Technologies and Methods for Improving the Capability of Brain-Computer Interfaces

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***Abstract*—Technologies are being developed at UCLA that will improve brain-computer interfaces (BCI) at multiple levels. Novel micromachined multi-electrode probes have been developed and are being used for deep-brain-computer-interface (DBCI) research. Head-stage integration is being advanced by combining amplification, filtering, signal processing, computing, and wireless communications all into a highly mobile 25-mm-diameter system. These and related technologies are being used, with operant conditioning, to study methods for creating high-reliability and high-quality BCI-based control signals in rodents. All aspects of these efforts are being positively impacted by the NSF-IGERT-Supported UCLA NeuroEngineering Training Program.**

***Index Terms*—neuroengineering, brain-computer interface, deep-brain-computer interface, MEMS, wireless sensor networks.**

I. Introduction

Brain-computer interfaces (BCI) are systems that transform biological signals recorded from neural tissue into electronic signals that control a computer interface (e.g., control the position of a cursor on the screen) [1]. Once such a level of control is achieved, it can be translated into a system that can control a machine or other physical device (e.g., robotic appendage) or that can be used to stimulate or activate biological tissues (e.g., muscles or other regions of the nervous system). Successful demonstrations of BCIs and BMIs have been realized that make use of signals non-invasively recorded from an electrode array placed on the scalp (i.e., electroencehpalogram or EEG) [2], an electrode array placed on the brain itself (i.e., electrocortiogram or ECOG) [3], and microelectrodes implanted into brain tissue that record from individual cells (i.e., signal-unit action potentials) or ensembles of cells (i.e., local field potentials) [4]. These neural signals are buffered, amplified, and filtered by electronics that are sometimes integrated into the probes themselves or more often assembled on a small board located near the electrodes (e.g., head-stage amplifier). In most cases, the amplified signals are routed by physical wires to a multi-channel analog-to-digital converter (ADC), which digitizes the neural signals for the subsequently attached computer.

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II. NeuroEngineering Training Program

In 1997 the National Science Foundation formed the Integrative Graduate Education and Research Training (IGERT) Program, which seeks to support highly innovative and multidisciplinary training programs for graduate students. In 1999, UCLA was awarded NSF IGERT support to create the UCLA NeuroEngineering Training (NET) Program, which has as its goals to prepare graduate students to be leaders in the revolutionary technological developments that will affect neuroscience in the 21st Century. By expanding the synergies between the UCLA Brain Research Institute (BRI) and the Henry Samueli School of Engineering and Applied Sciences (HSSEAS), the UCLA NET program promotes the application of new engineering technologies to neuroscience. This training program provides the formal structure for collaborative neuroengineering research and training.

As one example of how engineering technologies can impact neuroscientific research, consider the revolutionary implications of microelectromechanical systems (MEMS) technologies for neuroscience. The potential exists to develop arrays of microsystems that can be tailored to the physical and temporal dimensions of individual cells. Neuroscientists can now realistically envision sensing devices that allow real-time measurements at the cellular level of many different measurands (e.g., electrical, chemical, etc.). Information from such sensors could be monitored, analyzed, and used as a basis for experimental or medical intervention, again at a cellular level.

The objectives of the NET Program are (1) to enable students with a background in biological science to develop and execute projects that make use of state-of-the-art technology – including MEMS; in preparing students to use new technology, the NET Program also introduces them to basic concepts in engineering that are applicable to the study of systems neuroscience, including signal processing, communications, and information theory; (2) to enable students with a background in engineering to develop and execute projects that address problems that have a neuroscientific basis, including locomotion and pattern generation, central control of movement, and the processing of sensory information; and (3) to instill in all trainees the capacity for the multidisciplinary teamwork that will be necessary for new scientific insights and dramatic technological progress.

