# Guest Editorial
# Special Issue on New Developments in Neural Network Structures for Signal Processing, Autonomous Decision, and Adaptive Control

There has been continuously increasing interest in applying neural networks (NNs) to identification and adaptive control of practical systems that are characterized by nonlinearity, uncertainty, communication constraints, and complexity. The past few years have witnessed a variety of new developments in NN-based approaches for behavior learning, information processing, autonomous decision, and system control. Biologically inspired NN structures can significantly enhance the capabilities of information processing, control, and computational performance. New discoveries in neurocognitive psychology, sociology, and elsewhere reveal new neurological learning structures with more powerful capabilities in complex problem solving and fast decision in dynamic environments. The goal of the special issue is to consolidate recent new developments in NN structures for signal processing, autonomous decision, and adaptive control with application to complex systems. It includes contributions from a wide range of research aspects relevant to the topic, ranging from neural computing, adaptive control, cooperative control, autonomous decision systems, mathematical and computational models, neuropsychology decision and control, algorithms and simulation, to applications and/or case studies. This issue contains 24 papers and the contents of which are summarized below.

Bertsekas considers discrete-time infinite horizon problems of optimal control to a terminal set of states. These are the problems that are often taken as the starting point for adaptive dynamic programming (ADP). Under very general assumptions, the author establishes the uniqueness of solution of Bellman's equation, and provides convergence results for value and policy iteration (PI).

The paper by Kamalapurkar *et al.* provides an approximate online adaptive solution to the infinite-horizon optimal tracking problem for control-affine continuous-time nonlinear systems with unknown drift dynamics. To relax the persistence of excitation condition, model-based reinforcement learning is implemented using a concurrent learning-based system identifier to simulate experience by evaluating the Bellman error over unexplored areas of the state space. Tracking of the desired trajectory and convergence of the developed policy to a neighborhood of the optimal policy are established via Lyapunov-based stability analysis. Simulation results demonstrate the effectiveness of the developed technique.

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The work by Hausknecht *et al.* describes the learning and control capabilities of a biologically constrained bottom-up model of the mammalian cerebellum. Results are presented from six tasks: eyelid conditioning, pendulum balancing, PID control, robot balancing, pattern recognition, and MNIST handwritten digit recognition. These tasks span several paradigms of machine learning including supervised learning, reinforcement learning, control, and pattern recognition. Results over these six domains indicate that cerebellar simulation is capable of robustly identifying static input patterns even when randomized across the sensory apparatus. This capability allows the simulated cerebellum to perform several different supervised learning and control tasks. On the other hand, reinforcement learning and temporal pattern recognition both prove problematic due to the delayed nature of error signals and the simulator's inability to solve the credit assignment problem. These results are consistent with previous findings, which hypothesize that in the human brain, the basal ganglia are responsible for reinforcement learning while the cerebellum handles supervised learning.

Timely detection and identification of faults in railway track circuits is crucial to the safety and availability of railway networks. In the paper by Bruin *et al.*, the use of the Long Short-Term Memory Recurrent NN (RNN) is proposed to accomplish these tasks based on the commonly available measurement signals. By considering the signals from multiple track circuits in a geographic area, faults are diagnosed from their spatial and temporal dependences. A generative model is used to show that the LSTM network can learn these dependences directly from the data. The network correctly classifies 99.7% of the test input sequences, with no false positive fault detections. Additionally, the t-SNE method is used to examine the resulting network, further showing that it has learned the relevant dependences in the data. Finally, the authors compare their LSTM network to a convolutional network trained on the same task. From this comparison, they conclude that the LSTM network architecture better suited for the railway track circuit fault detection and identification tasks than the convolutional network.

