SCANNING THE ISSUE

Engineering Intelligent Electronic Systems Based on Computational Neuroscience

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I. OVERVIEW

This special issue of the Proceedings of the IEEE focuses on elucidating computational neuroscience: an interdisciplinary field of scientific research in which one of the primary goals is to understand how electronic activity in brain cells and networks enables biological intelligence.

Our objective is to provide a selection of papers that expose and review research efforts in aspects of computational neuroscience that demonstrate its rapidly growing intersection with electrical, electronic and computer engineering, and the prospects for interaction in the near and long-term future.

Before providing a brief overview of each paper and their alignment with this objective in Section II, we first discuss the motivation and context.

The papers in this special issue reveal a rapidly growing intersection between computational neuroscience and electronic engineering, that is leading to advances in reverse-engineering of brain function, and new brain-inspired technologies.

A. Understanding and Emulating Biological Intelligence

For millennia, humans have observed animals performing physical feats that we could not match. Insects and birds fly, horses run at high speeds with great endurance, and fish survive their entire lives under water. Eventually we mastered mechanical design and energy storage to the extent that we can mimic, and in many cases surpass, the physical abilities of other animals.

Yet, although we have also discovered how to skillfully manipulate electrons in ways that have transformed society, we have failed so far at convincingly reproducing one aspect in which biological organisms, including humans, excel. Biological brains combine sensory information with past experience to make predictions and decisions that enable their survival in the physical world. That is, they exhibit intelligence.

It is, therefore, arguably the case that two of this century's grandest scientific challenges are to:

- discover and understand the neurobiological mechanisms that support processing, learning, and intelligence in biological brains;
- design engineered systems that replicate the capabilities of biological intelligence.

In 2013, the importance of these challenges was recognized by the European Union, who have provided more than $1 billion to research in the area of computational neuroscience, in the form of the "Human Brain Project." This project's stated aims include advancing knowledge about brain function and creating new brain-inspired computation technology. Subsequently, in 2013, the United States announced the similarly large-scale BRAIN initiative.

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This special issue is, therefore, especially timely because these initiatives coincide with tremendous progress recently in the field of computational neuroscience, some of which has been specifically enabled by electrical, electronic, and computer engineers. Many of these achievements are described in the papers of the issue, as summarized in Section II. First, however, we discuss historical context, as many readers may be unfamiliar with this field of research.

B. The Origins of Computational Neuroscience and Its Historical Links With Electronic Engineering

Given that neurons exhibit electrical activity, there are natural research links between electronics and neuroscience. For example, Alan Hodgkin and Andrew Huxley published a famous paper in 1952 entitled "A quantitative description of membrane current and its application to conduction and excitation in nerve" [1], in which they proposed an electrical circuit model of current flow across a nerve membrane. The model included resistive, capacitative and voltage-dependent ionic currents. The work of Hodgkin and Huxley was recognized by the 1963 Nobel Prize in Physiology or Medicine, jointly with John Eccles.

Before this, in the 1940s, Norbert Wiener and many colleagues developed an interest in studying problems that are common to both biological organisms and machines. In 1948, Wiener gave a name to this topic in his book *Cybernetics: Or Control and Communication in the Animal and the Machine* [2]. Chapter V of Wiener's book, "Computing Machines and the Nervous System," discusses computation in the brain in terms of the properties of neurons and synapses. Other work by Wiener and his contemporaries was instrumental in the development of modern control theory, which is today important in understanding biological motor control in computational neuroscience (see, for example, the papers by Kao *et al.*, Franceschini, Sejnowski *et al.*, and Stewart & Eliasmith in this issue).

Going back further in time, famous names in the history of electrical engineering also made seminal contributions in the discovery of electrical activity in the nervous system, including Luigi Galvani, Alessandro Volta, and Hermann von Helmholtz.

There is also some interesting history in this area within the PROCEEDINGS OF THE IEEE. For example, in 1959, a paper entitled "What the frog's eye tells the frog's brain," by Lettvin, Maturanat, McCulloch, and Pitts was published in the *Proceedings of the IRE* (the original name for the PROCEEDINGS OF THE IEEE) [3]. Another example from the same journal was the 1962 paper "An active pulse transmission line simulating nerve axon," by Nagumo, Arimoto, and Yoshizawa [4], which articulated a model that was to become known as the "Fitzhugh–Nagumo neuron model."