III. BCI Research and Development

BCI-related research activities in the UCLA NeuroEngineering Technology Laboratory (NET Lab) include:

(1) improving the physical neural-electronic interface (e.g., implementing micromachined probes, electrode arrays, and related micro-electro-mechanical systems or MEMS);
(2) improving headstages for BCI systems by miniaturizing them and integrating bi-directional wireless communication, networking, digital-signal processing, and multi-channel stimulation; and
(3) developing new experimental platforms for BCI/BMI applications

A. Improving the Physical Neural-Electronic Interface of BCI Systems

The majority of human-based BCI research has employed non-invasive surface electrodes to record EEG signals that are filtered and processed through a variety of algorithms to correlate recorded brain activity with a desired output state. Although successes have been achieved, in general the performance has not been sufficient to rapidly drive the commercialization of the system. On the other hand, there has been a considerable amount of work on animal models, from rodents to primates, in which penetrating cortical probe arrays have been used to record single-units (i.e., spikes) or local-field potentials. With appropriate algorithm training, such cellular recordings in primates have successfully led to the real-time 1-D control of a robotic arm by rodents [7] and the 3-D control of robotic limbs by primates [8-9].

To improve the capability of physical neural-electronic interfaces, research is being performed on novel micromachined probe technologies. Although there has been great advances on micromachined multi-electrode cortical probe arrays, such probe arrays for interfacing with the increasingly interesting deep-brain structures are less well developed. Our approach has been to develop microfabrication process that can produce arrays that are: (1) long enough for deep-brain-computer interfaces (DBCI), (2) remain stiff enough to accurately target deep-brain structures, and (3) minimize tissue damage. A novel customizable 3-D plating process is used to microfabricate DBCI probes that combine the advantages of microwires (i.e., a smoothly tapered probe-shank width and thickness) with some of the advantages of micromachined probe arrays (i.e., multiple, precisely arranged, electrodes per probe shank) [10]. These probes are currently being used for Parkinson's disease and DBCI / DBMI research.

B. Improving Headstages for BCI Systems

The trend with head-stage development is to integrate into it more and more capability. The motivation driving this trend has been the need to maximize the ultimate signal-to-noise ratio of the recordings. To meet this need, headstages have incorporated buffer amplifiers, isolators, filters, and some gain. The ability to miniaturize headstages, while simultaneously increasing channel count, has been achieved by exploiting the technological advances provided by the integrated-circuit (IC) industry. Advances by the IC industry have allowed additional functionality to be integrated into headstages, such as more sophisticated filtering, higher gain stages, and wireless telemetry.

Such miniature wireless neural recording head-stage systems can enable brain researchers to study the neural activity of subjects ranging in size from humans to small rodents. The small size of contemporary head stages is of particular value for research performed on small rodents, as it allows them to live untethered by wires and in an enriched and even social environment (i.e., with other small rodents that could also be carrying a miniaturized headstage).

Methods for developing compact, low-power, bi-directional, and wireless neural interfaces have ranged from developing custom integrated circuits (IC) to assembling PC-based commercial off-the-shelf (COTS) components. The custom-IC approach can realize the smallest and lowest-power system, but the development time can be quite long and cost quite high [11]. The PC-COTS-based approach can realize the fastest and most capable system with a minimum of development time. As a consequence, the resulting system will be much larger, more massive, and perhaps only appropriate for large test subjects (i.e., human and perhaps primate) [12].

Our approach is to exploit the advances made by the large worldwide effort to develop wireless sensor networks. With hundreds of engineers and computer scientists working on the fundamental problems (e.g., miniaturization, integration, telemetry, networking, power management, signal processing, data compression, data mining, etc.), advances in each area are frequent and can be appropriately leveraged for BCI-related systems and applications.

Specifically, we are designing a comprehensive wireless neural recording, archiving, hosting, and stimulation system that uses miniature-scale wireless-enabled embedded computers as the local neural recording and stimulation nodes. These tiny computers, which are commonly known as "motes" and are about the size of a U.S. quarter, are capable of multi-channel data acquisition, signal processing, data reception, and transmission via a ZigBee-compliant radio. We are currently developing software to implement neural recording and stimulation, custom biological interface circuits for neural-signal amplification and stimulation, power-efficient algorithms for local spike detection and basic spike sorting, a database server, and a Java-based graphical client for browsing neural recordings and scheduling stimulation events.

