Guest Editorial
Sensorimotor Contingencies for Cognitive Robotics

***Abstract*—The sensorimotor approach to cognition states, that the key to bring semantics to the world of a robot, requires making the robot learn the relation between the actions that the robot performs and the change it experiences in its sensed data because of those actions. Those relations are called sensorimotor contingencies (SMCs). This special issue presents a variety of recent developments in SMCs with a particular focus on cognitive robotics applications.**

***Index Terms*—Cognitive architectures, cognitive robotics, multimodal perception, sensorimotor contingencies (SMCs).**

I. Scope of This Special Issue

THE SENSORIMOTOR approach to cognition breaks completely the classic sense-plan-act pipe that rules most of today's autonomous robots, by mixing sensation with action, aiming to bridge the gap between symbolic data and semantics for robots 1). Sensorimotor contingencies (SMCs) are defined as the relations learned by the robot between the actions that the robot performs and the change it experiences in its sensed data because of those actions. The goal of bringing SMCs to robotics is to build robots with a more robust behavior in real environments 2), 3).

In order to have robots outside of controlled environment, we need robots that understand their own environments 4), and it looks like a way to achieve this is by making the robot build by itself the SMCs that are common to every environment. Having robots that can generate such laws, will allow them to understand the world they are immersed, and make them by hence, more robust in real environments 5).

We selected these papers for this special issue to provide a broad view of the subject, and particularly promoted papers with practical embodied implementations that raise the current challenges in the field.

Among all the submissions what we observe is the agreement in considering the importance of multi-modal perception. The papers in this Special Issue use different combinations of proprioceptive sensors with visual cues and tactile sensors. We note that three of them rely on tactile information.

Lot of efforts have been made to understand the mechanism of perception, obviously linked to robot actions 6). Unfortunately, we realize that there is a very basic use of the robot capabilities, and the explored actions are still very simple. We envisage that the community will start soon to use more complex actions and take full advantage of the great robotic platforms we currently have available in research.

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II. Contribution to the Special Issue

The special issue is composed of five papers. The most theoretical of the selected works is presented by Lanillos *et al.* in the paper entitled *Yielding Self-Perception in Robots Through Sensorimotor Contingencies*, where authors address the problem of self-perception, including a novel model for self-detection, which does not need to track or store the body parts. Self-perception, taken as the understanding of the sensory consequences of performing an action, can improve the capabilities of the robot to interact in unknown environments. They propose that the concept of usability can be emerged this way. As perception they use artificial skin and visual cues, and the output is the discovery of the potential usable objects. For that purpose, an experiment is designed for discovering usable objects in the scene based on the taping or pushing setup proposed lately in [item 7) in the Appendix].

A different approach of this same idea, along with its implementation in a real robot, is presented by Zambelli and Demiris in their paper *Online Multimodal Ensemble Learning Using Self-Learnt Sensorimotor Contingencies*. Authors introduce a learning architecture where knowledge emerges from robot interactions and multimodal sensory system. The method produces predictors able to relate motor commands to perceptions of the robot sensory system. Notably, it does not require prior information about the kinematic or dynamic models of the robot. Hence, the proposed framework, initially developed using an iCub humanoid robot 8) and a piano keyboard, can be applied to different robotic platforms.

The manuscript by Giakos *et al.* entitled *Perception of Object Features During Robotic Sensorimotor Development* tackles the problem of perception, and proposes a mechanism to think in a stable representation of the world inspired in infant learning. The system is based on observing how the gaze control impacts on the perception of the objects, and provide an interesting insight on the emergence of features that can lead to object recognition. Experiments give a full demonstration of a longitudinal development of both sensorimotor development and early object perception on an iCub humanoid robot.

The paper by Marcel *et al.* entitled *Building a Sensorimotor Representation of a Naive Agent's Tactile Space* tackles the problem of the discovery of the inherent structure of the interaction with the robot body. This work is focused on the extension of the approach in [item 9) in the Appendix] to the building of an internal representation of an agent body, in the vein of Frolov's previous work. Authors present a method to build a perception of the environment, and provide a formalization of the so-called "sensorimotor invariants." The method is shown to be valid also to consider motion planning.

