Paul Sajda, Klaus-Robert Müller,
and Krishna V. Shenoy

Brain-Computer Interfaces

The human brain is perhaps the most fascinating and complex signal processing machine in existence. It is capable of transducing a variety of environmental signals (the senses, including taste, touch, smell, sound, and sight) and extracting information from these disparate signal streams, ultimately fusing this information to enable behavior, cognition, and action. What is perhaps surprising is that the basic signal processing elements of the brain, i.e., neurons, transmit information at a relatively slow rate compared to transistors, switching about 10^6 times slower in fact. The brain has the advantage of having a tremendous number of neurons, all operating in parallel, and a highly distributed memory system of synapses (over 100 trillion in the cerebral cortex) and thus its signal processing capabilities may largely arise from its unique architecture.

These facts have inspired a great deal of study of the brain from a signal processing perspective. Recently, scientists and engineers have focused on developing means in which to directly interface with the brain, essentially measuring neural signals and decoding them to augment and emulate behavior. This research area has been termed brain computer interfaces and is the topic of this issue of *IEEE Signal Processing Magazine*.

WHAT IS A BRAIN-COMPUTER INTERFACE?

A brain-computer interface (BCI) is a system that includes a means for measuring neural signals from the brain, a method/algorithm for decoding these signals and a methodology for mapping this decoding to a behavior or action. One of the primary rationales for developing BCI systems is to provide a means of communication for individuals with severe neurological disease and/or injury. For example, people afflicted with amyotrophic lateral sclerosis (ALS), also known as Lou Gerhig's disease, frequently lose all volitional control of their muscles in the later stages of the disease. However, their cognitive capacities often remain unaffected and thus decoding of direct measurement of neural activity from their brains (part of the central nervous system) can be used to bypass their malfunctioning peripheral nervous system.

[A BRAIN-COMPUTER INTERFACE IS A SYSTEM THAT INCLUDES A MEANS FOR MEASURING NEURAL SIGNALS FROM THE BRAIN, A METHOD/ALGORITHM FOR DECODING THESE SIGNALS AND A METHODOLOGY FOR MAPPING THIS DECODING TO A BEHAVIOR OR ACTION.]

In addition to clinical applications, BCI systems potentially represent a new type of interface with which people, with otherwise normal neurological function, can interact with a computer/machine. There is interest in using BCI systems in gaming environments and in high stress and intense workflow situations such as air traffic control.

BCI systems are typically divided into two classes, based on how the neural signals are collected. Invasive systems rely on implanted arrays of electrodes, are common in experiments involving rodents and nonhuman primates [1], and are well suited for decoding activity in the cerebral cortex. Such systems provide high signal-to-noise ratio (SNR) measurements and enable decoding of spiking activity from small populations of neurons. The current challenge with such systems is that electrodes need to be implanted in humans, with their functional lifetime limited to roughly a year. Nonetheless, companies are already beginning to develop systems for those with severe neurological impairment (e.g., Cyberkinetics Neurotechnology Systems Inc).

Noninvasive systems are better suited for situations in which a surgical implementation is not possible or warranted and thus have a much wider field of application. Electroencephalography (EEG) is the most commonly used measurement modality for noninvasive recordings. The challenge with EEG is typically a low SNR. Recent advances in developing high-spatial density EEG has called for multi-dimensional signal processing techniques to be employed, resulting in substantial increases in SNR and ultimately performance.

There is growing interest for BCI in the machine learning and signal processing communities, as evidenced by published proceedings [2] and data analysis competitions [3]–[5]. The time appears right for a broader exposure of BCI to the signal processing community.

CONTENT OF THIS SPECIAL ISSUE

The authors contributing to this special issue represent researchers who have one foot in the signal processing and

Digital Object Identifier 10.1109/MSP.2007.909526

machine learning community and one foot in the world of the neurosciences. The contributed articles thus represent a marriage of the two disciplines, though with an emphasis on the signal processing aspects and challenges.

The first two articles, by Linderman et al. and Sanchez et al., broadly describe the technological and signal processing challenges for creating robust brain computer interfaces. These are followed with articles by Blankertz et al. and Kachenoura et al. that focus on some of the more commonly employed spatial filtering techniques for analyzing neural data collected both invasively and noninvasively. Common to these techniques is the idea of using spatial filters to unmix neural signals from background noise and artifacts, i.e., the "neural cocktail party problem."

The next two articles focus specifically on brain computer interface systems for motor control. Hammon et al. describe how the noninvasively recorded EEG can be decoded to predict target location during reaching. Kulkarni and Panisnki describe an efficient state-space approach for decoding goal-directed movements. Computational efficiency is a major design concern for a BCI system due to the need for real-time implementations on portable, low-power signal processing hardware.

The final three articles describe new imaging modalities and applications for BCI. The articles by Matthews et al. and Sitaram et al. describe how functional near-infrared imaging (fNIR) and functional magnetic resonance imaging (fMRI), which do not measure neural activity directly but instead measure hemodyamics correlates, offer a new set of noninvasive signal acquisition modalities for brain computer interfaces. The final article by Parra et al. describes a particular application of brain-computer interfaces which goes beyond augmenting motor control and instead looks to exploit the decoding of signals related to shifts of visual attention to develop a system for triaging large databases of images.

Together these nine articles provide expansive coverage of the signal processing methods, technology developments, and applications at the forefront of brain computer interface research.

REFERENCES

[1] G. Santhanam, S.I. Ryu, B.M. Yu, A. Afshar, and K.V. Shenoy, "A high-performance brain-computer interface," *Nature*, vol. 442, no. 7099, pp. 195–198, 2006.

[2] G. Dornhege, J. Millan, T. Hinterberger, D. McFarland, K.-R. Muller, Eds. *Toward Brain Computer Interfacing*. Cambridge, MA: MIT Press 2007.

[3] P. Sajda, A. Gerson, K.-R. Müller, B. Blankertz, and L. Parra, "A data analysis competition to evaluate machine learning algorithms for use in brain-computer interfaces," *IEEE Trans. Neural Syst. Rehab. Eng.*, vol. 11, no. 2, pp. 184–185, June 2003.

[4] B. Blankertz, K.-R. Müller, G. Curio, T.M. Vaughan, G. Schalk, J.R. Wolpaw, A. Schlogl, C. Neuper, G. Pfurtscheller, T. Hinterberger, M. Schroder, and N. Birbaumer, "The BCI competition 2003: Progress and perspectives in dectection and discrimination of EEG trials," *IEEE Trans. Biomed. Eng.*, vol. 51, no. 6, pp. 1044–1051, 2004.

[5] B. Blankertz, K.-R. Müller, D.J. Krusienski, J.R. Wolpaw, A. Schlogl, G. Pfurtscheller, J. Millan, M. Schroder, and N. Birbaumer, "The BCI competition III: Validating alternative approaches to actual BCI problems," *IEEE Trans. Neural Syst. Rehab. Eng.*, vol. 14, no. 2, pp. 153–159, 2006.

SP