Dario Farina, Arash Mohammadi, Tülay Adali,
Nitish V. Thakor, and Konstantinos N. Plataniotis

Signal Processing for Neurorehabilitation and Assistive Technologies

During the last few decades, the number of seniors over the age of 60 has increased significantly. A recent study from the United Nations has shown that the number of people aged 65 years or over will increase from 727 million in 2020 to 1.5 billion by 2050 [1]. Consequently, the proportion of the global population aged 65 years or over will increase from 9.3% in 2020 to 16% in 2050. In parallel with the aging of the world population, there has been an increase in age-related health issues, such as stroke, sensorimotor disorders, Parkinson's disease, and essential tremor, which significantly impact health-care systems. With a system that is underresourced, patients are transferred from hospitals to home while still suffering from major functional deficits. In this aging crisis, a potential solution is to develop technologies and techniques that can provide 1) efficient, effective, widely accessible, and affordable means of neurorehabilitation; and 2) intuitive and agile assistance to maximize the patients' independence during activities of daily living. Biosignal processing (BSP) plays an imperative role in the development of these advanced, intelligent, and dynamic rehabilitation and assistive solutions.

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Human–machine interfacing

Neurorehabilitation and assistive technologies are based on processing, decomposing, and decoding of bioelectrical, biomechanical, and biochemical signals. The nonstationary and nonlinear nature of biological signals requires innovative techniques beyond conventional approaches. The ultimate goal is to implement practical and effective augmentation techniques for the sensorimotor capabilities of patients to achieve either 1) the instantaneous replacement of lost functions (that is, assistive solution) or 2) the gradual enhancement of the residual functions (that is, rehabilitative solution). Achieving these goals require the development of human–machine interface (HMI) systems, which aim at the fusion of human neuromechanics and robotics.

Biosignal processing plays an imperative role in the development of these advanced, intelligent, and dynamic rehabilitation and assistive solutions.

HMIs have been substantially improved by recent advances in BSP and machine learning (ML), in particular through the use of deep neural networks. An ideal HMI should provide consistent, direct, intuitive, and accurate decoding of motor intent with minimal training and calibration. Furthermore, it should include sensory feedback mechanisms to enable bidirectional interaction, thus creating a closed control loop. Recent HMI systems, developed in research laboratories, have become increasingly sophisticated to address some of these goals. This has been achieved through the use of embedded mechatronic systems in combination with state-of-the-art ML modules and real-time BSP pipelines designed to achieve high robustness and versatility. The design of increasingly complex HMI systems is a challenging multidisciplinary BSP problem.

This special issue of *IEEE Signal Processing Magazine* (*SPM*) bridges several disciplines, including signal processing, robotics, machine intelligence, neuroscience, and statistics and control, applied to the domain of neurorehabilitation, neuroprosthetics, and assistive systems. It describes advanced real-time processing of multichannel and multimodal biological signals—for example, electroencephalogram (EEG), video, speech, electronystagmography (ENG), electrocorticography (ECoG), and electromyography (EMG)—for effective and alternative treatments and diagnosis, with applications in neurorehabilitation, neuroprosthetics, wearable health technologies, and hybrid brain–computer interfaces. The articles in this special issue address these challenges and provide an overview of HMIs for upper-limb prosthesis control, noninvasive brain stimulation, Internet-of-Things (IoT)–based assistive technologies, and neurosteered hearing devices.

In this issue

The first article of the special issue, by Ahmadizadeh et al., focuses on techniques used to process biosignals with the purpose of developing HMIs for upper-limb prosthesis control. This article provides an overview of the main research trends in this field, with a particular emphasis on three challenges: advanced data acquisition systems and intention prediction, intuitiveness of the control, and transfer to real-life situations. Emerging technologies in each of these categories are highlighted. A core aspect of this research is the need to fill the existing gap between research developments and commercially available devices in a translation effort based on solid clinical evaluation of technologies in research laboratories.

> **The articles in this special issue highlight the crucial importance of BSP in the field of neurorehabilitation and assistive technologies and provide insights on how BSP will enable future directions in this research area.**

The next article, by Dantas et al., provides an overview of technologies and algorithms for decoding movement intent from bioelectrical signals, such as EMG, EEG, ENG, and ECoG. First, the article reviews traditional movement decoders based on Kalman filters and ML models. Then, to mitigate the identified deficiencies of these conventional methods, three approaches are reviewed: 1) data aggregation-based training to improve decoder performance when only limited amounts of training data are available; 2) a shared controller that incorporates estimates of movement goals; and 3) an adaptive decoder designed to compensate for time variations in human–machine interaction. The numerous actions in complex tasks and the nonstationary neural states form a vast and dynamic state-action space, imposing a computational challenge in the decoder to detect the emerging neural patterns and to quickly establish and adjust the globally optimal policy.

In the next contribution, Wang and Principe focus on reinforcement learning (RL) methods implemented in reproducing kernel Hilbert space to address the challenges imposed on decoder design. RL-based decoders enable the user to learn the interaction with an external system without desired target signals and to better represent the subject's goal to complete the task. The RL decoder needs to assign credit not only over time but also over space, that is, to infer potential goals over multiple objects and devise the best trajectory. This work shows the potential to advance brain–machine interface design toward online continuous learning of tasks as required for full restoration of motor function.

ML models have been introduced to both decode and interpret features in EMG signals for myoelectric control. In their article, Shehata et al. present an overview of how ML is used in EMG signal-driven upper-limb prostheses control, along with a discussion of the need for improving the robustness and reliability of these devices.