More recently, electronic engineering intersected with computational neuroscience in Carver Mead's influential work on neuromorphic engineering, described in his 1989 book *Analog VLSI and Neural Systems* [5]. This field of research employs analog very large-scale integration (VLSI) electronic circuits to mimic neurobiological circuitry. Mead and other pioneers of this field founded the Telluride Neuromorphic Engineering Workshop, which has been meeting annually since 1994. Twenty five years after Mead's book, neuromorphic engineering continues to flourish, as evidenced by papers in this special issue, such as those of Benjamin *et al.*, Hamilton *et al.*, and Rahimi Azghadi *et al.*

Today, there are numerous research avenues that link study of the nervous system with electronics, physics, mathematics, computer science, and technology. Such research has been described using any number of names. When such research has a scientific focus, it is labeled, for example, as computational neuroscience, systems neuroscience, theoretical neuroscience, mathematical neuroscience, neural modeling, neural coding, theoretical neurobiology, and integrative neuroscience. This kind of research can also be thought of as a subfield of computational biology or systems biology. Research with a dominant engineering design focus has been called, for example, neuromorphic engineering, neuroengineering, neurorobotics, and neural engineering.

Although this diversity of names for highly interrelated research is suggestive of both major and slightly different focuses and methodologies, it is arguably more significant for two facts that it also highlights:

- understanding the principles of computational brain function is a hard and complex problem;
- the nature of this problem necessarily requires application of multidisciplinary expertise.

The second fact is a current challenge in brain research. Researchers with different disciplinary training tend to approach the problem of understanding computation in the brain using methods that have been successful for other problems in their fields, and communicate their results in their "native" disciplinary language; this can be reflected in how the research becomes labeled.

However, the overall objective provides common ground, and differences are increasingly being overcome as researchers from diverse disciplinary backgrounds more frequently work together with the common aim of advancing knowledge about the brain, or utilizing knowledge about the brain in applications.

Of all the terms mentioned, we have used computational neuroscience, since it seems to be emerging as a consensus term across relevant disciplines. There is now a global Organization for Computational Neurosciences (OCNS), and Germany prioritizes research in the area, via their "National Bernstein Network Computational Neuroscience" with large research centers in many cities.

The term "computational neuroscience" itself is attributable to Prof. Eric Schwartz, now of Boston University (Boston, MA, USA), who coined the term as a name for a scientific symposium held in Carmel, CA, USA, in June 1987. As discussed in a resulting book published in 1990, the term "computational neuroscience" was introduced to contrast the differences between research that overlaps neuroscience and computer science, and the development of methods such as traditional artificial neural networks that, while of clear utility in engineering, have "no grounding or constraint in actually observed neural data." One of the papers in the book was also published by Sejnowski, Koch, and Churchland in the journal *Science* in 1988, under the title "Computational neuroscience" [6], and this helped to popularize the term.

We next turn our attention to articulating three specific areas within contemporary computational neuroscience that are arguably of most relevance to electrical, electronic, and computer engineering.

C. Contemporary Contributions of Electronic Engineering to Computational Neuroscience

Computational neuroscience is a broad interdisciplinary field, and its practitioners have diverse objectives, such as seeking understanding about the origins of mental disorders in neural circuit pathologies, designing biomedical interfaces between brains and computers, and proving mathematical theorems about neuronal information capacity. This special issue, therefore, does not seek to review the entire field, and excludes, for example, specific coverage of the design of electronic devices and software for experimental neuroscience usage, as well as engineering applications that are merely inspired by the brain, such as traditional artificial neural networks.

What the special issue does emphasize is three ways in which electrical, electronic, and computer engineers can best contribute to the problems of understanding computation in the brain and building intelligent systems that utilize this knowledge:

1) enabling technologies: the development of scientific sensors, data processing algorithms, and simulation platforms used by computational neuroscientists;
2) reverse engineering the brain: research that links empirical neuroscience evidence with hypotheses about how neurobiological systems manipulate information;
3) biomimetic/neuromorphic computation and robotics: imitation of neurobiological computation mechanisms in designed applications.

The following paragraphs expand on the motivation for focusing on these themes; given the objective of emulating biological intelligence, it is natural to discuss them in reverse order.

Mimicking neurobiology: The Wright brothers were the first to emulate bird flight by designing an aircraft that allowed controlled human flight. Electrical, electronic, and computer engineers are arguably those best placed to follow in their footsteps with respect to designing systems that match and exceed animal neurobiological intelligence.

Just as the Wright brothers did not design an aircraft with wings that flap, but still gained inspiration from observing how birds glide and turn, a practicable approach for replicating animal-like intelligence is to combine mimicry of selected aspects of neurobiological solutions with entirely different implementation mechanisms, such as silicon-based electronics.

