Editorial
Biologically Learned/Inspired Methods for Sensing, Control, and Decision

THE Special Issue aims at collecting new ideas and contributions at the frontier of bridging the gap between biological and engineering systems. Contributions include a wide range of related research topics, from neural computing to adaptive control and cooperative control, from autonomous decision systems to mathematical and computational models, and from neuropsychology-based decision and control to engineering system sensing and control algorithms, as well as applications and case studies of biologically inspired systems. This editorial note provides a brief overview of the accepted articles.

I. Overview of the Special Issue

Sensing, control, and decision making are subjects of extensive investigation for decades in control system theory and control system design. An important focus of the studies is for engineered systems to achieve desired performance, and be resilient to externally or internally caused errors and unpredictable failures. In essence, this requires engineered systems capable of learning and self-reconfiguring, and having awareness of itself and the environment within which it is operating. Thus, reliable sensing and decision making in engineered systems are called for. Traditional engineering approaches have taken into account these design considerations, but usually, the solutions are costly. Yet, biological organisms in nature have successfully demonstrated their superior capability of processing a large amount of information, dealing with uncertainties when perceiving and processing information of their surroundings, adapting to environmental changes, and recovering from their internal errors and failures. All these important attributes are what engineered systems long for. It is therefore expected that biologically learned and inspired methods may offer fundamentally new theoretical frameworks for and new design approaches to addressing system robustness and reliability. Thus, seeking inspiration from biological systems for modeling, control and decision making has naturally become a prudent and promising option. The goal of the Special Issue aims at collecting new ideas and contributions at the frontier of bridging the gap between biological and engineering systems. Contributions include a wide range of related research topics, from neural computing to adaptive control and cooperative control, from autonomous decision systems to mathematical and computational models, and from neuropsychology-based decision and control to engineering system sensing and control algorithms, as well as applications and case studies of biologically inspired systems. In response to the call for papers for this Special Issue, 79 manuscripts were received and reviewed, and 30 manuscripts were accepted for publication, making an acceptance rate of approximately 38%. These manuscripts have been classified into three groups. Below, we highlight the main features of each article.

II. Bioinspired Decision and Control

In [A1], Gao and Yin present a two-level event-triggered mechanism for neuroadaptive control with exponential convergence property. The two-level event-triggered mechanism, which incorporates both static and dynamic event-triggered features, is motivated by how biological systems adapt in response to low- and high-speed changes in the environment. The simulation results demonstrate that the proposed method can guarantee system stability while consuming less communication resources.

In [A2], Homchanthanakul and Manoonpong propose a bioinspired control approach based on neuroscientific studies of cats for lifelong continuous (online) adaptation of autonomous walking robots. It integrates three main functions of biological neural systems, namely, control, memory, and learning. The functions are realized through a neural central pattern generator (CPG)-based control, an artificial hormone network with embedded temporal memory, and an unsupervised input correlation-based learning. All these neural mechanisms rely on information from proprioceptive sensory feedback, rather than exteroceptive sensory feedback or an environmental model, to control and continuously adapt robot leg movement. By doing so, the robot successfully traverses complex and novel terrains, such as gravel, grass, and extreme random stepfield, with energy-efficient locomotion. It also performs proactive obstacle negotiation involving long-lasting working memory guided by short-term memory.

Spiking neurons are widely used in neuromorphic computing, a main motivation of which is energy efficiency. Under similar motivation of spiking neural networks, Wei *et al.* [A3] propose a new bioinspired adaptive dynamic programming (ADP) method, called spiking ADP (SADP). It aims to solve optimal impulsive control problems for discrete-time nonlinear systems. By means of the SADP method, where spike train and spiking interval data are obtained from biological experiments and modeled as a Poisson process, optimal spiking instances and optimal spiking control laws at each spiking instance are obtained. This work advances from previous work that relies on fixed impulsive intervals.

Inspired by an octopus's ability to use vacuum grippers and suction cups to flexibly grip objects, Qian *et al.* [A4] develop a new microgripper for deformation control of biological

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samples. An adaptive robust controller is designed to diminish the influence from model nonlinearities and parameter uncertainties for accurate control. Experiments are carried out using zebrafish larvae as testing biological samples. Results suggest that the deformation of a biological sample is well controlled and the gripping is efficient and functional.

