Guest Editorial
Special Issue on Hybrid Brain–Computer Collaborative Intelligent System

BRAIN–MACHINE fusion, also known as hybrid intelligence or brain–computer interface (BCI), is considered one of the most promising technologies of the 21st century. Its potential impact spans a wide range of disciplines, including cognitive science, information science, artificial intelligence, biology, neuroscience, and engineering. The research in this field aims to seamlessly integrate biological intelligence (i.e., the human brain) with machine intelligence (computers or robots) to create a new, powerful form of hybrid intelligence that far surpasses the limitations of current biological and machine intelligence systems. Brain–machine fusion not only signifies the convergence of cutting-edge science and technology but also heralds a new era in which the way humans interact with machines undergoes a profound transformation. The research in this field delves deep into the understanding of human thought processes and cognition, as well as the creation of novel sensory and motor channels to facilitate more natural and intuitive interactions. The scope of brain–machine fusion research extends beyond mere information exchange, encompassing the integration of emotions and motivations. Understanding and interpreting a user's emotional state and motivations are crucial for optimizing the performance of fusion systems, aiding in better meeting user needs and providing more personalized experiences. A key objective is enhancing a user's operational capacity in handling complex tasks. This can encompass highly intricate decision making, problem solving, and task execution, with broad applications in fields, such as healthcare, military, industry, and entertainment. Furthermore, brain–machine fusion necessitates the development of cognitive interaction models that can adapt actively to a user's cognitive characteristics and integrate with machine learning algorithms to achieve personalized adaptability in intelligent systems, thereby enhancing the level of interaction between the user and the system.

The development of hybrid brain–machine collaborative intelligence systems represents a complex and interdisciplinary endeavor aimed at achieving deeper levels of human–machine interaction and cooperation. The advancements in this technology will have far-reaching implications in fields, such as healthcare, education, entertainment, industrial automation, and many others, offering unprecedented opportunities to enhance the quality of life and drive the forefront of technology. However, the field of brain–machine fusion also comes with a range of ethical, privacy, and security challenges that require careful consideration and resolution. The ongoing developments in this field promise to bring both exciting prospects and challenges.

To achieve the aforementioned goals, the guest editors of the IEEE TRANSACTIONS ON COGNITIVE AND DEVELOPMENTAL SYSTEMS (TCDS) special issue conducted a comprehensive assessment of the originality, quality, and relevance of all submitted papers. Through a rigorous and thorough review process, 14 high-quality papers were selected for publication. These papers collectively provide practical and intriguing approaches from different perspectives aimed at improving the accuracy of methods related to brain–machine fusion. Through these carefully chosen papers, researchers can gain an intuitive understanding of the latest status, challenges, and future directions in brain–machine fusion-related research. The following is the detailed information on these papers.

For practical applications in brain–computer fusion, Lu et al. designed a 3-D tactile glove in [A1]. This glove combines pressure-sensitive force sensors and resistance bend sensors for object recognition. The study leverages deep learning methods to enhance recognition accuracy and highlights applications in human–machine interaction, prosthetics, and humanoid robot design.

In the context of cognitive state recognition in enhanced hybrid intelligent systems, the selected five research papers address issues related to emotion recognition and epilepsy identification. They aim to provide methodological references for the assessment of cognitive states in the human brain. Specifically, in [A2] by Li et al., a novel and effective emotion recognition method is proposed, which comprises two complementary modules: 1) TAR and 2) GCN. TAR optimizes the local pairwise positions of multichannel EEG sets, providing an improved graphical representation for GCN to classify the global correlations among these sets.

Graph convolutional neural network (GCNN)-based methods have been widely used in EEG-related works. However, their performance tends to deteriorate as network depth increases. To address this, Li et al. proposed the residual graph convolutional broad network (Residual GCB-Net) in [A3], which enhances the network's performance at deeper levels and extracts higher level information. Experimental results show the excellent classification performance of Residual GCB-net in EEG emotion recognition.

To fully explore other correlations between EEG channels, Kong et al. analyzed the interchannel interactions in [A4]. The

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causal relationship between EEG channels is used to construct an asymmetric causal graph with direction, and then depthwise separable convolution is adopted to extract emotional features from multichannel EEG signals. Experimental results show that the Granger causality is more effective in revealing the correlations between EEG channels in emotion recognition.

Steady-state visual evoked potentials (SSVEP) signals, known for their high signal-to-noise ratio and stable spectrum, have been considered as recognition features. However, current research predominantly relies on extracting features characterizing the activity of single brain regions, neglecting the functional coupling between different brain regions. Zhang et al. addressed this in [A5], proposing a novel approach that considers the functional connectivity of SSVEP signals collected by different electrodes as practical biometric features. Experimental results indicate that distinctive features in SSVEP functional networks among individuals can achieve high-precision identification potential. This suggests that SSVEP spectral coherence and phase synchronization hold promise for biometric applications.

To eliminate the need for an independent monitor to display stimulus targets, in the traditional SSVEP-BCI system, Fang et al. proposed a novel stimulation interface of the AR-based SSVEP-BCI system for the human–robot interaction in [A6]. The proposed system equipped with the robotic arm has both real-time performance and high accuracy, resulting in the potential to be used in complex and changeable scenarios.

Considering BCIs for human–machine interaction systems, three selected papers focus on EEG signal decoding and motion imagery, aiming to address human–machine interaction in collaborative cognitive systems. For instance, in [A7] by Sun et al., a novel framework is proposed, combining a gating mechanism and dilated convolutional neural network (GDCNN) to decode EEG signals induced by four different driving intentions. Experimental results indicate that GDCNN is beneficial for EEG decoding and holds potential applications in BCI systems based on video stimuli.