Reverse-engineering the brain: Incorporation of useful insights from biology requires that we first understand how neurobiological computation mechanisms work, and this requires that we can make sufficiently detailed observations of them during their normal operating conditions. Given the extreme complexity of neurobiology, including multiple scales of biochemical, electronic, and anatomical organization spanning ions, molecules, cells, networks, and brain regions, obtaining necessary information and extracting principles has proven much more difficult than observing the mechanics of bird flight.

Design of enabling technologies: Nevertheless, the field of computational neuroscience aims to do exactly this. Partly due to enabling technology developed by engineers, such as fast hardware-based methods for running simulations, and partly due to scientific collaborations that benefit from the knowledge of engineers in designing information processing systems, it is beginning to mature and make progress toward its goals.

II. CONTENTS OF THE SPECIAL ISSUE

The three themes described above align with three schools of thought about how best to understand a complex system:

1) increase the quality and quantity of observations and data;
2) devise a hypothesis and test its validity;
3) the principle famously expressed by Richard Feynman: "*what I cannot create, I do not understand*."

Computational neuroscientists and engineers are beginning to collaborate in ways that combine all three approaches.

Will these interdisciplinary approaches solve the challenges in reverse-engineering animal intelligence? How do we best combine insights from biology with existing engineered platforms and algorithms? What obstacles need to be overcome in order to better observe real biological computation in action? These questions and partial answers are reviewed and discussed in the papers of this issue, which we summarize in this section.

Although we assign each paper to one main theme, many papers overlap themes, as suggested in Fig. 1. This figure also highlights four "objectives" that can be described as common objectives to electronic engineering and biological behavior. These "objectives" are: 1) sensing and motion;

Objective	Highly relevant IEEE Societies	Neuroscientific topics	Theme I: Enabling Technologies	Theme II: Reverse Engineering the brain	Theme III: Biomimetic Computation and Robotics
Sensing and Motion	Control Systems Instrumentation and Measurement Photonics Robotics and Automation Signal Processing Systems, Man and Cybernetics	Vision Audition Locomotion Echolocation Brain-machine interfaces	Kao et al	Franceschini Sejnowski et al Zucker	Bongard and Lipson Franceschini Stewart and Eliasmith
Computation and Learning	Computational Intelligence Computer Signal Processing Systems, Man and Cybernetics Solid-state Circuits	Spike codes Plasticity and learning Network dynamics Perception Attention Decision making	Benjamin et al Furber et al Kim et al Kao et al	Franceschini Jadi et al Rahimi Azghadi et al Sejnowski et al Sengupta and Stemmler	Hamilton et al Maass Stewart and Eliasmith
Devices and Communications	Antennas and Propagation Circuits and Systems Communications Electomagnetic Compatibility Electron Devices Information Theory	Neurons Synapses Dendrites Ion channels Neuronal microcircuits Connectomics	Benjamin et al Kim et al Rahimi Azghadi et al	Jadi et al Jadi and Sejnowski	Hamilton et al
Reliability and Energy	Engineering in Medicine & Biology Power and Energy Reliabiliity Systems, Man and Cybernetics	Mental disorders Brain injuries Brain-computer interfaces Evolution Noise Energy consumption Bionics	Benjamin et al Kao et al	Sengupta and Stemmler	Bongard and Lipson Hamilton et al Maass

Fig. 1. ***Summary of themes in this special issue, and summary of alignment of papers with each theme, engineering objectives, and IEEE Societies. Examples of neuroscientific topics under each objective are provided; not all of these are discussed in the papers.***

2) computation and learning; 3) (design/evolution of) devices and communications; and 4) reliability and energy efficiency. We have suggested against each objective which of the IEEE Societies are likely to be most relevant, with the aim of suggesting to readers with specific expertise which of the papers might be of most interest. For example, the paper by Kao *et al.* touches on control theory including feedback control and Kalman filters, and might be of interest to members of the IEEE Control Systems and Signal Processing Societies.

A. Theme I: Enabling Technologies and Tools

Furber *et al.* describe the design of a massively parallel computer that is suitable for computational neuroscience modeling of large-scale spiking neural networks in biological real time.

Kao *et al.* review systems that convert neural signals from motor regions of the brain into control signals to guide prosthetic devices, with a particular focus on how computational neuroscience knowledge informs the design of feedback control methods for increasing performance and robustness.

