Guest Editorial
Neuro-Robotics Systems: Sensing, Cognition, Learning, and Control

NEURO-ROBOTICS systems (NRSs) are the most advanced research in the field of robotics, promoting the seamless exchange of knowledge between neuroscience and robotics. Recent breakthroughs in human brain neuroscience could be applied to robots to improve their perception, cognition, learning, and control abilities, which even help to develop a brain for robots. A challenge of robotics research is to break through technical bottlenecks by the findings in neuroscience and make robots move more flexibly, have more intelligent perception and control, and communicate with humans more naturally. To address the challenge, this special issue focuses on the latest advances in the area of NRS, particularly, the research concentrating on human-like sensing, multimodal information fusion, cognition, learning, and control technology. The development of these technologies aims to bring innovations into robotics and NRSs.

I. SCOPE OF THIS SPECIAL ISSUE

Although robotics has made many advancements, robots still cannot move as flexibly as humans, have limited intellectual perception and control, and cannot yet interact with environments like humans [item 1) in the Appendix]. However, the development of neuroscience makes it possible to break through these technical bottlenecks for developing robots with more flexible motions, higher intelligent perception, and better cognitive and learning capabilities. As a branch of neuroscience within robotics, NRS has been included in many countries' brain projects [items 2) and 3) in the Appendix], where achievements in brain science help to develop novel robotic models with neuro-inspired intelligence [items 4)–6) in the Appendix], simultaneously, novel discoveries in neuroscience can be achieved through advanced robotic platforms [items 7) and 8) in the Appendix]. With the framework of neuro-robotics, it is possible to endow a robot with a brain, which can generate control signals to drive the robot to move according to the environmental information perceived by a set of sensors. In turn, the robot's motions affects its future sensory inputs and, thus, brain and body cooperate with each other to respond appropriately to given stimuli.

There are mainly two aspects included in the research of neuro-robotics. One focuses on biologically inspired robots with bodies, sensors, and actuators that imitate the structure and function of organisms. Such robots generally have strong flexibility and adaptability, and rich perceptual and behavioral capabilities [item 9) in the Appendix]. The other devotes to brain-inspired control architectures, which are generally constructed for specific tasks through a combination of neural networks, computer vision, and machine learning algorithms [item 10) in the Appendix]. Based on these advancements, robots can be equipped with a strong body and even a "brain" so that they can not only do much more work but also be smart enough to implement complex tasks independently.

To this end, this special issue brings together the contributions of different research fields, such as human-like sensing, multidimensional information fusion, cognition, learning, and control technology, which also provides a comprehensive perspective on the research of NRSs. This issue looks forward to bringing innovations in robotics and NRSs.

II. CONTRIBUTIONS TO THIS SPECIAL ISSUE

This special issue includes 12 papers, each of which describes the latest advancements in neuro-robotics, spreading the topic of neuro-robotics from multiple perspectives. We briefly describe the main contributions of each paper as follows.

The special issue begins with a comprehensive survey of neuro-robotics: "Combined sensing, cognition, learning, and control for developing future neuro-robotics systems: A survey," by Li *et al.* This paper discusses the development of neuro-robotics, inspired by the advancements in the inevitable technologies, such as sensing, cognition, learning, and control. Especially, principal approaches and principal challenges facing the development of neuro-robotics, as well as some potential directions for future neuro-robotics are discussed in detail.

The second paper, "Multimodal human hand motion sensing and analysis—A review," by Xue *et al.*, extends the motion sensing function of NRS, especially, multimodal hand motion sensing. This paper reviews the development of multimodal hand motion sensing techniques and motion analytical methods for robotic revolution and innovation. Furthermore, frontier applications of hand motion analysis as well as the challenges and future directions are discussed.

The third paper, "Active visual-tactile cross-modal matching," by Liu *et al.*, inspired by human-like sensing mechanisms, develops an active visual-tactile cross-modal matching framework to solve the matching problem of tactile and visual

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modalities, which often appears in cognitive robotics. To address the problem of weak pairing between tactile and visual modes in the process of matching, this paper designs a shared dictionary learning model, which not only learns the projection subspace but also the potential shared dictionary for visual and tactile measurements. Then, the solution to the shared dictionary learning problem is obtained through an optimization algorithm. Finally, experiments on the PHAC-2 data sets verify that the developed framework is effective.

