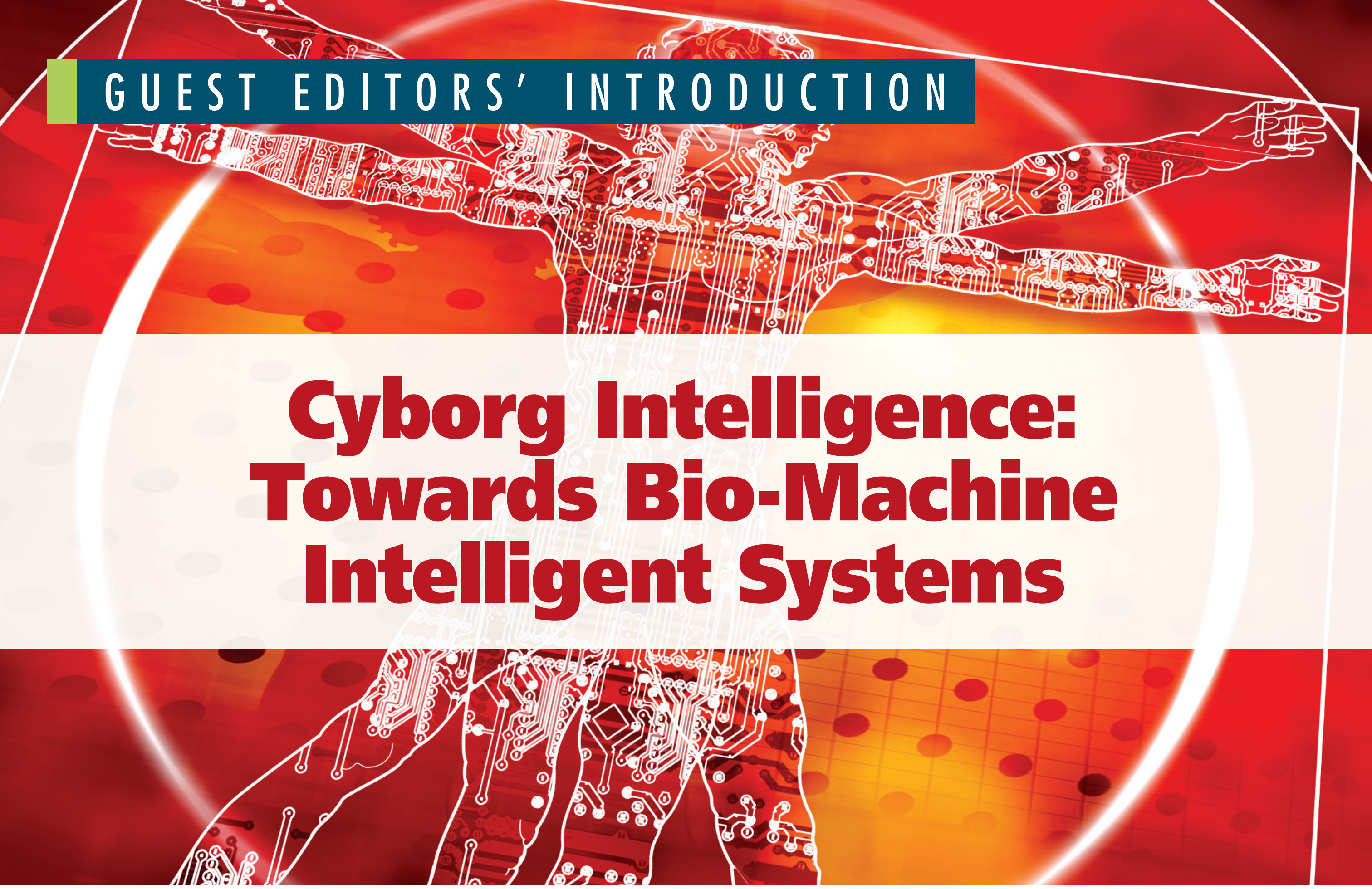

GUEST EDITORS' INTRODUCTION

Cyborg Intelligence: Towards Bio-Machine Intelligent Systems

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Artificial intelligence's goal is to design computers that process information and act like human brains. Several milestones in specific applications have been achieved in the last two decades. For example, the chess-playing computer, Deep Blue, defeated the world chess champion Garry Kasparov in 1997. The unpiloted vehicles by the Stanford Racing Team successfully completed a 212-km off-road course with more than 100 sharp left and right turns and won the 2005 DARPA Grand Challenge. The computer system of answering questions in natural language by IBM competed on the quiz show *Jeopardy!* against two former winners and won the prize in 2011. These advances highlight the growing importance of AI.

However, human-level AI remains impossible to achieve. All biological organisms display specific skills showcasing biological intelligence that is difficult to imitate. They possess special sensory capabilities (such as dogs, with their heightened olfactory senses), adaptability to living environments, and special cognitive capabilities (such as reasoning and planning). Naturally, biological and machine intelligence have their own intrinsic merits, and integration of both kinds of intelligence is emerging. From the biological side, machines can assist and augment biological beings, while from the machine side,

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biological beings may help solve machine tasks.[1]

Cyborg Intelligence

As research continues, the line between humans and machines begins to blur. In fact, AI is extending to include biological intelligence. For instance, in collective intelligence or crowdsourcing, the machine asks humans to solve a problem, then collects and integrates their solutions. However, in these approaches, the connection between humans and machines is loosely coupled in the traditional human-computer interaction manner.