In [A5], Liu *et al.* propose a novel multi-output selective ensemble regression (SER) evolving model for online identification of multi-output nonlinear and time-varying processes. The method is inspired by the fundamental evolving principle of biological systems, namely, the ability to acquire new knowledge into memory and to remove out-of-date knowledge from the memory so that intelligent decisions can be made based on the latest and the most relevant memory. Two real-world industrial case studies have demonstrated that the proposed multi-output selective ensemble identification technique attains the best online modeling accuracy when compared with a range of state-of-the-art methods for online identification of nonlinear and nonstationary multi-output processes, while imposing a reasonably low online computational complexity which meets the real-time operation constraint.

Studies of mammalian brain networks have revealed highly intricate structures about the connections between neurons that consist of several clusters, where the neurons within the same cluster establish more connections with one other while the neurons within different clusters establish less connections. By mimicking this character of the neural system, Chen *et al.* [A6] present a diversified multiclustered echo state network and apply it to deal with modeling uncertainties and coupling nonlinearities in the control systems. Consequently, a diversified multiclustered echo state network-based method is established for the asymptotic tracking control of a class of uncertain multi-input multi-output systems. The effectiveness of the proposed method is confirmed by numerical simulation and by comparing it with a multilayer feedforward network-based control scheme and a traditional ESN-based control.

Yu *et al.* [A7] propose a distributed adaptive fault-tolerant time-varying formation control scheme for multiple unmanned airships (UAs) to provide safe observation of a smart city in the presence of actuator faults, limited communication range, and input saturation. A distinctive feature of the proposed control scheme is a simultaneous consideration of multiple design challenges due to time-varying formation flight, actuator faults including bias and loss-of-effectiveness faults, limited communication range, and input saturation. It is proven by Lyapunov stability analysis that all UAs can achieve a safe formation flight for the smart city observation even in the presence of actuator faults.

In [A8], Zhao *et al.* propose an event-triggered ADP for nonzero-sum games of continuous-time nonlinear systems with completely unknown system dynamics. Compared with the traditional time-triggered mechanism, the proposed algorithm updates the neural network weights as well as the inputs of players only when a state-based event-triggered condition is violated. It is shown that the system stability and neural network weight convergence are still guaranteed under mild assumptions with reduced demand on communication and computation resources.

Inspired by how some biological organisms make decisions collectively, such as that of a honeybee swarm searching for a new colony, Li *et al.* [A9] study the dynamic collective choice problem for a large number of heterogeneous agents under the influence of adversarial disturbances. To address this problem, they present a new robust mean-field game (RMFG) with respect to non-convex and non-smooth cost functions. Optimal control strategies are designed through Nash certainty equivalence principle. The proposed method provides a decentralized approach to realizing the collective decision-making behavior emerged in biological systems.

III. Bio/Neural-Inspired Computing

Biological brains effectively avoid catastrophic forgetting through the cooperation of three brain regions: hippocampus, neocortex and prefrontal cortex. The hippocampus and the neocortex contribute to specific and generalized forms of memory, respectively. The interplay of such two memory systems can be mediated by the prefrontal cortex. Inspired by such a brain strategy, Wang *et al.* [A10] propose a novel approach named triple memory networks for continual learning. This is the first attempt to model the triple-network theory (hippocampus-prefrontal cortex-(sensory) cortical modules) of the brain memory system for continual learning, which bridges the two fields of artificial neural networks and biological neural networks.

Neural coding, including encoding and decoding, is a key subject in neuroscience for understanding how the brain uses neural signals to relate sensory perception and motor behavior with neural systems. In [A11], Xu *et al.* propose a transcoding framework to encode multi-modal sensory information into neural spikes and then reconstruct stimuli from spikes. This framework is not only feasible to accurately reconstruct dynamical visual and auditory scenes, but it also rebuilds the stimulus patterns from functional magnetic resonance imaging (fMRI) of brain activities. More importantly, it is characterized by its immunity to various types of artificial noise and noise from the ambient environment.