In the work proposed by Rajagopal *et al.*, an offline ADP approach using NNs is proposed for solving a class of finite horizon stochastic optimal control problems. There are two approaches available in literature: one based on stochastic maximum principle (SMP) formalism and the other based on solving the stochastic Hamilton-Jacobi-Bellman (HJB) equation. However, in the presence of noise, the SMP formalism becomes complex and results in having to solve a couple of backward stochastic differential equations. Hence, current solution methodologies typically ignore the noise effect. On the other hand, the inclusion of noise in the HJB framework is very straightforward. Furthermore, the stochastic HJB equation of a control-affine nonlinear stochastic system with a quadratic control cost function and an arbitrary state cost function can be formulated as a path integral problem. However, due to curse of dimensionality, it might not be possible to utilize the path integral formulation for obtaining comprehensive solutions over the entire operating domain. An NN structure called "adaptive critic design" paradigm is used to effectively handle this difficulty. In this paper, a novel adaptive critic approach using the path integral formulation is proposed for solving stochastic optimal control problems. The potential of the algorithm is demonstrated through simulation results from a couple of benchmark problems.

The work by Vanli *et al.* studies online nonlinear learning over distributed multiagent systems, where each agent employs a single hidden layer feedforward neural network (SLFN) structure to sequentially minimize arbitrary loss functions. In particular, each agent trains its own SLFN using only the data that are revealed to themselves. On the other hand, the aim of the multiagent system is to train the SLFN at each agent as well as the optimal centralized batch SLFN that has access to all the data, by exchanging information between neighboring agents. We address this problem by introducing a distributed subgradient-based extreme learning machine algorithm. The proposed algorithm provides guaranteed upper bounds on the performance of the SLFN at each agent and shows that each of these individual SLFNs asymptotically achieves the performance of the optimal centralized batch SLFN. Our performance guarantees explicitly distinguish the effects of data- and network-dependent parameters on the convergence rate of the proposed algorithm. The experimental results illustrate that the proposed algorithm achieves the oracle performance significantly faster than the state-of-the-art methods in the machine learning and signal processing literatures. Hence, the proposed method is highly appealing for applications involving big data.

Li and Yang investigate the problem of adaptive fault tolerant synchronization control of a class of complex dynamical networks (CDN) with actuator faults and unknown coupling weights. The considered input distribution matrix is assumed to be an arbitrary matrix, instead of a unit one. Within this framework, an adaptive fault tolerant controller is designed to achieve synchronization for the CDN. Moreover, a convex combination technique and an important graph theory result are developed, such that the rigorous convergence analysis of synchronization errors can be conducted. Especially, it is shown that the proposed fault tolerant synchronization control approach is valid for the CDN with both time-invariant and time-varying coupling weights. Finally, two simulation examples are provided to validate the effectiveness of the theoretical results.

In the work by Zhou *et al.*, cluster synchronization on multiple nonlinearly coupled dynamical subnetworks of complex networks with nonidentical nodes and stochastic perturbations is studied. Based on the general leader–followers model, an improved network structure model that consists of multiple pairs of matching subnetworks, each of which includes a leaders' subnetwork and a followers' subnetwork, is proposed. Moreover, the dynamical behaviors of the nodes belonging to the same pair of matching subnetworks are identical, while the ones belonging to different pairs of unmatched subnetworks are nonidentical. In this new setting, the aim is to design some suitable adaptive pinning controllers on the chosen nodes of each followers' subnetwork, such that the nodes in each subnetwork can be exponentially synchronized onto their reference state. Then, some cluster synchronization criteria for multiple nonlinearly coupled dynamical subnetworks of complex networks are established, and a pinning control scheme that the nodes with very large or low degrees are good candidates for applying pinning controllers is presented. Suitable adaptive update laws are used to deal with the unknown feedback gains between the pinned nodes and their leaders. Finally, several numerical simulations are given to show the effectiveness and applicability of the proposed approach.

Mu *et al.* propose a novel composite control approach with learning and adaptation capabilities for an air-breathing hypersonic vehicle tracking control based on both ADP and sliding mode control (SMC). The control action is generated by the combination of SMC and the proposed ADP controller to track the desired velocity and the desired altitude. Specifically, the ADP controller is based on the derivation between the actual velocity/altitude and the desired velocity/altitude, and then provides a supplementary control action accordingly. As an ADP controller does not rely on the accurate mathematical model function, it is purely data-driven, and thus has very promising properties for uncertainties and noises. Meanwhile, it is capable to adjust its parameters online over time under various working conditions, which is very suitable for a hypersonic vehicle system. They verify the adaptive composite control approach versus the traditional SMC in the cruising flight, and provide three simulation studies to illustrate the improved performance with the proposed approach.

