot when moving through the world.

In [22] authors implement an embodied cognition approach to mental rotation processes extending the neuro-computational model TRoPICAL. The extended model develops new features that allow it to implement mental simulation, sensory prediction, as well as enhancing the model's capacity to encode somotosensorial information. The model, applied to a simulated humanoid robot (iCub) in a series of mental rotation tests, show the ability to solve the mental rotation tasks in line with results coming from psychology research. The authors also claim that the emergence of links between overt movements with mental rotations, suggesting that affordance and embodied processes play an important role in mental rotation capacities.

C. Motor imagery in robot fine motor control

Recent research, both in experimental as well as practical contexts, suggests that imagined and executed movement planning relies on internal models for action [23].

Schack and Ritter examine the cognitive architecture of human action, showing how it is organized over several levels and how it is built up [24]. Basic action concepts (BACs) are identified as major building blocks on a representation level. These BACs are cognitive tools for mastering the functional demands of movement tasks. It is concluded that such movement representations might provide the basis for action implementation and action control in skilled voluntary movements in the form of cognitive reference structures. The cognitive architecture is used in the context of grasping with a five-fingered anthropomorphic robot hand, and then challenges and issues are discussed.

In [25], the authors present a detailed study that explored the application mental simulation to robot controllers, with the aim of mimic the mental training techniques to improve the motor performance of the robot. To this end, a model of a motor controller based on neural networks was designed to allow the iCub to autonomously improve its sensorimotor skills (see Figure 1). This is achieved by endowing the controller of a secondary neural system that, by exploiting the sensorimotor skills already acquired by the robot, is able to generate additional *imaginary* examples that can be used by the controller itself to improve the performance through a simulated *mental training*.

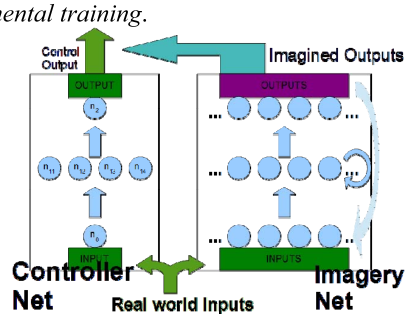

Figure 1. The ANN architecture that models the mental training process [25].

In a follow-up study, [26], authors builds on the previous architecture showing that the robot could *imagine* or *mentally* recall and accurately execute movements learned in previous training phases, strictly on the basis of the verbal commands. Further tests show that data obtained with *imagination* could be used to simulate *mental training* processes, such as those that have been employed with human subjects in sports training, in order to enhance precision in the performance of new tasks through the association of different verbal commands.

D. Imagery improved robot Navigation and environment perception

An autonomous environmental visual perception approach for humanoid robots is presented in [27]. The proposed framework exploits the available model information and the context acquired during global localization by establishing a vision-model coupling in order to overcome the limitations of purely data-driven approaches in object recognition and surrounding status assertion. The inclusion of mental imagery enables the prediction of the environment appearance and enables the extraction of proprioceptive cues for cognitive filtering. After an experimental evaluation with the humanoid robot ARMAR, Authors conclude that the exploitation of the model-vision coupling through the proprioceptive components is the key element to solve complex visual assertion-queries with proficient performance.

The study presented in [28] show how simulated robots evolved for the ability to display a context-dependent periodic behavior can spontaneously develop an internal model and rely on it to fulfil their task when sensory stimulation is temporarily unavailable. Results suggest that internal models might have arisen for behavioral reasons and successively exapted for other cognitive functions. Moreover, the obtained results suggest that self-generated internal states need not match in detail the corresponding sensory states and might rather encode more abstract and motor-oriented information.

A computational model of mental simulation that includes biological aspects of brain circuits that appear to be involved in goal-directed navigation processes is presented in [29]. The model supports the view of the brain as a powerful anticipatory system, capable of generating and exploiting mental simulation for predicting and assessing future sensory motor events. The authors show how mental simulations can be used to evaluate future events in a navigation context, in order to support mechanisms of decision-making. The proposed mechanism is based on the assumption that choices about actions are made by simulating movements and their sensory effects using the same brain areas that are active during overt actions execution.

Internal simulations can help artificial agents to solve the stereo matching problem, operating on the sensorimotor domain, with retinal images that mimic the cone distribution on the human retina [30]. This is accomplished by applying internal sensorimotor simulation and (subconscious) mental imagery to the process of stereo matching. Such predictive matching is competitive to classical approaches from computer vision, and it has moreover the considerable advantage that it is fully adaptive and can cope with highly distorted images.