In [A12], Zhang *et al.* analyze problems that backpropagation (BP) faces in a deep spiking neural network (deepSNNs), namely, the nondifferentiable spike function, the exploding gradient, and the dead neuron problems. To address these issues, the authors propose a rectified linear postsynaptic potential function (ReL-PSP) for spiking neurons and a spike-timing-dependent BP (STDBP) learning algorithm for DeepSNNs. They evaluate the proposed method on both a multilayer fully connected SNN and a C-SNN. Evaluations using the MNIST dataset show an accuracy of 98.5% in the case of the fully connected SNN and 99.4% with the C-SNN, which is the state-of-the-art in spike-driven learning algorithms for DeepSNNs.

In [A13], Galan *et al.* present a novel digital implementation of a time difference encoder for temporal encoding on event-based signals. It translates the time difference between two consecutive input events into a burst of output events. The number of output events along with the time intervals between events encodes the temporal information. The proposed model has been implemented as a digital circuit with a configurable time constant, allowing it to be used in a wide range of sensing tasks that require encoding of time differences between events, such as optical flow-based obstacle avoidance, sound source localization, and gas source localization.

In [A14], using a "divide and conquer" strategy, Wu *et al.* propose a chain-structure echo state network (CESN) with stacked subnetwork modules as a new deep recurrent neural network. The network structure, mathematical model, training procedure, and stability analysis are studied for CESN. Then, the stochastic local search (SLS) algorithm is adopted to fine-tune the output weights of CESN in order to further enhance the accuracy and generalization ability of CESN. The experimental results based on four time series prediction tasks clearly demonstrate that the proposed SLS-CESN outperforms the BP, Elman, and ESN benchmarks.

Intrinsic plasticity (IP), which changes the intrinsic excitability of an individual neuron by adaptively tuning the firing threshold, has been shown crucial for efficient information processing. However, this learning rule imposes an overhead on computation time at each step, causing additional energy consumption and compromising computational efficiency. In [A15], Zhang *et al.* present two novel event-driven IP learning rules, namely, input-driven and self-driven IP, based on the basic IP learning. It is demonstrated that the two event-based IP rules significantly reduce IP updating operations, and thus result in sparse computation and accelerated processing of recognition tasks.

As an alternative approach in emulating biological functions of the human brain, oscillatory neural networks (ONNs) are potentially suitable for solving large and complex associative memory problems. In [A16], Todri-Sanial *et al.* investigate the dynamics of coupled oscillators to implement ONNs and present a novel method based on subharmonic injection locking (SHIL) for controlling the oscillatory states of coupled oscillators that allow them to lock in frequency with distinct phase differences. The circuit-level simulation results indicate the effectiveness of SHIL and its applicability to large-scale oscillatory networks for pattern recognition.

Inspired by memory replay and synaptic consolidation mechanism in the brain, a novel and simple framework termed memory recall (MeRec) for continual learning with deep neural network is presented by Zhang *et al.* [A17]. The authors propose a memory module to store statistical features from certain layers of deep networks and an orthogonal regularization to update the network. With both modules, deep networks are expected to remember knowledge from previous tasks. The experiment results show that MeRec outperforms previous state-of-the-art approaches with at least 50% accuracy drop reduction for several compared tasks. Furthermore, MeRec achieves this performance with a small memory budget (only two feature vectors for each class) for continual learning on CIFAR-10 and CIFAR-100 datasets.

Deep-learning-based methods have achieved remarkable performance in 3-D sensing since they perceive environments in a biologically inspired manner. Nevertheless, existing approaches trained by monocular sequences are still prone to failure in dynamic environments. In [A18], Sun *et al.* mitigate the adverse influence of dynamic environments on the joint estimation of depth and visual odometry (VO) through hybrid masks. They propose a cover mask and a filter mask to alleviate the adverse effects, respectively. As the depth and VO estimation are tightly coupled during training, the improved VO estimation promotes depth estimation as well. The experimental results show that both depth prediction and globally consistent VO estimation are state of the art when evaluated on the KITTI benchmark.