In the work by Zhang *et al.*, a novel LQR-based optimal distributed cooperative design method is developed for the synchronization control of general linear discrete-time multiagent systems on a fixed, directed graph. Sufficient conditions are derived for synchronization, which restrict the graph eigenvalues into a bounded circular region in the complex plane. The synchronizing speed issue is also considered and it turns out that the synchronizing region reduces as the synchronizing speed becomes faster. To obtain more desirable synchronizing capacity, the weighting matrices are selected by sufficiently utilizing the guaranteed gain margin of the optimal regulators. Based on the developed LQR-based cooperative design framework, the ADP technique is successfully introduced to overcome the (partially or completely) model free cooperative design for linear multiagent systems. Finally, two numerical examples are given to illustrate the effectiveness of the proposed design methods.

Chen *et al.* investigate the complete synchronization problem for the drive-response switched Boolean networks (SBNs) under arbitrary switching signals, where the switching signals of the response SBN follow those generated by the drive SBN at each time instant. First, the definition of complete synchronization is introduced for the drive-response SBNs under arbitrary switching signals. Second, the concept of switching reachable set starting from a given initial states set is put forward. Based on it, a necessary and sufficient condition is derived for the complete synchronization of the drive-response SBNs. At last, we give a simple algebraic expression for the switching reachable set in a given number of time steps, and two computable algebraic criteria are obtained for the complete synchronization of the SBNs. A biological example is given to demonstrate the effectiveness of the obtained main results.

Zhu *et al.* propose a data-driven model-free adaptive control method with dual radial basis function neural networks (RBFNNs) for a class of discrete-time nonlinear systems. The novelty lies in that it provides a systematic design method for a controller structure by the direct usage of I/O data, rather than using the first principle model or offline identified plant model. The controller structure is designed by equivalent-dynamic-linearization representation of the ideal nonlinear controller and the controller parameters are tuned by the pseudogradient information extracted from I/O data of the plant, which can deal with the unknown nonlinear system. The stability of the closed-loop control system and stability of the training process for RBFNNs are guaranteed by rigorous theoretical analysis. Meanwhile, the effectiveness and applicability of the proposed method are further demonstrated by the numerical example and Aspen HYSYS simulation of distillation column in crude Styrene produce process.

Wang and Le present a two-time-scale neurodynamic approach to constrained minimax optimization based on using two coupled NNs. One of the RNNs is used for minimizing the objective function and another is used for maximization. It is shown that the coupled neurodynamic systems operating in two different time scales work well for minimax optimization. The effectiveness and characteristics of the proposed approach are illustrated by using several examples. In addition, the proposed approach is applied for $H\infty$ model predictive control and real-time portfolio optimization.

In the work by Wang *et al.*, the issue of finite-time state estimation for coupled Markovian NNs subject to sensor nonlinearities is investigated, where the Markov chain with partially unknown transition probabilities is considered. A Luenberger-type state estimator is proposed based on incomplete measurements, and the estimation error system is derived by using the Kronecker product. By constructing a mode-dependent Lyapunov function, sufficient conditions are established, which guarantee that the estimation error system is finite-time bounded in a given interval. Then the estimator gains are proposed via solving a set of coupled linear matrix inequalities. Finally, a numerical example is given to illustrate the effectiveness of the proposed new design method.