As stated previously, the rapidly aging population worldwide has spurned interest in developing new strategies to cope with age-related neural decline and neurodegenerative disorders. Noninvasive brain stimulation (NIBS) is being increasingly used to both explore functional mechanisms of the brain and to induce therapeutic modulation of behavior, cognition, and emotion. Liu et al. focus on galvanic vestibular stimulation (GVS), a safe and well-tolerated NIBS technique that modulates the activity of cortical and subcortical areas involved in vestibular and multisensory processing. A key facet of GVS is that the resulting effects depend on the stimulus waveform delivered in a subject-specific manner. Most of the existing GVS systems, however, use a generic stimulus across large subject populations. In their article, Liu et al. provide a signal processing–focused overview of the current state-of-the-art of GVS in neurorehabilitation, including general stimulation design, concurrent analysis with neuroimaging data, and suggestions for potential future directions in this area.

Because of the recent pandemic, older individuals currently spend more time alone in their homes. Therefore, assisted living and health-care monitoring of the elderly may become a critical issue. In this context, Baucas et al. discuss IoT-based assistive technologies. In their article, they review popular categories of IoT-based applications for health care. The aim is to answer how research can properly address the open issues associated to IoT-based assistive devices to improve viable solutions for future health-care applications. On the other hand, Qian et al. provide a comprehensive overview on combining artificial intelligence (AI) and the IoT applied to the elderly in assisted living and health-care monitoring. The data modalities and application scenarios are presented together with the relevant signal processing and ML algorithms.

Finally, Geirnaert et al. focus on EEG-based auditory attention decoding (AAD). Recent neuroscientific advances have shown that it is possible to determine the focus of auditory attention from noninvasive neurorecording techniques such as EEG. Based on these new insights, a multitude of AAD algorithms have been proposed, which could, when combined with the appropriate speaker separation algorithms and miniaturized EEG sensor devices, lead to so-called neurosteered hearing devices. The authors provide a broad review and a statistically grounded comparative study of EEG-based AAD algorithms and highlight the main signal processing challenges in this field.

Overall, the articles in this special issue highlight the crucial importance of BSP in the field of neurorehabilitation and assistive technologies and provide insights on how BSP will enable future directions in this research area.

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Guest Editors

Dario Farina (d.farina@imperial.ac.uk) received his Ph.D. degrees in automatic control and computer science and in electronics and communications engineering from the Ecole Centrale de Nantes, Nantes, France, and Politecnico di Torino, Italy, in 2001 and 2002, respectively. He is a full professor and chair in neurorehabilitation engineering in the Department of Bioengineering of Imperial College London, SW7 2BT, U.K. He serves as the editor-in-chief of *Journal of Electromyography and Kinesiology*. He is also an editor of *Science Advances*, *IEEE Transactions on Biomedical Engineering*, *IEEE Transactions on Medical Robotics and Bionics*, *Wearable Technologies*, *Journal of Physiology*, and *IEEE Reviews in Biomedical Engineering*. He received an honorary doctorate degree in medicine from Aalborg University, Denmark; the IEEE Engineering in Medicine and Biology Society Early Career Achievement Award; and the Royal Society Wolfson Research Merit Award. His research interests include biomedical signal processing, neurorehabilitation technology, and neural control of movement. He is a Fellow of IEEE.

Arash Mohammadi (arash.mohammadi@concordia.ca) received his Ph.D. degree in electrical engineering and computer science from York University. He is an associate professor with Concordia Institute for Information Systems Engineering, Concordia University, Montreal, H3G-2W1, Canada. He serves as director of membership development of the IEEE Signal Processing Society; general cochair of the 2021 IEEE International Conference on Autonomous Systems, and associate editor of *IEEE Signal Processing Letters*. He has received several awards, including the Gina Cody School of Engineering and Computer Science research and teaching awards; Concordia President's Excellence in Teaching Award; and the Eshrat Arjomandi Award. His research interests include biomedical signal processing, machine learning/artificial intelligence, and distributed signal processing. He is a Senior Member of IEEE.

Tülay Adali (adali@umbc.edu) received her Ph.D. degree in electrical engineering from North Carolina State University, Raleigh, North Carolina, USA. She is a distinguished university professor in the department of computer science and electrical engineering at the University of Maryland, Baltimore County, Baltimore, Maryland, 21250, USA. She has served on numerous editorial boards and technical committees of the IEEE Signal Processing Society (SPS). She is a recipient of a Humboldt Research Award, an IEEE SPS Best Paper Award, the University System of Maryland Regents' Award for Research, and an NSF CAREER Award. Her research interests include statistical signal processing, machine learning, and applications in medical image analysis and fusion. She is a Fellow of IEEE.

Nitish V. Thakor (eletnv@nus.edu.sg) received his Ph.D. degree in biomedical engineering from the University of Wisconsin-Madison. He is a professor of biomedical engineering and electrical and computer engineering at Johns Hopkins University, Baltimore, Maryland, 21218, USA. He serves as editor-in-chief of *Medical and Biological Engineering and Computing*. He is a recipient of a Research Career Development Award from the National Institutes of Health, a Presidential Young Investigator Award from the National Science Foundation, and the Academic Career Award and Technical Excellence in Neuroengineering from the IEEE Engineering in Medicine and Biology Society. His research focuses on neuroengineering, where he has pioneered many technologies for brain monitoring to prosthetic arms and neuroprosthesis. He is a Life Fellow of IEEE.

Konstantinos N. Plataniotis (kostas@ece.utoronto.ca) received his Ph.D. degree in electrical engineering from the Florida Institute of Technology Melbourne, Florida, USA. He is a professor and the Bell Canada Chair in Multimedia with the Electrical and Computer Engineering Department at the University of Toronto, Ontario, M5S-3G4, Canada. He serves as the general cochair for IEEE ICASSP 2021. His research interests include knowledge and digital media design, multimedia systems, biometrics, image and signal processing, communications systems, and pattern recognition. He is a Fellow of IEEE.

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