In [A19], Jang and Simeone investigate the capacity of probabilistic spiking neural networks (SNNs) to generate independent outputs when queried over the same input. It is shown that multiple output samples from probabilistic SNNs can be used during inference to robustify decisions and to quantify uncertainties - a feature that deterministic SNN models cannot provide. They also introduce an online learning rule based on generalized expectation–maximization (GEM) that follows a three-factor form with global learning signals and is referred to as GEM-SNN. The experimental results on the neuromorphic dataset MNIST-DVS are used to evaluate multisample inference and GEM-SNN learning rules, which has improved training and testing performance in terms of accuracy and calibration result over conventional single sample schemes.

In [A20], Ladosz *et al.* present a new bioinspired neural architecture that combines a modulated Hebbian network (MOHN) with deep Q-network (DQN), called as modulated Hebbian plus Q-network architecture (MOHQA), for solving partially observable Markov decision process (POMDP) problems. The key idea is to use a Hebbian network with rarely correlated bio-inspired neural traces to bridge temporal delays between actions and rewards when confounding observations and sparse rewards result in inaccurate TD errors. It was shown that the combination of DQN and MOHN can match and even outperform advanced algorithms such as A2C, AMRL, and QRDQN + LSTM on confounding POMDPs.

IV. Bio-Inspired Applications

Guo *et al.* [A21] propose a new distributed learning-based real-time optimization algorithm which mimics how human minds process information and make decisions by first reaching into their experience library followed by further fine-tuning. Their design addresses the allocation of power among all dispatchable and distributed energy resources in an islanded microgrid system. Under the proposed two-layer distributed framework, a group of deep neural networks coordinated by a dynamic average consensus algorithm is used to generate an approximated optimal solution. It is further finetuned by a balance generation and demand algorithm to obtain a global optimal solution. Case studies show that the proposed distributed learning framework achieves orders of magnitude speedup in computational time while guaranteeing similar optimal results to typical distributed numerical optimization methods.

Surface electromyography (sEMG) signals have been applied widely in the control of a prosthetic hand. however, signal dropping is common during sEMG signal acquisition due to wireless interference or failure during data transmission. To recognize hand gestures under mild signal dropping conditions, Duan and Yang [A22] propose a data split reorganization (DSR) strategy to fully utilize available data. The authors demonstrate improved performance in dealing with signal dropping by using a weighted multiple neural network voting (WMV) approach.

In [A23], Wang *et al.* propose a multi-objective evolutionary nonlinear ensemble learning model with an evolutionary feature selection mechanism (MOENE-EFS) for silicon prediction in a blast furnace. In MOENE-EFS, the input features of each base-learner are automatically selected by a multiobjective evolutionary algorithm, which makes it possible to discover potentially better input feature combinations that have a significant effect on the change of silicon content. The experimental results indicate that the proposed strategy is effective in improving the accuracy and stability of the prediction model and outperforms other prediction models based on both benchmark data and practical industrial data.

In [A24], Xing *et al.* propose a novel spiking neural network using three biologically plausible modules to imitate how multiple brain regions work together to create visual guidance when manipulating fragile objects in a tight operating space. The three brain regions, which include the visual cortex, cerebellum, and prefrontal cortex, are emulated to represent the functions of sensation, reaction, and prediction, respectively. Experimental results validate the proposed algorithm by showing collision-free movements with high precision.

Inspired by the biological self-repair mechanism of astrocytes, Hong *et al.* [A25] propose a self-repairing neuron network circuit that utilizes a memristor to simulate changes in neurotransmitters when a set threshold is reached. When faults occur in a synapse, the neuron module becomes silent or near silent because of the low release probability (PR) of the synapses. The damaged neuron can be repaired by enhancing the PR of other healthy neurons, analogous to the biological repair mechanism of astrocytes. This self-repairing circuit implemented on the robot provides improved tolerance to failure and effectively improves the dependability and stability of the robot.