Sahoo *et al.* present an approximate optimal control of nonlinear continuous-time systems in affine form by using the ADP with event sampled state and input vectors. The knowledge of the system dynamics are relaxed by using an NN identifier with event sampled inputs. An approximate solution to the HJB equation, which is referred to as a value function is generated by using an event-sampled NN approximator. Subsequently, the NN identifier and approximated value function are utilized to obtain the optimal control policy. Both the identifier and value function approximator weights are tuned only at the event-sampled instants leading to an aperiodic update scheme. A novel adaptive event sampling condition is designed to determine the sampling instants such that the approximation accuracy and stability are maintained. A positive lower bound on the minimum intersample time is guaranteed to avoid the accumulation point and the dependence of intersample time upon the NN weight estimates is analyzed in detail. The extension of the Lyapunov theory is utilized to guarantee the local ultimate boundedness of the resulting nonlinear impulsive dynamical closed-loop system. Finally, a numerical example is utilized to evaluate the performance of the near optimal design through simulation studies. The net result is the design of event-sampled ADP-based controller for nonlinear continuous-time systems.

Deng *et al.* study the problem of training the computer to beat the experienced traders for financial assert trading. They try to address this challenge by introducing a recurrent deep NN for real-time financial signal representation and trading. Their model is inspired by two biologically related learning concepts of deep learning (DL) and reinforcement learning (RL). In the framework, the DL part automatically senses the dynamic market condition for informative feature learning. Then, the RL module interacts with the deep representations and makes trading decisions to accumulate the ultimate rewards in an unknown environment. The learning system is implemented in a complex NN that exhibits both the deep and the recurrent structures. The authors hence propose a task-aware back propagation through time method to cope with the gradient vanishing issue in deep training. The robustness of the neural system is verified on both the stock and the commodity future markets under broad testing conditions.

Battiti and Brunato present a new algorithm based on multiscale stochastic local search with binary representation for training NNs. In particular, the authors study the effects of neighborhood evaluation strategies, the effect of the number of bits per weight and that of the maximum weight range used for mapping binary strings to real values. Following this preliminary investigation, they propose a telescopic multiscale version of local search where the number of bits is increased in an adaptive manner, leading to a faster search and to local minima of better quality. An analysis related to adapting the number of bits in a dynamic way is also presented. The control on the number of bits, which happens in a natural manner in the proposed method, is effective to increase the generalization performance. The method's learning dynamics are discussed and validated on a highly nonlinear artificial problem and on real-world tasks in different application domains; the algorithm is finally applied to a control problem requiring either feed-forward or recurrent architectures for feedback control. The results demonstrate the effectiveness of the proposed method.

In the work by Wang and Song, the problem of containment control of networked multiagent systems is considered with special emphasis on finite-time convergence. A distributed neural adaptive control scheme for containment is developed, which, different from most existing results, is able to achieve dynamic containment in finite time with sufficient accuracy despite unknown nonaffine dynamics and mismatched uncertainties. Such a finite time feature, highly desirable in practice, is made possible by the fraction dynamic surface control design technique based on the concept of virtual fraction filter. In the proposed containment protocol, only the local information from the neighbor followers and the local position information from the neighbor leaders are required. Furthermore, since the available information utilized is local and is embedded into the control scheme through fraction power feedback, rather than direct linear or regular nonlinear feedback, the resultant control scheme is truly distributed. In addition, although mismatched uncertainties and external disturbances are involved, only one single generalized neural parameter needs to be updated in the control scheme, making its design and implementation straightforward and inexpensive. The effectiveness of the developed method is also confirmed by numerical simulation.

Hierarchical NNs have been shown effective in learning representative image features and recognizing object classes. However, most existing networks combine the low/middle level cues for classification without accounting for any spatial structures. For applications such as understanding a scene, how the visual cues are spatially distributed in an image becomes essential for successful analysis. Li *et al.* extend the framework of deep NNs by accounting for the structural cues in the visual signals. In particular, two kinds of NNs have been proposed. First, the author develops a multitask deep convolutional network, which simultaneously detects the presence of the target and the geometric attributes (location and orientation) of the target with respect to the region of interest. Second, a recurrent neuron layer is adopted for structured visual detection. The recurrent neurons can deal with the spatial distribution of visible cues belonging to an object whose shape or structure is difficult to explicitly define. Both networks are demonstrated by the practical task of detecting lane boundaries in traffic scenes. The multitask convolutional neural network provides auxiliary geometric information to help the subsequent modeling of given lane structures. The RNN automatically detects lane boundaries, including those areas containing no marks, without any explicit prior knowledge or secondary modeling.