The fourth paper, "Fused fuzzy Petri nets: A shared control method for brain–computer interface systems," by Sun *et al.*, proposes a new shared control strategy based on fused fuzzy Petri nets (FFPNs) for brain–computer interface (BCI) systems. The proposed method combines fuzzy control with Petri nets to replace the robot automatic control or BCI control alone. This shared control system is asynchronous, that is, the user does not need to keep the brain working in a specific paradigm throughout the process. Barrett robot hand experiments for the task of grasping object show that the proposed shared control strategy has an increased success rate and improves safety and robustness of the system.

The fifth paper, "Bio-inspired equilibrium point control scheme for quadrupedal locomotion," by Shi *et al.*, inspired by the equilibrium point hypothesis and biological motor behaviors, sets up an equilibrium point control strategy to ensure the stable movements of a quadrupedal robot. The equilibrium point trajectories are appropriately modified from two perspectives: one directly compensates for the pose angle errors according to torso pose compensation; and the other relies on the foot force tracking algorithm and admittance model. Throughout this paper, the mechanism that the equilibrium point controller implements the dynamic balance of the robot without inputting inertial parameter identification or terrain information estimation can be obtained.

The sixth paper, "Episodic memory multimodal learning for robot sensorimotor map building and navigation," by Chin *et al.*, proposes a learning model for episodic memory, that is, enhanced episodic memory adaptive resonance theory (EEM-ART), which can encode a robot's experiences into the environment and generate a cognitive map. The proposed EEM-ART model contains multilayer ART networks, which can extract new events and encode the spatiotemporal connections among these events as episodes by gradually creating cognitive neurons. These episodes are then connected to build a sensorimotor map for real-time path planning and navigation.

The seventh paper, "An initiative service method based on fuzzy analytical hierarchy process and context intention inference for drinking service robot," by Hao *et al.*, proposes an active service algorithm for drinking service robots based on fuzzy analytic hierarchy process and context intention inference (FAHP-CII) to ensure the right amount water for people. A two-level hierarchical architecture based on human intentions and intention degrees is presented, where intention degrees are calculated by fuzzy Naïve Bayesian networks. It should be emphasized that this method takes into account the context features that affect human intentions, and obtains the relationship between the context features and intentions through FAHP. In addition, a demand analysis model that links human intentions with their demands is constructed so that robots can provide active drinking services according to humans' demands.

The eighth paper, "Fuzzy linguistic odor cognition for robotics olfaction," by Yan *et al.*, presents an odor cognition method based on fuzzy linguistics for robotic olfaction to help the robot to recognize the environment through odors. The proposed method aims to use the fuzzy linguistic rules to represent the brain-inspired knowledge, where the inputs are the signals perceived by the gas sensors on the robot's electronic nose and the output is the odor label. In addition, the proposed method is validated on two real robotic olfaction data sets, and is compared with other methods, such as decision tree, support vector machine (SVM), and neural network.

The ninth paper, "Evolving a sensory-motor interconnection structure for adaptive biped robot locomotion," by Saputra *et al.*, presents an evolving sensory-motor interconnection structure for a bio-inspired biped robot to minimize the constraints during locomotion. Sensory-motor coordination model is represented by the interconnections between sensory neurons and motor neurons, where the number of joints and the number of neurons in each joint are reconstructed by an evolutionary computation technique according to the environmental conditions, leading to the dynamic changes in the number of joints, the number of neurons, and the interconnection structure. The system is actually applied to a humanoid robot for running in several different environmental conditions.

Due to the advantage of regrasp planning in reorienting the object with kinematic constraints and collisions, the tenth paper extends it to develop new regrasp planning algorithms based on stable object poses: "Regrasp planning using stable object poses supported by complex structures," by Ma *et al.* Two processes in the developed regrasp planner are performed in parallel. One relies on a dynamic simulator to calculate instantaneous stable postures on given supporting structures. Another process is to build a regrasp graph through the steady states and find a series of reorient movements by searching the graph. Experimental verifications are carried out and compared to evaluate the performance of the developed planner.

Based on intracortical brain–machine interfaces, the eleventh paper investigates the potential of high-frequency local field potentials (LFPs) in movement intention decoding: "Using high-frequency local field potentials from multicortex to decode reaching and grasping movements in monkey," by Zhang *et al.* In this paper, wavelet packet transform (WPT) is adopted to extract the time–frequency features of high-frequency LFP signals, principal component analysis (PCA) is used for feature reduction, and then SVM acts as a decoder to recognize the reaching movements and grasping postures in the monkey. In the experiments, high decoding accuracy is achieved, which shows the effectiveness of the application of high-frequency LFP signals to motion intention decoding in brain–machine interfaces.