The work by Arriola-Rios and Wyatt entitled *A Multi-Modal Model for Prediction and Classification of Object Deformation During Robotic Manipulation* introduces a method to learn deformation models from robot interaction. Manipulation of 3-D deformable objects is a challenging task 10); in this paper authors propose a method to predict the forces and behavior after the contact, and at the same time classify the material. Compared to other works with simple use-cases, here authors can deal this challenging task because some knowledge is parameterized in the system, and the SMC is used to learn some of the parameters, demonstrating that SMC approaches are useful also as partial learners.

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APPENDIX
RELATED WORK

1) J. K. O'Regan and A. Noë, "A sensorimotor account of vision and visual consciousness," *Behav. Brain Sci.*, vol. 24, no. 5, pp. 939–973, 2001.
2) A. Maye and A. K. Engel, "A discrete computational model of sensorimotor contingencies for object perception and control of behavior," in *Proc. IEEE Int. Conf. Robot. Autom.*, Shanghai, China, May 2011, pp. 3810–3815.
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Guillem Alenya received the Ph.D. (Doctor Europeus) degree from the Polytechnic University of Catalonia, Barcelona, Spain, in 2007, with a research on mobile robot navigation using active contours.

He holds a tenured position with Spanish Scientific Research Council CSIC, Madrid, Spain. His Ph.D. research was partly developed with the Robosoft company in France, where he was supported by a EU-FP6 Marie-Curie scholarship. He has been a visitor with Karlsruhe Institute of Technology, Karlsruhe, Germany, in 2007, INRIA, Grenoble, France, in 2008, and Bristol Robotics Laboratory, Bristol, U.K., in 2016. He has participated in numerous scientific projects involving image understanding, next-best-view, rule learning, and plan execution tasks. He is currently a local IP of the EU MSCA training network SOCRATES, a co-IP of the EU project IMAGINE, and a Leader of numerous technological transfer projects. From 2009 to 2011, he served as the Head of the Robotics Department.

Ricardo Tellez received the Ph.D. degree in artificial intelligence from Universitat Politècnica de Catalunya, Barcelona, Spain, with a research about the generation of dynamic gaits in real quadruped robots using evolutionary algorithms.

He is currently a CEO and a Founder of the Construct, a robotics software company. He was a Post-Doctoral Fellow with Spanish Scientific Research Council CSIC, Madrid, Spain. He has over 10 years experience in the service robots industry, specially researching in the development of humanoid robots at PAL Robotics. He has served as a Team Leader several times in service robots competitions integrating industry and academia partners. He has been also participating in numerous technological transfer projects.

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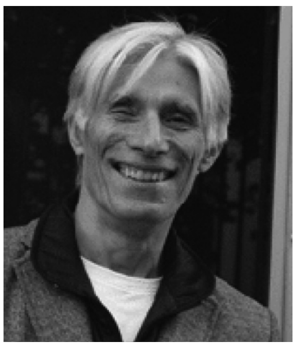
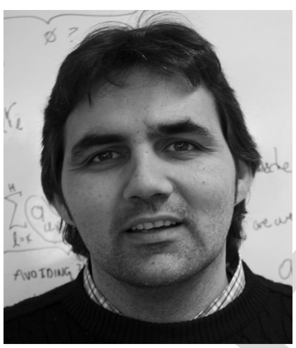


Kevin O'Regan is an Ex-Director of the Laboratoire Psychologie de la Perception, CNRS, Universite Paris Descartes, Paris, France. After early research on eye movements in Reading, he was led to question established notions of the nature of visual perception, and to discover, with collaborators, the phenomenon of "change blindness." He has published a book entitled *Why Red Doesn't Sound Like a Bell: Understanding the Feel of Consciousness* (Oxford University Press) in 2011. In 2013, he received a five year Advanced ERC grant to explore his "sensorimotor" approach to consciousness in relation to sensory substitution, pain, color, space perception, developmental psychology, and robotics.



Cecilio Angulo received the B.Sc. and M.Sc. degrees in mathematics from the University of Barcelona, Barcelona, Spain, in 1993, and the Ph.D. degree in sciences from the Department of Automatic Control, Technical University of Catalonia (UPC), Barcelona, in 2001.

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Dr. Angulo is an Associate Editor of the IEEE TRANSACTIONS ON COGNITIVE AND DEVELOPMENTAL SYSTEMS, and has also served as the Chair for several international conferences.

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