



## Editorial

## Neurobiologically Inspired Robotics: Enhanced Autonomy through Neuromorphic Cognition



Neurobiologically inspired robotics goes by many names: brain-based devices, cognitive robots, neurobots, and neuromorphic robots, to name a few. The field has grown into an exciting area of research and engineering.

The common goal is twofold: Firstly, developing a system that demonstrates some level of cognitive ability can lead to a better understanding of the neural machinery that realizes cognitive function. The often used phrase, “understanding through building”, implies that one can get a deep understanding of a system by constructing physical artifacts that can operate in the real-world. In building and studying neurobiologically inspired robots, scientists must address theories of neuroscience that couple brain, body, and behavior. Secondly, the deep theoretical understanding of cognition, neurobiology and behavior obtained by constructing physical systems, could lead to a system that demonstrates capabilities commonly found in the animal kingdom, but rarely found in artificial systems, most notably their adaptive and flexible autonomous behavior.

This Special Issue includes eleven papers that represent the current state of the art in neurobiologically inspired robotics. In general, the collection of papers takes on three major issues that are of the utmost importance for research in neuroscience and cognitive science, as well as advancing robotics: (1) reaching, planning, and control, (2) navigation through spatial environments, and (3) interaction with people or human robot interaction. It also presents several computational approaches to developing neurally inspired robots.

**Reaching, planning, and motor control.** Motor control in humans and other animals requires attention, planning, and spatial awareness relative to the body and environment. In one article by Strauss and colleagues, a choice reaction task was carried out using a LEGO arm robot (Strauss, Woodgate, Sami, & Heinke, 2015). This required attentional selection of reaching targets that could “leak” into the motor system. Using competitive target selection and topological representations of motor parameters their model was able to mimic this leakage effect. They also showed how a green square among red squares or vice versa led to straighter reaching trajectories, which is similar to empirical results. In another article on reaching, Fard and colleagues explored how humans can point fairly accurately to memorized states when closing their eyes despite slow or even missing sensory feedback (Fard, Hollensen, Heinke, & Trappenberg, 2015). They were able to show how a path integration mechanism could be trained from few examples and learn to compensate an image acquisition delay in the sensory system. Both these papers on reaching have implications on how

the parietal cortex and motor cortex interact to make motor plans and have applications for control strategies in robotics.

A more “cognitive” paradigm related to planning is mental rotation, which tests the capacity of humans to mentally rotate a seen object to decide if it matches a target object. The article by Seep-anomwan and colleagues presents a novel neurobotic model that has a macro-architecture constrained by knowledge held on brain, and a biologically plausible decision making mechanism (Seep-anomwan, Caligiore, Cangelosi, & Baldassarre, 2015). The model was tested using the humanoid robot iCub in tasks requiring the robot to mentally rotate 2D geometrical images appearing on a computer screen. The results showed that the robot gained an enhanced capacity to generalize mental rotation to new objects. The model identifies embodied neural mechanisms that may underlie mental rotation in humans and might also enhance planning capabilities in robotic systems.

**Navigation through spatial environments.** A major challenge in autonomous mobile robotics is how to get from one place to another. Robotic mapping and localization systems typically operate at a fixed spatial scale. In contrast, recent discoveries in neuroscience have indicated that animals navigate the world using multiple parallel maps, with each map encoding the world at a specific spatial scale. Two papers in this special issue present neurobiologically inspired solutions to spatial navigation in light of these results. Chen and colleagues present a multi-scale mapping system mimicking the rodent entorhinal cortex and hippocampus (Chen, Lowry, Jacobson, Hasselmo, & Milford, 2015). Their system is homogeneous, distinguishable only by scale, like rodent neural maps. Llofriu and colleagues demonstrate how the multi-scale nature of hippocampal place cells and entorhinal grid cells can improve goal-oriented navigation (Llofriu et al., 2015). In both cases, these results demonstrate that multi-scale approaches improve place recognition performance in autonomous robot navigation, and are capable of producing better than state of the art performance compared to existing robotic navigation algorithms.