An interpretation of mental imagery based on the context of homeostatic adaptation is presented in [31], where the internal dynamics of a highly complex self-organized system is loosely coupled with a sensory-motor dynamic guided by the environment. This original view is supported by the analysis of a neural network model that controls a simulated agent facing sensor shifts. The agent is able to perceive a light in the environment through some light sensors placed around its body and its task is that of approaching the light. When the sensors are swapped, the agent perceives the light in the opposite direction of its real position and the control systems has to autonomously "detect" the shifting sensor and act accordingly. The authors speculate that mental imagery could be a viable way for creating self-organized internal dynamics that is loosely coupled with sensory motor dynamics. The loose coupling allows the creation of endogenous input stimulations, similar to real ones that could allow the internal system to sustain its internal dynamics and, eventually, reshape such dynamics while modifying endogenous input stimulations.

In [32], authors explored how the relationship between spatial mental imagery practice in a training phase, could increase accuracy in sports related performance. The focus is on the capability to estimate, after a period of training with proprioceptive and visual stimuli, the position into a soccer field when the robot acquires the goal.

A neural network model to produce an anticipatory behavior by means of a multi-modal off-line Hebbian association has been recently proposed in [33]. The model emulates a process of mental imagery, in which visual and tactile stimuli are associated during a long-term predictive simulation chain motivated by covert actions. Such model was studied by means of two experiments with a physical Pioneer 3-DX robot that developed a mechanism to produce visually conditioned obstacle avoidance behavior.

III. FUTURE RESEARCH DIRECTIONS AND IDEAS

Further advances in the field of cognitive robotics and, in particular, of artificial mental imagery, require a radically new and highly interdisciplinary approach to produce a paradigm shift in the field of robot control that allows going over the simple problem solving [15].

In the following sections, some directions and ideas for the research are briefly introduced and discussed in the view of the relevant scientific literature.

A. Synergies from interdisciplinary studies of mental imagery in humans and robots

To address the challenge of more efficient and adaptable interaction and motor control, new interdisciplinary research in synergy with robotics experiments is needed to extend these artificial models of mental imagery in order to go beyond simple task execution by taking full advantage of the new resources available in robotic engineering.

Humans are able to acquire many skilled motor behaviours in their lifetime, and the learning of these complex behaviours is achieved through the constant repetition of movements over and over, with certain components segmented into reusable elements known as motor primitives. These motor primitives are then flexibly reused and dynamically integrated into novel sequences of actions [34]. As an example, the action of lifting an object can be broken down into a combination of multiple motor primitives. Some motor primitives would be responsible for reaching the object, some for grasping it and some for lifting it. These primitives are represented in a general manner and should be applicable to objects with different properties.

As an example, motor imagery plays a role when moving towards an object to grab it, indeed, the brain is running offline motor plans to determine the optimal hand positioning and grip strength to pick up the object [35].

The information processing strategy in the context of motor control is studied with a high interdisciplinary vision by Grush in [36], where the emulation theory of representation is presented and discussed. The emulator is defined as a device that implements the same (or very close) input-output function as the plant. So when it receives a copy of the control signal (it is thus getting the same input as the plant), it produces an output signal, the emulator feedback, identical or similar to the feedback signal produced by the plant.

Taking inspiration from Grush work and the dual recurrent network model proposed in [37], a possible control scheme for imagery enabled cognitive robots is presented in Figure 2.

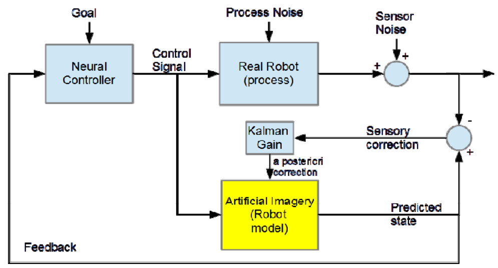

Figure 2. A proposal for the possible control scheme for imagery enabled cognitive robots, which resembles a Kalman filter to update an internal model.

B. Integration with most recent neuromorphic technologies

Starting from the a recently proposed a technique [38] for self-learning a dynamical model of the iCub humanoid robot, motor imagery can be potentially exploited to improve the robot sensorimotor skills. Within this interdisciplinary context, motor imagery corresponds to the forward integration of the system dynamic equations for which several standard numerical solutions are commonly employed [39]. Similarly, training by mental imagery corresponds to refining motor control by repetitive trials (e.g. [40]–[42]) This implementation of mental imagery is based on an artificial discretization of time, which is not linked to the timing of the real world. The discretization step length for the solution of the dynamic equation is internally generated and, therefore, independent from the sensorimotor temporal evolution of the physical system. Mainstream robotics is based on clock-based architectures that intrinsically suffer of such limitations.