The work by Song *et al.* establishes an off-policy integral reinforcement learning (IRL) method to solve nonlinear continuous-time non-zero-sum (NZS) games with unknown system dynamics. The IRL algorithm is presented to obtain the iterative control and off-policy learning is used to allow the dynamics to be completely unknown. Off-policy IRL is designed to do policy evaluation and policy improvement in PI algorithm. Critic and action networks are used to obtain the performance index and control for each player. Gradient descent algorithm makes the update of critic and action weights simultaneously. The convergence analysis of the weights is given. The asymptotic stability of the closed-loop system and the existence of Nash equilibrium are proven. Simulation study demonstrates the effectiveness of the developed method for nonlinear continuous-time NZS games with unknown system dynamics.

$H_\infty$ control is a powerful method to solve disturbance attenuation problems that occur in some control systems. The design of such controllers relies on solving the zero-sum game. But in practical applications, the exact dynamics is mostly unknown. Identification of dynamics also produces errors that are detrimental to the control performance. To overcome this problem, an iterative adaptive dynamic programming algorithm is proposed by Zhao *et al.* to solve the continuous-time, unknown nonlinear zero-sum game with only online data. A model-free approach to the Hamilton–Jacobi–Isaacs equation is developed based on the PI method. Control and disturbance policies and value are approximated by NNs under the critic–actor–disturber structure. The NN weights are solved by the least-squares method. According to theoretical analysis, their algorithm is equivalent to a Gauss–Newton method solving an optimization problem, and it converges uniformly to the optimal solution. The online data can also be used repeatedly, which is highly efficient. Simulation results demonstrate its feasibility to solve the unknown nonlinear zero-sum game. When compared with other algorithms, it saves a significant amount of online measurement time.

Wang *et al.* establish a complex-valued memristive recurrent neural network (CVMRNN) model to study its existence, uniqueness of equilibrium point, as well as its exponential stability. Using the differential inclusion theory and the definition of homeomorphism, sufficient conditions of the existence and uniqueness of the equilibrium point are derived. Furthermore, sufficient criterion of exponential stability for the CVMRNNs is obtained by the Lyapunov theory.

Wu and Yang investigate the problem of adaptive output NN control for a class of stochastic nonaffine and nonlinear systems in the presence of actuator dead-zone inputs. The priori knowledge of the bound of the derivative of the nonaffine and nonlinear function is not required. By employing NNs to approximate the appropriate nonlinear functions, the corresponding adaptive NN tracking controller with the adjustable parameter updated laws is designed via backstepping technique, which ensures that all the closed-loop signals are bounded in probability, and the system output tracking error can converge to a small neighborhood in the sense of mean quartic value.

In the work by Zhang *et al.*, the problem of sampled-data synchronization for Markovian NNs with generally incomplete transition rates is investigated. Unlike traditional Markovian NNs, each transition rate is treated completely unknown or only its estimate value is known, making the proposed model more practical. The time-dependent Lyapunov–Krasovskii functional is constructed to synchronize drive system and response system. By applying an extended Jensen's integral inequality and Wirtinger's inequality, new delay-dependent synchronization criteria are obtained, which fully utilize the upper bound of variable sampling interval and the sawtooth structure information of varying input delay. In addition, the desired sampled-data controllers are obtained.

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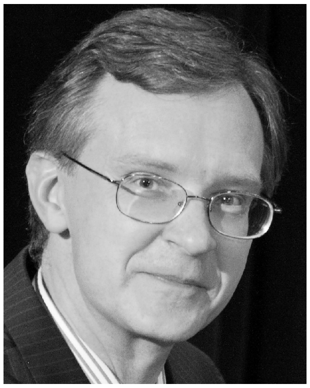

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