The twelfth paper, "Biologically inspired motion modeling and neural control for robot learning from demonstrations," by Yang *et al.*, proposes a learning framework for robots to learn human skills from demonstrations. Inspired by neurobiology and human behavior, the dynamic movement primitive (DMP) method is combined with the fuzzy Gaussian mixture model (FGMM) to make the robot learn from multiple demonstrations. Furthermore, a neural network based on a cerebellar model articulation controller (CMAC) is modified to track the motion trajectories produced by learning human skills from demonstrations, where CMAC is used for compensating for unknown robot dynamics. The successful pick-and-place tasks for a Baxter robot verify the effectiveness of the proposed method.

III. CONCLUSION

NRSs are an emerging multidisciplinary study of endowing robots with human-like sensing, sensorimotor learning, cognition and control abilities, allowing them to act like humans. This special issue extends the concept and function of NRS, and makes a set of contributions, from which we could draw some conclusions.

1) A robot with multiple sensors (e.g., vision, touch, olfaction, etc.) has the ability to perform more advanced human-like manipulations by sensory information fusion.
2) The essential memory function during learning and cognition allows robots to be better able to interact with different environments.
3) Bio-inspired control architectures are obtained by simulating humans or animals' nervous system, which help robots to adapt their behaviors autonomously with little knowledge of their kinematic configurations to prevent accidental disturbances, thereby achieving stable and robust movements.
4) In human–robot interaction, when endowed with the capability of understanding human emotions during human intention decoding, robots could meet human needs and serve people better. These contributions provide new perspectives and approaches to understand neuro-robotics, and paves the way for developing a real brain and an anthropomorphic mind for future robots [item 11) in the Appendix].

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APPENDIX
RELATED WORK

1) W. He, Z. J. Li, and C. L. P. Chen, "A survey of human-centered intelligent robots: Issues and challenges," *IEEE/CAA J. Automatica Sinica*, vol. 4, no. 4, pp. 602–609, Oct. 2017.
2) P. Dario *et al.*, "Robotics as a future and emerging technology: Biomimetics, cybernetics, and neuro-robotics in European projects," *IEEE Robot. Autom. Mag.*, vol. 12, no. 2, pp. 29–45, Jun. 2005.
3) K. Amunts, C. Ebell, J. Muller, M. Telefont, A. Knoll, and T. Lippert, "The human brain project: Creating a European research infrastructure to decode the human brain," *Neuron*, vol. 92, no. 3, pp. 574–581, 2016.
4) L. Zollo *et al.*, "An anthropomorphic robotic platform for progressive and adaptive sensorimotor learning," *Adv. Robot.*, vol. 22, no. 1, pp. 91–118, 2008.
5) H. Tang, R. Yan, and K. C. Tan, "Cognitive navigation by neuro-inspired localization, mapping, and episodic memory," *IEEE Trans. Cogn. Develop. Syst.*, vol. 10, no. 3, pp. 751–761, Sep. 2018.
6) G. Chen *et al.*, "Toward brain-inspired learning with the neuromorphic snake-like robot and the neurorobotic platform," *IEEE Trans. Cogn. Develop. Syst.*, vol. 11, no. 1, pp. 1–12, Mar. 2019.
7) E. Burdet, R. Osu, D. W. Franklin, T. Yoshioka, T. E. Milner, and M. Kawato, "A method for measuring endpoint stiffness during multi-joint arm movements," *J. Biomech.*, vol. 33, no. 12, pp. 1705–1709, 2000.
8) E. Burdet, R. Osu, D. W. Franklin, T. E. Milner, and M. Kawato, "The central nervous system stabilizes unstable dynamics by learning optimal impedance," *Nature*, vol. 414, no. 6862, pp. 446–449, 2001.
9) T. P. Tomo *et al.*, "A new silicone structure for uSkin—A soft, distributed, digital 3-axis skin sensor and its integration on the humanoid robot iCub," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2584–2591, Jul. 2018.
10) B. R. Cox and J. L. Krichmar, "Neuromodulation as a robot controller," *IEEE Robot. Autom. Mag.*, vol. 16, no. 3, pp. 72–80, Sep. 2009.
11) G. Sandini and A. Sciutti, "Humane robots—From robots with a humanoid body to robots with an anthropomorphic mind," *ACM Trans. Human–Robot Interact.*, vol. 7, no. 1, 2018, Art. no. 7.