Guest Editorial Special Issue on Neuromorphic Computing and Cognitive Systems

I. Scope of This Special Issue

In recent years, neuromorphic computing has become an important emerging research area. Neuromorphic computing takes advantage of computer architectures and sensors whose design and functionality are inspired by the brain. There has been rapid progress in computational theory, spiking neurons, learning algorithms, signal processing, circuit design and implementation, which have shown appealing computational advantages over conventional solutions [1]. The low size, weight, and power of these hardware architectures shows great potential for embedded cognitive systems [2].

Starting from emulating the computational principles and architecture found in neural systems, neuromorphic computing aims to integrate sensory coding and attempts to develop neuromorphic sensors and chips, and cognitive behaving systems such as robots [3], [4]. By using neural spikes to represent the outputs of sensors and for communication between computing blocks, and using spike timing-based learning algorithms, neuromorphic computational models and hardware have achieved promising real-time learning performance. Neuromorphic hardware has provided a fundamentally different technique for data representation and learning (e.g., asynchronous events, such as pixel changes, rather than regularly sampled frames of images). Various hardware systems leveraging on neural spikes-based computing have been reported to achieve good performance with much lower power consumption [5], [6]. Therefore, neuromorphic computing can inform cognitive systems because the algorithms that run on this hardware must be neurobiologically inspired. A huge potential exists for applying this emerging computing framework to the next generation of cognitive systems and robotics, neuro-inspired sensors and processors, etc. [7].

Thus, a special issue that reports state-of-the-art approaches and recent advances on: 1) learning algorithms constrained by limits of biology and neuromorphic hardware; 2) neuromorphic hardware for cognitive systems; and 3) applications of neuromorphic architecture or hardware to cognitive robotics is very timely to all researchers in these related areas.

II. Contributions to the Special Issue

This Special Issue includes seven original articles that describe work inspired by neuromorphic computing, spreading light on this topic from multiple perspectives. Below, we briefly highlight the field of article and the main contribution of each article.

The first paper, titled "Adaptive robot path planning using a spiking neuron algorithm with axonal delays," presents a path planning algorithm for outdoor robots, which is based on neuronal spike timing. The algorithm is inspired by recent experimental evidence for experience-dependent plasticity of axonal conductance. Based on this evidence, a novel learning rule is developed that alters axonal delays corresponding to cost traversals and demonstrates its effectiveness on real-world environmental maps. The spiking neuron path planning algorithm is implemented on an autonomous robot that can adjust its routes depending on the context of the environment. The robot demonstrates the ability to plan different trajectories that exploit smooth roads when energy conservation is advantageous, or plan the shortest path across a grass field when reducing distance traveled is beneficial. The algorithm is suitable for spike-based neuromorphic hardware, it has the potential of realizing orders of magnitude gains in power efficiency and computational gains through parallelization.

The second paper, titled "Neuro-activity-based dynamic path planner for 3-D rough terrain," presents a natural mechanism of the human brain for generating a dynamic path planning in 3-D rough terrain. The proposed model not only emphasizes the inner state process of the neuron but also the development process of the neurons in the brain. There are two algorithm processes in this proposed model, the forward transmission activity for constructing the neuron connections to find the possible way and the synaptic pruning activity with backward neuron transmission for finding the best pathway from current position to target position and reducing inefficient synaptic connections. Dynamic path planning is also considered in this proposed model to respond and avoid unpredictable obstacles. An integrated system for applying the proposed model in the real cases is also presented. In order to prove the effectiveness of the proposed model, computer simulations and real-world experiments were carried out with a four-legged robot on rough terrain. Unpredictable collision detection is also performed in those experiments. The result shows that the model can find the best pathway and facilitate the safe movement of the robot. When the robot found an unpredictable collision, the path planner dynamically changed the pathway.

The third paper, titled "EMPD: An efficient membrane potential driven supervised learning algorithm for spiking neurons," presents an efficient membrane potential driven (EMPD)

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supervised learning method capable of training neurons to generate desired sequences of spikes. There are two processes in the learning rule of EMPD, at desired output times, the gradient descent method is implemented to minimize the error function defined as the difference between the membrane potential and the firing threshold and at undesired output time, synaptic weights are adjusted to make the membrane potential below the threshold. For efficiency, at undesired output times, EMPD calculates the membrane potential and makes a comparison with firing threshold when the neuron is most likely to cross the firing threshold. Experimental results show that the proposed EMPD approach has higher learning efficiency and accuracy over the existing learning algorithms.

