Introduction to the Special Issue on Fuzzy Analytics and Stochastic Methods in Neurosciences

NEUROSCIENCE investigates the structure and function of the nervous system at various scales that range from molecular and cellular biology to the organizational principles of perception, behavior, and cognition of humans. Recent theoretical and technological advancements provide new and deeper insights into the fundamental mechanisms of information processing in the neural system. This important process is accompanied by the tremendous rise of experimental data, which are waiting for further exploration. Modern methodologies and tools from neuroimaging, brain imaging, optogenetic devices, and *in vitro* and *in vivo* multielectrode recordings today generate high-quality neurophysiological data with a resolution quality that has never been reached before. These accelerating developments offer promising pathways to enhance our comprehension of the nervous system. Most innovative approaches of computational neuroscience lead to more realistic biophysical models that provide amazing chances for refined analyses of intracellular signaling and dynamics in heterogeneous neural networks, intrinsic connections of space-time processes, multisensory integration, and conditional behavior or links between brain regions in economic and daily-life decision making.

Significant computational challenges arise from the high complexity of neural systems and the large number of constituents with yet unknown functional interconnections. A scientific effort that is highly characteristic consists of the invention of mathematical model classes that imply the multiple influences of noise, uncertainty, and, especially, fuzziness and stochasticity in both their static and time-dependent counterparts. The quality of prediction by a model hinges on a smart integration of imprecise or missing data and the quantification of uncertain structural parameters. An elaborated analysis of the impact of all those classes of randomness is indispensable for appropriate and creative preparation of reliable neuro-computational systems and models.

This IEEE TFS Special Issue has succeeded to cover a broad range of subjects in the modern areas of neuroscience, by navigating and benefitting from the emerging advances in the sectors of neurocomputational models and simulations under randomness such as fuzzy-based computational models and fuzzy-trace theory as well as stochastic neural computation, neural and brain modeling with stochastic differential equations, and stochastic regime switching.

This Special Issue is collating together *fuzzy* and *stochastic* methods. We would like to highlight that we have included some articles which focus primarily on *nonfuzzy* approaches as comparators to the *fuzzy approaches*. The intention has been been to compare and contrast the two approaches and to stimulate further *fuzzy* research in the area.

Based on highly careful and rigorous reviewing processes, 11 papers were accepted for publication and became part of this exclusive collection of articles—our IEEE TFS Special Issue. Short descriptions of them subsequently follow.

In their article entitled "Firing rate oscillation and stochastic resonance in cortical networks with electrical–chemical synapses and time delay," H. Yu *et al.* study the stochastic dynamics of neural networks and find the phenomenon of stochastic resonance in inhibitory neurons, with firing rate close to the frequency of external stimulation. Time delay in the neural coupling process can induce multiple stochastic resonances at integer multiples of the oscillation period of the input signal. The authors discover that the time delay can induce a periodic oscillation of the neural firing rate, being a potential cause of multiple stochastic resonances. As gap-junction and inhibitory–inhibitory chemical coupling become stronger, the maximal resonant value increases, whereas the resonant frequency remains unchanged. However, along with the coupling strength of excitatory–inhibitory chemical synapses, also the resonant frequency and peak value increase. The authors apply the mean-field theory to a time-delayed network model to validate the obtained numerical results. Both time-delay and electrical–chemical synapses are very important for firing rate oscillation and stochastic resonance within the cortical network, determining the ability to enhance information transmission in neural systems.

In the article "Extraction of SSVEPs-based inherent fuzzy entropy using a wearable headband EEG in migraine patients," Z. Cao *et al.* present a novel application of multiscale relative inherent fuzzy entropy, which reflects the robustness of brain systems, using repetitive steady-state visual evoked potentials (SSVEPs) to investigate an EEG-complexity change between two migraine phases: interictal (baseline) and preictal (before migraine attacks) phases. The authors employ a wearable headband EEG device to collect EEG signals from 80 participants [40 migraine patients and 40 healthy controls (HCs)] under two basic conditions. They find a significant enhancement in occipital EEG entropy with increasing stimulus times in both HCs and patients in the interictal phase, but a reverse trend in patients within the preictal phase. Regarding the transitional variance of EEG entropy between the first and fifth SSVEPs, patients in the preictal phase exhibit significantly lower values than patients in the interictal phase. In the classification model, AdaBoost ensemble learning shows an accuracy of $81 \pm 6\%$ and AUC of 0.87 for classifying the interictal and preictal phases. In contrast, there are no differences in EEG entropy among groups

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or sessions by using the other competing entropy models, including approximate entropy, sample entropy and fuzzy entropy. Hence, an inherent fuzzy entropy offers novel applications in visual stimulus environments and may provide a preictal alert to migraine patients.