Spatial navigation not only requires localization and mapping, but it also requires rapid and fluid reactions to traverse cluttered environments with ease. Beyeler and colleagues present a cortical neural network model for visually guided navigation that has been embodied on a physical robot exploring a real-world environment (Beyeler, Oros, Dutt, & Krichmar, 2015). The model includes a rate based motion energy model for area V1, and a spiking neural network model for cortical area MT. They demonstrate how neural signals in area MT might provide sufficient motion information to

steer a physical robot on human-like paths around obstacles in a real-world environment.

Another important aspect of spatial navigation is how organisms utilize these “cognitive maps” to take appropriate actions. Such goal-oriented behavior can be decomposed into ‘how’, ‘why’, ‘what’, ‘where’, ‘when’ (H4W) events. Maffei and colleagues address this problem from the perspective of the Distributed Adaptive Control (DAC) theory of mind and brain (Maffei, Santos-Pata, Marcos, Sánchez-Fibla, & Verschure, 2015). In a robot foraging task that unifies the theoretical principles of DAC with biologically constrained models of several brain areas, they show that efficient goal-oriented behavior results from the interaction of parallel learning mechanisms accounting for motor adaptation, spatial encoding and decision-making.

**Human–Robot Interaction.** Robots are becoming more commonplace in our everyday lives. As such, human–robot interaction (HRI) is an important consideration. Several papers in this special issue address HRI issues from a socio-cognitive viewpoint. Park and Tani present neurorobotics experiments on acquiring skills for “communicable congruence” with humans via learning (Park & Tani, 2015). In their work, they used a recurrent neural network model, which was characterized by multiple timescales, to control a humanoid robot that learned to imitate sequential movement patterns generated by human subjects. In work that demonstrates how sequential organization of tasks can be acquired from social learning interactions with people, Sousa and colleagues presented a model that was inspired by the hypothesis that the nervous system uses the off-line re-activation of initial memory traces to incrementally incorporate new information into knowledge (Sousa, Erlhagen, Ferreira, & Bicho, 2015). They tested this idea in an HRI study where a humanoid robot interacted with a human partner to develop an assembly plan to construct a toy together.

Another important aspect of HRI is emotional state recognition. By determining emotion expressions, robots can identify important variables of human behavior and use these to communicate in a more human-like fashion and thereby extend the interaction possibilities. In their article, Barros and colleagues present a model that uses a hierarchical feature representation to deal with spontaneous emotions, and learns how to integrate multiple modalities for non-verbal emotion recognition, making it suitable to be used in an HRI scenario (Barros, Jirak, Weber, & Wermter, 2015).

**Computational approaches.** This special issue also highlights the wide variety of computational approaches that can be used to control neurobiologically inspired robots. Some of the approaches presented in this special issue include spiking neural networks, firing rate neurons, recurrent neural networks, and dynamic neural fields. A commonality among all these approaches is that they are neuromorphic in their architecture; they contain neuronal elements and synaptic connectivity inspired by what is currently known about the nervous system. Another important commonality is that all of the models in this special issue were embedded on physical devices (i.e., robots). For these systems to operate over a long period of time outside a laboratory setting, they need to minimize the size, weight and power of their computing engines. Thus, a promising direction for neurobiologically inspired robots is the advent of neuromorphic chip designs. Unlike standard Von Neumann CPUs, these chips can not be simply programmed with a standard programming language, rather they compute through the interaction of silicon neurons and synapses. Also, like real brains, they are low power and efficient. Thus the neurobiologically inspired solutions presented in this Special Issue are poised to take advantage of this neuromorphic hardware. In their article, Walter and colleagues provide an overview of available neuromorphic chip designs and analyze them in terms of neural computation, communication systems

and software infrastructure, as well as review neurobiological learning techniques. (Walter, Röhrbein, & Knoll, 2015). They further investigate how to program neuromorphic chips by means of learning, rather than programming.

**Final Thoughts.** We hope you enjoy reading these articles that highlight the potential of neurobiologically inspired systems to advance the field of autonomous robots and our understanding of the human brain. All these papers illustrate the importance of embodiment, as behavior is deeply coupled not only with the underlying dynamics of the nervous system, but also with the anatomical constraints of the physical body it controls. We are at an interesting time where technological advances in computation and materials are occurring in conjunction with massive amounts of new empirical data from the nervous system. These embodied systems are poised to leverage these advances in many exciting ways that we can only imagine.

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