Cyborg intelligence[2] is dedicated to integrating AI with biological intelligence by tightly connecting machines and biological beings, for example, via brain-machine interfaces (BMIs). BMIs bring the promise to enhance strengths and compensate for weaknesses by combining the biological perception/cognition ability with the machine's computational ability. Here, cyborg refers to a symbiotic bio-machine system, consisting of both organic and computing components. Tightly-coupled connection between the organic and computing parts is a key feature of cyborg intelligence.

There are two critical emerging technologies pushing the convergence of machine and biological intelligence. The first one is BMIs, often with real-time neurofeedback (NF). BMIs aim at a communication pathway in bridging the workings of machines and the brain. BMIs operate at the nexus of thought and action, exploiting the brain's electrical signals to maneuver external machine actuators and feeding the machine-coded neural information back to the brain to regulate the brain's behaviors. Bidirectional BMIs with real-time NF are promoting the connection of machines and the brain at multiple levels.

The second technology is neuromorphic computing, which further envisions the closely-coupled connection of the organic and computing components and machines. Neuromorphic computing uses digital, analog, and mixed-mode digital/analog circuits and software systems to mimic biological models of neural systems (such as perception, motor control, and multisensory integration). It often attempts to incorporate detailed behavior models of an individual neuron, even including realistic neural conductance and ion channel models. The fine-grained electric mimicry of the nervous system makes the machine side closer to the biological side. Thus, it reduces the difficulty in integrating machine and biological intelligence.

The future of cyborg intelligence may lead towards many promising applications such as neural intervention, rehabilitation, medical treatment, and early diagnosis of some neurological and psychiatric disorders. It may replace, repair, assist, and augment human sensory-motor or cognitive functions. For example, neuroprosthetics can replace a missing body part and still interface with the human nervous system and brain to increase precision and comfort of movements, or memory chips for restoring and enhancing memory function. Cyborg intelligence has the potential to make the bionic man reality. While cyborg intelligence has many potential exciting applications, research in this area is still in the preliminary stages.

In This Special Issue

For this special issue, we focus on work on models and applications of cyborg intelligent systems. Four articles were selected; three address models and one is an application article.

Computational modeling plays a very important role in cyborg intelligence. The first article, "A Computational Model of the Hybrid Bio-Machine MPMS for Ratbots Navigation" by Lijuan Su and her colleagues,[3] builds a rat cyborg, where electrodes are

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implanted in the medial forebrain bundle (MFB) so that real-time neural feedback can be achieved by micro-electric stimulus. With the rat cyborg system, a comprehensive computational model is presented for the novel multiple parallel memory system (MPMS). The model explains the learning and memory processes underlying the enhanced performance of the rat cyborg in maze navigation tasks. The authors also demonstrate that the computational model can predict the trial number to finish a maze task, matching well with behavioral experiments.

In high-level cognition, conceptualization is a fundamental step for knowledge, which is usually learned from many particular instances. In "Brain-Inspired Concept Networks: Learning Concepts from Cluttered Scenes,"[4] Juyang Weng and Matthew Luciw describe a brain-inspired concept network. Their work takes visual sensory modality as an example for exploration. Also, a learning algorithm is developed for building the concept network. As the article notes, the network acquires concepts through autonomous, incremental, and optimal self-wiring and adaptation. The concept network's goal is to generate current actions to direct its next internal operation. Its concepts aren't restricted by a handcrafted world model, as it learns and practices in an open-ended manner.

Machines and brains often need to collaborate, oriented for a task, in cyborg intelligent systems. The article on "Computational Cognitive Models for Brain-Machine Collaborations" by Zhongzhi Shi and his colleagues[5] presents cognitive models for three levels: the awareness-based model at the perception level, the motivation-based model at the information processing level, and the joint-intention-based model at the command execution level. The cognitive models mainly employ multiagent theory and techniques. These models could be helpful for brain-machine collaboration.

The final article in this special issue demonstrates an example of a cyborg intelligent systems. In "Toward Cyber-Enhanced Working Dogs for Search and Rescue,"[6] Alper Bozkurt and his colleagues report on a Cyber-Enhanced Working Dog (CEWD), connecting human and canine intelligence. The CEWD is bidirectional, and from the dog to machine, inertial sensors detect the dog's posture and behavior, while physiological states are monitored by non-invasive photo-plethysmogram and electrocardiogram. In the reverse direction, from machine to dog, haptic feedback and auditory cues are integrated to provide remote command and feedback delivery. The combined system is expected to amplify the remarkable sensory capacities of search-and-rescue dogs to save more lives.

These articles are a meager representation of some of the challenges and potential solutions emerging in this field. Research on cyborg intelligence is still in the preliminary stages. We hope that this collection provides insight into this exciting, fascinating, and productive area, and fosters future innovations.

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