Neuromorphic engineering is currently emerging as a new biologically inspired technology that overcomes these limitations by using asynchronous systems driven by the temporal evolution of the external world [43].These systems do not equip the robot with a “traditional” vision system, rather, they provide an encoding of the sensory signal that is more efficient and adequate for extracting relevant information for producing appropriate behaviour. Successful application of the use of neuromorphic sensors and processors in the field of visual selective attention [44], object tracking and recognition [45] and real-time computation of the optical [46] show the potential breakthrough and advantages of the development of technologies and cognitive systems based on neuromorphic sensing, that is currently applied to the design of autonomous robots, endowed with event-driven artificial perceptive systems [47], [48]. The unique characteristics of event-driven sensory acquisition make the neuromorphic approach a necessary enabling technology for the full application of the possibilities offered by imagery enabled artificial cognitive agents, whereby the time discretization of mental imagery is driven by the temporal pace of external stimuli, as encoded by asynchronous event-driven neuromorphic sensors.

In addition, to apply the advanced cognitive abilities envisioned in this work in realistic complex scenarios it is crucial to increase the amount of computational resources available to efficiently process the data flow coming from the sensors. In this view, a recent breakthrough in massively parallel and distributed neuromorphic systems architectures offers the optimal substrate needed by the integration of complex artificial cognitive systems, able of mental simulation, with the parallel and asynchronous data flow from neuromorphic sensors. The SpiNNaker project has delivered a state-of-the-art real-time neuromorphic modelling environment that can be scaled-up to model up to a billion point-neuron models [49]. This allows models to be substantially scaled up and to be transferred to environments such as robotics that demand real-time response. Within this context, mental imagery models will address the problem of achieving real-time performance by combining the benefits of (mental) simulations with those associated to neuromorphic designs. Classical architectures are characterized by a time resolution, which is limited by the resolution of available clocks. The synchronicity of events clearly suffers from these limitations. In both mental simulations and neuromorphic sensing, synchronicity can be more effectively represented due to the intrinsic continuous representation of time. The benefits of mental simulations and neuromorphic designs seem, therefore, to have a natural validation scenario in the execution of spatially and temporally precise movements.

C. Applications in human robot interactions

After the successful development of *Socially Assistive Robotics* (SAR) [50], which provided evidence of the application of robotics in the area of child, elderly and disabled care. Here, the challenge is to search for novel control strategies, which would allow the robot to automatically adapt to the individual needs and the therapy, while remaining under the supervision of a caregiver or a therapist [51].

In this scenario, the enhanced interaction capabilities offered by the envisioned imagery-enabled cognitive systems will be the foundation of next generation of humanoid robotic platforms with life-like features and motion. These targeted characteristics might allow people to more easily identify the desired social overture that the robot is making, or facilitate the transfer of skills learned in human-robot encounters to human-human interactions. This humanization will positively impact the acceptance of robots in social environments, as they will be perceived as less dangerous [52]. Therefore, we expect imagery-enabled robots to have a large socio-economic impact, especially in the fields of social care, companionship, therapy, domestic assistance, entertainment and education.

In particular, we expect synergies with motor and athletic rehabilitation and recovery after injuries or traumas, especially in sports, but more generally in physiotherapeutic practice, which have shown to be enhanced by mental imagery processes [53].

IV. CONCLUSION

This paper has reviewed the current state of the scientific research that deals with strategies based on artificial implementations of mental imagery in cognitive robotics and we proposed some future directions and ideas for further advance in the field.

Definitely, the next generation of robotic systems needs to reach a level of cognition and motor intelligence that will provide autonomy in any environment (household or industrial), effective interaction with humans, and adaptation of their actions to an ever-growing range of open, dynamic situations. Robots are expected to be able to predict perceptual and functional changes, that result as a consequence of human actions, and replicate human activities taking into consideration their own capabilities and limitations. The main foreseen breakthrough of the incorporation of artificial mental imagery in cognitive robots is to allow the implementation of real-time interaction through event-driven vision and motor planning in order to strongly contribute to the foundation of the future generations of socially integrated neuromorphic humanoid robots. These robots will be able to reason, behave and interact in a human-like fashion, thanks to the integration of the capabilities to mentally represent the physical and social world, resemble experiences and simulate actions. The imagery-enabled cognitive robotic agents will be able to handle and manipulate objects and tools autonomously, to cooperate and communicate with other robots and humans, and to adapt their abilities to changing internal, environmental, and social conditions.

As a final remark, the author would stress that cognitive robotics is an highly interdisciplinary field, in which joint efforts of neuroscientists, computer scientists, psychologists, sociologists, and robotic engineers are needed to further advance the field towards a new stage, which will open up new developmental strategies for the design of cognitive robots and their application in real life scenarios with high social impact. This will drastically improve the robotics industry, as human-like performance and interaction will significantly impact the acceptance of robots in social environments, widening the applications.

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