Kim *et al.* discuss challenges in analysis of modern neuroscience data sets that span multiple modalities and time scales. The paper reviews appropriate signal processing methods for addressing these challenges, such as hierarchical Bayesian inference.

Benjamin *et al.* describe the design of the first hardware system to provide computational neuroscientists with the capability of performing biological real-time simulations of a million neurons and their synaptic connections.

Rahimi Azghadi *et al.* review challenges and progress in silicon implementations of timing-based neuronal learning mechanisms.

B. Theme II: Reverse-Engineering the Brain

Biological brains use remarkably low power consumption in comparison with designed electronic systems. Sengupta and Stemmler review mathematical models that help computational neuroscientists understand the relationship between neuronal energy consumption and information processing capabilities.

Franceschini reviews the design and construction of small insect-like robots that navigate and control their motion using biologically inspired visual strategies and circuits designed based on knowledge from computational neuroscience.

Neurons are highly complex nonlinear systems. Jadi *et al.* review research into the computational capabilities that this complexity imparts to individual neurons.

In the context of discussing reinforcement learning in the brain, Sejnowski *et al.* describe the idea that brains form cognitive strategies by prospective optimization, which is the planning of future actions to optimize rewards.

Zucker discusses computational problems faced by the mammalian visual system, articulates theoretical models of its solution methods, and outlines the implications for computer vision applications.

Jadi and Sejnowski discuss the hypothesis that the narrowband oscillations frequently observed in electrical activity recorded from the brain are potentially important for coding and routing of information, as well as describing mathematical models that explain how neuronal networks in the brain can produce the observed oscillations.

C. Theme III: Biomimetic Computation and Robotics

Hamilton *et al.* review nondeterministic methodologies for computation in hardware, and introduce the concept of stochastic electronics, as a new way to design circuits and enhance performance in highly noisy and mismatched fabrication environments.

Random variability and stochastic noise are ubiquitous in neurobiology. Maass discusses biologically inspired machine learning methods based on theories about how the brain exploits noise to carry out computations, such as probabilistic inference through sampling.

Stewart and Eliasmith review a system capable of performing multiple cognitive functions using a combination of biologically plausible spiking neurons, and an architecture that mimics the organization, function, and representational resources used in the mammalian brain.

Bongard and Lipson discuss the two-way interaction between brains and bodies, and the consequences for adaptive behavior, along with reviewing research that builds on insights from the neurobiology of these interactions, to inform the design of evolving and adaptive robots.

III. CONCLUDING REMARKS

This special issue highlights that electrical, electronic, and computer engineers today increasingly contribute to contemporary computational neuroscience, and utilize its findings, through the design of enabling technologies, reverse-engineering the brain, and biomimetic/neuromorphic engineering. Given the relevance of electronic engineering to the long-term challenge of engineering electronic systems that emulate biological intelligence, there is every reason to expect continued growth in the interaction between engineering and neuroscience. Perhaps in coming years, this growth will result in new IEEE journals, such as an IEEE TRANSACTIONS ON COMPUTATIONAL NEUROSCIENCE.

In closing, we wish to express our sincere gratitude to all invited authors for their valuable contributions, and also to the reviewers who have put their time and effort into providing feedback to the authors. We also warmly thank Vaishali Damle, the Managing Editor, and Jim Calder, the now retired former Managing Editor, for the opportunity to create this special issue. We also gratefully acknowledge Jo Sun's tireless administrative assistance. ■

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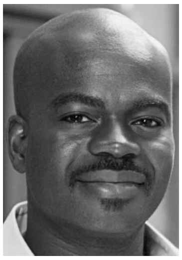

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Prof. Ijspeert has received the Best Paper Award at the 2002 IEEE International Conference on Robotics and Automation (ICRA2002), the Industrial Robot Highly Commended Award at CLAWAR2005, and the Best Paper Award at the 2007 IEEE-RAS International Conference on Humanoid Robots (Humanoids 2007), with his colleagues. He was an Associate Editor for the IEEE TRANSACTIONS ON ROBOTICS (2009–2013), and has acted as Guest Editor for the IEEE TRANSACTIONS ON MECHATRONICS, the IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, *Autonomous Robots*, and *Biological Cybernetics*. He is/was the Technical Program Chair of five international conferences, and has been a program committee member of over 40 conferences.

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Dr. Sejnowski is only one of 12 living scientists in all three of the National Academies: Sciences, Engineering, and Medicine. He received the IEEE Neural Networks Pioneer Award in 2002 and the IEEE Frank Rosenblatt Award in 2013.