The main aim of the article by P. Masulli *et al.*, "Fuzzy clustering for exploratory analysis of EEG event-related potentials," is to provide a method for the unsupervised analysis of electroencephalography (EEG) data focused on event-related potentials (ERPs). The new approach implies a fuzzy clustering algorithm based on possibilistic clustering and includes a data-driven noise and artifact rejection phase. Before the clustering step, the authors apply weights to the feature vectors, optimizing them to enhance the variance within the dataset, and they compute interval-valued features based on the time windows of different lengths. The data processing workflow captures the differences and similarities in a set of epochs of EEG signals and groups them meaningfully related to the experimental conditions. The analysis is applied to a set of ERPs recorded during an emotional Go/NoGo task. The authors compute a measure based on the clusterization rate of trials in different experimental conditions to evaluate the performance of the unsupervised analysis.

In their article "Multiple stochastic resonances and oscillation transitions in cortical networks with time delay," H. Yu *et al.* provide an analytical comprehension of how time delay affects the stochastic resonance and firing rate oscillation of cortical neuronal networks. Stochasticity and oscillation are vital in neural signal processing; time delay has a significant effect on the dynamics of neuronal networks. A cortical network is established and mean-field theory is applied to analytically compute the dynamical response of networks. If the frequency of external stimulation is near to the intrinsic frequency of neuronal networks, the firing rate shows coherent oscillation and stochastic resonance in inhibitory neurons. Time delay can induce multiple stochastic resonances, appearing intermittently at integer multiples of the period of the input signal, due to the transition of network dynamics induced by time delays. The fluctuation of membrane potential and instantaneous firing rate of cortical networks attain its maximum periodically with the variation of time delay. Furthermore, time delay and electrical coupling play complementary roles in determining network responses. Network oscillation can transit from unstable to stable, when the coupling strength exceeds a critical value. The transition threshold is lower for time delays close to the integer multiples of the input period, where the resonant response of cortical network enhances the formation of stable oscillation.

In the article "Self-supervised learning for specified latent representation" by C. Liu *et al.*, the authors attempt to propose a specified latent representation with physical semantic meaning, as the current latent representation methods by unsupervised learning have no semantic meaning, i.e., it is hard to directly express their physical tasks in the real world. First, a few labeled samples are used to generate a framework of latent space; these labeled samples are mapped to framework nodes in the latent space. Second, a self-learning method using structured unlabeled samples shapes the free space between the framework nodes in the latent space. The offered specified latent representation, therefore, possesses the advantages provided by both supervised learning and unsupervised learning. The new methodology is verified by numerical simulations and real-world experiments.

The article of H. Yu *et al.*, named "Supervised network-based fuzzy learning of EEG signals for Alzheimer's disease identification," presents a novel machine learning method *"network-based Takagi–Sugeno–Kang"* (N–TSK) for Alzheimer's disease (AD) identification, which employs the complex network theory and TSK fuzzy system. The topological features of weighted and unweighted networks are extracted by the construction of functional network of AD subjects. Treating the network parameters as independent inputs, a fuzzy-system-based TSK model is developed and further trained in order to identify AD EEG signals. Experimental results show the effectiveness of this new scheme in AD identification and the ability of N–TSK fuzzy classifiers. The highest accuracy can achieve 97.3% and 94.78% for patients with closed or open eyes, respectively. The performance of weighted N–TSK largely exceeds unweighted N–TSK. Through a further optimization of the network features utilized in the N–TSK fuzzy classifiers, local efficiency and clustering coefficient turn out to be the most effective factors in AD identification. The novel methodology offers a potential tool for identifying neurological disorders from the perspective of functional networks with EEG signal, especially for identification and diagnosis of AD.

In their article "Modeling of adaptive chemical plume tracing algorithm of insect using fuzzy inference," S. Shigaki *et al.* focus on a known engineering challenge, namely, the chemical plume tracing (CPT) problem. In nature, animals solve this CPT by modifying their behavior adaptively, according to a turbulent environment. Thus, the authors propose a CPT methodology of high engineering value by modeling the CPT algorithm of an animal; in fact, as a model, they consider a male silkworm moth. The authors perform simultaneous measurement experiments including CPT behavior and explore the links between the brain's neural activity and behavioral patterns. Moreover, they measure the brain's neural response in the lateral accessory lobe (LAL) that generates motion commands. To analyze the relationship between the CPT behavior and LAL neural activity, the authors employed fuzzy inference. Eventually, they modeled the obtained phenomenon and verified its effectiveness through a constructive method. Compared with the conventional moth algorithm, the search performance has become improved.