Previous research has explored the use of deep neural networks for motor imagery recognition based on EEG but mostly focused on individual subject recognition performance. These models struggled with the challenges posed by the individual differences and low signal-to-noise ratio in EEG signals. To address these issues, Zhang et al. focused on EEG-based motor imagery recognition in [A8] and introduced a co-teaching graph learning method. This method aims to strike a balance between generality and personalization, achieving higher accuracy in motor imagery recognition tasks. Experimental results prove the effectiveness of the proposed work and can be fine-tuned efficiently for new subjects.

To quantitatively analyze the different emotion states, Chao et al. applied exploratory cross-frequency coupling (CFC) and scaling analysis on different categories of emotions in [A9]. Experimental results show that the proposed work provides a theoretical basis for phase-amplitude coupling to regulate emotional process and proves the feasibility of the new method of emotional calculation, which has great prospects in auxiliary diagnosis.

In the realm of visual perception research for brain–computer fusion, An et al. introduced an enhanced visual coding model in [A10]. This model aims to simulate the biological characteristics of retinal ganglion cells to predict responses to visual stimuli accurately. Experimental results demonstrate that the proposed work has high accuracy, adaptability, and biological interpretability.

With the motivation of analyzing the attention patterns of depression patients from raw eye movement data while considering head movement, Yang et al. proposed a novelty ROI analysis method based on spatiotemporal clustering in [A11]. The proposed work has the potential to provide methodological reference on the assessment of mental disorders based on eye movements.

Considering that the existing motor priming strategies generally take dozens of minutes, leading to reduced effective treatment time and rehabilitation prescription flexibility. Sun et al. investigated the short-term priming effects using EEG in [A12]. Experimental results confirm that a few seconds of motor priming can promote subsequent motor training, supporting short-term motor priming as a feasible technique to improve rehabilitation efficiency.

In view of the complexity of functional magnetic resonance imaging (fMRI) data and the spatial dependencies in existing methods, Tong et al. presented a low-computational cost and spatially less dependent whole-brain functional segmentation algorithm for individual fMRI segmentation in 3-D space in [A13]. Experimental results indicate that this method exhibits reduced spatial structure dependencies and yields better functional segmentation results.

To accurately predict epilepsy before seizures, Wang et al. proposed a novel network with an extended series mean amplitude spectrum (MAS) of EEG signals in [A14]. Through rationally combining the spatial and temporal feature extraction modules with the extended series MAS features, STCARN receives high accuracy in the epilepsy detection tasks.

In conclusion, this special issue has presented 14 key research papers, all dedicated to the interdisciplinary exploration of brain–machine integration. These papers offer innovative approaches across various domains, and their outcomes hold the potential to make a significant impact on related research within the field of brain–machine integration. As guest editors, we wish to express our heartfelt gratitude to all the authors and reviewers who contributed their efforts to ensure the quality of the selected papers. In addition, we would like to express our heartiest gratitude for the great support of the Editor-in-Chief, Prof. Huajin Tang and the editorial office throughout the editing process of this special issue. We hope that all the selected papers will further accelerate the development of research in brain–machine integration and its related fields.

Appendix: Related Articles

[A1] X. Lu et al., "3-D tactile-based object recognition for robot hands using force-sensitive and bend sensor arrays," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1645–1655, Dec. 2023.

[A2] W. Li, M. Wang, J. Zhu, and A. Song, "EEG-based emotion recognition using trainable adjacency relation driven graph convolutional network," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1656–1672, Dec. 2023.

[A3] Q. Li, T. Zhang, C. L. P. Chen, K. Yi, and L. Chen, "Residual GCB-Net: Residual graph convolutional broad network on emotion recognition," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1673–1685, Dec. 2023.

[A4] W. Kong, M. Qiu, M. Li, X. Jin, and L. Zhu, "Causal graph convolutional neural network for emotion recognition," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1686–1693, Dec. 2023.

[A5] Y. Zhang, H. Shen, M. Li, and D. Hu, "Brain biometrics of steady-state visual evoked potential functional networks," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1694–1701, Dec. 2023.

[A6] B. Fang et al., "Brain–computer interface integrated with augmented reality for human–robot interaction," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1702–1711, Dec. 2023.

[A7] J. Sun, Y. Liu, Z. Ye, and D. Hu, "A novel multiscale dilated convolution neural network with gating mechanism for decoding driving intentions based on EEG," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1712–1721, Dec. 2023.

[A8] Y. Zhang et al., "Graph learning with co-teaching for EEG-based motor imagery recognition," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1722–1731, Dec. 2023.

[A9] J. Chao, S. Zheng, C. Lei, H. Peng, and B. Hu, "Exploratory cross-frequency coupling and scaling analysis of neuronal oscillations stimulated by emotional images: An evidence from EEG," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1732–1743, Dec. 2023.

[A10] L. An, Z. Yan, W. Wang, J. K. Liu, and K. Yu, "Enhancing visual coding through collaborative perception," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1744–1753, Dec. 2023.

[A11] M. Yang, C. Cai, and B. Hu, "Clustering based on eye tracking data for depression recognition," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1754–1764, Dec. 2023.

[A12] Z. Sun, Y.-C. Jiang, Y. Li, J. Song, and M. Zhang, "Short-interval priming effects: An EEG study of action observation on motor imagery," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1765–1772, Dec. 2023.

[A13] K. W. Tong, X.-Y. Zhao, Y.-X. Li, and P. Li, "Individual-level fMRI segmentation based on graphs," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1773–1782, Dec. 2023.

[A14] Q. Wang, C. Huang, Q. Zeng, C. Li, and T. Shu, "A spatiotemporal channel attention residual network with extended series mean amplitude spectrum for epilepsy detection," *IEEE Trans. Cogn. Develop. Syst.*, vol. 15, no. 4, pp. 1783–1794, Dec. 2023.

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