In [A26], Ran *et al.* propose a novel edge-computing system for image recognition via memristor-based blaze block circuit. In the backward propagation, the authors use batch normalization (BN) layers to accelerate the convergence. In the forward propagation, the proposed circuit combines depthwise separable convolution neural network (DwCNN) layers/CNN layers with nonseparate BN layers, which means that the required number of operational amplifiers is reduced. The experimental results show that the proposed memristor-based circuit achieves an accuracy of 84.38% on the CIFAR-10 data set with advantages in computing resources, computation time, and power consumption.

In [A27], Raz and Akbarzadeh propose a chemo-mechanical cancer-inspired swarm perception (CMCISP) based on online nano fuzzy haptic feedback for early disease diagnosis and targeted therapy. Furthermore, a hybrid computational framework of the Cellular Potts Model (CPM) at mesoscale, swarm perception at the microscale, and fuzzy decision-making at the nanoscale is presented. Epithelial cancer cell's scaffold is performed as a carrier, its properties as a distributed perception mechanism, and its motility patterns of anti-durotaxis, blebbing, and chemotaxis as swarm movements. Cancer site convergence with CMCISP is analytically proved using swarm control theory and artificial potential functions. The numerical experiment results, based on actual clinical data from in vivo experiments, demonstrate the merits of the CMCISP in early cancer detection, converging to the cancer tumor, and improved normoxic cell density, even in a noisy environment.

Head direction cells (HDCs), found in the limbic system of animals, are proven to play an important role in identifying the directional heading allocentrically in the horizontal plane. However, practical HDC models that can be implemented in robotic applications are rarely investigated. In [A28], Bing *et al.* propose a computational HDC network that is consistent with several neurophysiological findings concerning biological HDCs. The authors demonstrated its implementation in robotic navigation tasks. The experiment results show higher accuracy of estimating the directional heading of the robot than the previous work and better robustness than the method that directly integrates the angular velocity.

In [A29], Wang *et al.* propose a multivariate variational mode decomposition and canonical correlation analysis (MVMD-CCA) algorithm to improve the recognition capability of steady-state visual-evoked potential (SSVEP) electroencephalogram signals. The algorithm takes advantage of electroencephalogram (EEG) signals characterized by multivariate modulated oscillations and multi-channel representation. First, MVMD is used to decompose non-linear and nonstationary EEG signals into a fixed number of sub-bands, so as to enhance the effect of SSVEP-related sub-bands. Then, CCA is performed between multivariate oscillations and reference signals, and the target frequency is identified according to the correlation coefficients. Offline experiments on a public dataset and the SSVEP-based online grasping experiment of Baxter robots are used to demonstrate the performance. It is shown that the recognition accuracy and the information transfer rate of the MVMD-CCA algorithm are significantly improved over the filter bank canonical correlation analysis (FBCCA) algorithm.

In [A30], Zhang *et al.* investigate the bin-packing problem in a changing environment, where a number of items of different shapes are to be packed at different time instances. By mimicking the experience-based reasoning process of humans, they propose a novel brain-inspired experience reinforcement model, which takes advantage of both biological and engineering systems, to derive an optimal decision process that maximizes the utilization of bins. The proposed model mimics functional coordination among brain regions by employing knowledge representation and knowledge extraction modules. The first module emulates the function of information processing and experience storage, and the second module is for training reasoning strategies and improve the decision performance. Experimental results validate that the proposed model is capable of adapting under information uncertainty and outperforms the state-of-the-art methods in solving bin packing problems in varying environments.

YONGDUAN SONG, *Editor-in-Chief*
School of Automation
Chongqing University
Chongqing 400044, China

JENNIE SI, *Guest Editor*
School of Electrical, Computer and Energy Engineering
Arizona State University
Tempe, AZ 85281 USA

SONYA COLEMAN, *Guest Editor*
Intelligent Systems Research Centre
University of Ulster
Londonderry BT48 7JL, U.K.

DERMOT KERR, *Guest Editor*
Intelligent Systems Research Centre
University of Ulster
Londonderry BT48 7JL, U.K.

APPENDIX: RELATED ARTICLES

[A1] H. Gao and L. Yin, "Bio-motivated two-level event-triggered controller for nonlinear systems," *IEEE Trans. Neural Netw. Learn. Syst.*, early access, Jan. 29, 2021, doi: 10.1109/TNNLS.2020.3047120.

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