The fourth paper, titled "Robotic homunculus: Learning of artificial skin representation in a humanoid robot motivated by primary somatosensory cortex," presents work studying how representations of the whole skin surface resembling those found in primate primary somatosensory cortex can be formed from local tactile stimulations traversing the body of the physical robot. The authors present a modification of the standard SOM algorithm that makes it possible to restrict the maximum receptive field (MRF) size of neuron groups at the output layer. It is motivated by findings from biology where basic somatotopy of the cortical sheet seems to be prescribed genetically and connections are localized to particular regions. The different settings of the MRF and the effect of activity-independent (input–output connections constraints implemented by MRF) and activity-dependent (learning from skin stimulations) mechanisms on the formation of the tactile map are explored. The framework conveniently allows one to specify prior knowledge regarding the skin topology and thus to effectively seed a particular representation that training shapes further. Furthermore, this paper shows that the MRF modification facilitates learning in situations when concurrent stimulation at nonadjacent places occurs ("multitouch"). The procedure is sufficiently robust and not intensive on the data collection and can be applied to any robots where representation of their "skin" is desirable.

The fifth paper, titled "A novel parsimonious cause-effect reasoning algorithm for robot imitation and plan recognition," presents an imitation learning framework based on causal reasoning that infers a demonstrator's intentions. Most imitation learning systems replicate a demonstrator's actions rather than obtaining a deeper understanding of why those actions occurred. As with imitation learning in people, the proposed approach constructs an explanation for a demonstrator's actions, and generates a plan based on this explanation to carry out the same goals rather than trying to faithfully reproduce the demonstrator's precise motor actions. This enables generalization to new situations. This paper presents novel causal inference algorithms for imitation learning. The proposed approach is validated using a physical robot, which successfully learns and generalizes skills involving bimanual manipulation. Human performance on similar skills is also reported. Computer experiments using the Monroe Plan Corpus further validate the proposed approach. These results suggest that causal reasoning is an effective unifying principle for imitation learning. The proposed system provides a platform for exploring neural implementations of this principle in future work.

The sixth paper, titled "Predicting spike trains from PMd to M1 using discrete time rescaling targeted GLM," presents a linear-nonlinear-Poisson cascade framework for prediction of spike trains, whose objective function is changed from maximizing log-likelihood of the spike trains to minimizing the penalization of a discrete time rescaling Kolmogorov–Smirnov statistic. This eliminates the separation between optimization and evaluation of the model. The authors apply their model on the task of predicting firing probability of neurons from primary motor cortex with spike trains from dorsal premotor cortex as input, which are two cerebral cortices associated with movements planning and executing. The experimental results show that by introducing the goodness-of-fit metric into the objective function, results of the model will gain a significant improvement, which outperforms the state-of-the-art.

The seventh paper, titled "Visual pattern recognition using enhanced visual features and PSD-based learning rule," presents a feedforward visual pattern recognition model based on spiking neural network (SNN). The proposed model mainly includes four functional layers: 1) feature extraction; 2) encoding; 3) learning; and 4) readout. A modified HMAX model is first presented to extract features from external stimuli. In order to reduce the computational cost, a single Gabor filter window is used to simplify the S1 layer. To simulate biological vision's sensitivity to the vertical direction, the feature of filtered orientation in 90° is strengthened by adding a sharpened replica of the filtered image in 90° before max pooling in C1 layer. The phase encoding approach is then used to convert the extracted visual features into spike patterns that will be learned by PSD-based learning rules in an SNN. Experimental results on benchmark datasets including MNIST, Caltech 101, and optical characters demonstrate the efficiency and robustness in noisy environments of the proposed model.

We hope that the ideas of the above-mentioned papers will provide insights into the further development and applications in the fields of neuromorphic computing and cognitive systems.

Finally, as the Guest Editors of the Special Issue, we would like to thank all authors for their contributions, the reviewers for their valuable efforts in reviewing these articles and their constructive comments for the authors to improve their work.

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APPENDIX
RELATED WORK

1) Z. Wu, R. Benosman, H. Tang, and S.-C. Liu, "Guest editorial learning in neuromorphic systems and cyborg intelligence," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 28, no. 4, pp. 774–777, Apr. 2017.
2) G. Indiveri and S.-C. Liu, "Memory and information processing in neuromorphic systems," *Proc. IEEE*, vol. 103, no. 8, pp. 1379–1397, Aug. 2015.
3) H. Tang, R. Yan, and K. C. Tan, "Cognitive navigation by neuro-inspired localization, mapping and episodic memory," *IEEE Trans. Cogn. Develop. Syst.*, to be published, doi: 10.1109/TCDS.2017.2776965.
4) Q. Yu, H. Tang, J. Hu, and K. C. Tan, *Neuromorphic Cognitive Systems: A Learning and Memory Centered Approach*. Cham, Switzerland: Springer-Verlag, 2017.
5) G. K. Cohen *et al.*, "Skimming digits: Neuromorphic classification of spike-encoded images," *Front. Neurosci.*, vol. 10, p. 184, Apr. 2016.
6) J. L. Krichmar, P. Coussy, and N. Dutt, "Large-scale spiking neural networks using neuromorphic hardware compatible models," *ACM J. Emerg. Technol. Comput. Syst.*, vol. 11, no. 4, pp. 1–18, 2015.
7) A. Basu *et al.*, "Low-power, adaptive neuromorphic systems: Recent progress and future directions," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 8, no. 1, pp. 6–27, Mar. 2018.

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