In the article "Classification of motor imagery task by using novel ensemble pruning approach," M. A. Ali *et al.* use ensemble methods and generate an algorithm for EEG classification evoked by an motor imagery (MI) task. In fact, a brain–computer interface (BCI) assists communication, especially, for the disabled and handicapped. BCIs usually are EEG based and include MI. EEG signals are known for being nonstationary and sensitive to artifacts from various sources, such as physical and mental state of a patient, his/her mood, and any external noise or distraction. Processing these data directly affects the classification accuracy. Ensemble learning has been employed and proven to be robust for many kinds of BCI classification applications, including MI and P300 ERPs. In order to achieve their goal, the authors extract features from an EEG dataset and train a range of SVMs to establish a diverse ensemble of classifiers. Then, this ensemble is pruned and optimized with a difference-of-convex-functions optimization algorithm that was not applied on the EEG data before.

The article of M. Liu *et al.*, "Fuzzified image enhancement for deep learning in iris recognition," is concerned with a stable and secure biometric modality which has been a primary method for people identification: iris recognition. Deep learning techniques have attained good results for it, but the deep learning methods are computationally expensive and time consuming and for eyelashes, skin, and background noise, the model requires a high number of iterations to get meaningful iris patterns. Multiple iris segmentation techniques can be applied to target irises, but because of some nonideal situations, it is hard to get good boundary detection of pupil and iris; then, discarding the rest parts beyond the boundary can lead to a loss of valuable information. Therefore, the authors employ Gaussian, average, and median smoothing filters to preprocess the image in order to improve the signal-to-noise ratios, by fuzzifying the region beyond the boundary. In fact, they apply the enhanced images through fuzzy operations to train deep learning methods, herewith accelerating the process of convergence and increasing the accuracy rate of recognition.

The main aim of the article by A. Veloz *et al.*, "Fuzzy general linear modeling for functional magnetic resonance imaging analysis," is to provide a new functional magnetic resonance imaging (fMRI) processing pipeline that captures the intrinsic intra and intersubject variabilities of the haemodynamic response (HR). Actually, the classic fMRI analysis pipeline is based on the assumption that the HR is the same across brain regions, time, and subjects. But there is evidence that this assumption does not hold. The core of the new pipeline is the definition of a fuzzy haemodynamic response function (HRF), including a novel fuzzy general linear model (GLM) that is able to handle the fuzzy HRF, including a practical realization based on the LR representation of fuzzy numbers. The article also describes how to obtain activation maps from the fuzzy GLM, and how to compute the statistical power of the analysis. The method is evaluated in the synthetic and real fMRI data and compared with the other contemporary techniques. Experiments based on the synthetic data show that the fuzzy GLM approach is more robust under uncertainty regarding the true specific shape of the HR. Experiments made suggest that the presented method can prevent false negative errors in the boundaries of target brain regions in which HR should be negligible.

In their article entitled "$\mathcal{H}\infty$ filtering for fuzzy jumping genetic regulatory networks with round-robin protocol: A hidden-Markov-model-based approach," H. Shen *et al.* develop a method to design distributed filters for fuzzy jumping genetic regulatory networks. With a multisensor communication mechanism, the case where the filters cannot directly utilize the mode information of the plant is taken into account. The authors introduce a hidden Markov model to address such an obstacle. Furthermore, a mature scheduling method, called the round-robin protocol, is employed to optimize the data transmission among the sensor nodes of fuzzy jumping genetic regulatory networks. On the basis of both fuzzy model approach and stochastic analysis technique, some novel conditions are established that ensure the average $\mathcal{H}\infty$ performance constraint and stochastic stability of the error system. The distributed filter parameters can be presented via addressing a convex optimization problem. Finally, the feasibility of the results obtained is illustrated by addressing the fuzzy genetic regulatory networks subject to stochastic jumping parameters.

We, as guest editors, trust that this IEEE TFS special issue underlines and further strengthens the particular and unique position of IEEE TRANSACTIONS ON FUZZY SYSTEMS worldwide as a *Premium Journal* of academic excellence and scientific foresight of rigor and vision.

Now, it is up to us to wish you all great enrichment and pleasure when first browsing through and then reading in closer details this exciting work. We hope that it will benefit all humans scientifically, personally, and societally!

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