The front-end neural interface circuits will leverage state-of-the-art circuit-design methods that have been used to successfully realize ultra-low-noise low-power integrated preamplifiers and stimulators. Furthermore, we will add software-based gain and bandwidth programmability via an I2C interface to the microprocessor in the mote. A multi-channel signal-acquisition, filtering, compression, and transmission framework will enable the motes to either perform spike detection and as-needed reduced-set data transmission, or to constantly transmit full-range and full-bandwidth analog neural-signal data. In addition, lossless data-compression algorithms are being investigated for maximizing output-signal bandwidth and improving power efficiency. The database server will allow users to browse recorded waveforms and schedule stimulus events over an Ethernet or Internet connection via a browser-based client.

To date we have successfully demonstrated a two-channel wireless EEG transmitter [13], and a comprehensive neural recording, archiving, and hosting system capable of transmitting up to eight channels of neural signals at a collective data rate of 44 kilobits per second [14].

C. Developing New Experimental Platforms for BCI/BMI Applications

Based on previous experiments with brain plasticity, we have a hypothesis that the brain is capable of remapping the cortex to accommodate an independent BMI communication channel. In other words, an interface may permit a subject to activate the BMI when intended, and to prevent activating the BMI when it does not intend. Learning to control the appropriate neural activity pattern will permit the subject to behave normally without activating the BMI. For example, moving a leg should not activate the BMI. Conversely, activating the BMI should not require that the subject move a leg. Simple patterns will first be used, but more complex patterns may be required to prevent inadvertent reproduction of the patterns during free-foraging. To test BMI performance during free-behavior, animals are kept unrestrained during the task.

We are currently testing these hypotheses with a rat model. In order to train the rats, conventional operant-conditioning procedures are used. Target patterns of neural activity, which do not naturally occur, will be established. Periods of cue/no cue (e.g., lamp or tone on/off) are presented as conditioned stimuli. Negative and positive reinforcements are delivered in order to reinforce the BMI response at the appropriate time and to discourage the response at the inappropriate times. Our goal is to reduce the number of false positive responses in presence of a disrupting activity such as foraging.

We are initially concentrating on establishing such high-quality control of a single neural “switch”, followed by studies intent on increasing the bandwidth of this reliable communication channel. Our current BMI methods use a small number of electrodes in a single localized area of the motor cortex, recording from both single neurons and local field potentials.

IV. Conclusion

The research being performed at UCLA on BCI/BMI-related technologies covers all aspects of such a system: from the physical and electronic interface to the computational algorithms and biological models. Most of this work is being greatly facilitated by the NSF-supported integrative graduate education and training program (IGERT) program at UCLA.

References

[1] J.R. Wolpaw, et al., “Brain-computer interfaces for communication and control”, *Clin Neurophysiol*, vol. 113, no. 6, pp. 767–91, 2002.

[2] J.R. Wolpaw, D.J. McFarland, G.W. Neat, and C.A. Forneris, “An EEG-based brain–computer interface for cursor control”, *Electroenceph clin Neurophysiol*, vol. 78, pp. 252–259, 1991.

[3] J.R. Wolpaw, et al., “Brain–computer interface technology: a review of the first international meeting”, *IEEE Trans Rehabil Eng*, vol. 8, pp. 161–163, 2000.

[4] Wessberg J, Stambaugh CR, Kralik JD, Beck PD, Laubach M, Chapin JK, Kim J, Biggs J, Srinivasan MA, Nicolelis MA. Real-time prediction of hand trajectory by ensemble of cortical neurons in primates”, *Nature*, vol. 408, pp. 361–365, 2000.

[5] www.nsf.gov (IGERT Program)

[6] Jack W. Judy and Allan J. Tobin, “NeuroEngineering – The Integration of Neuroscience with Engineering”, *International Conference on Engineering Education*, Valencia, Spain, (July 21-25, 2003).

[7] Chapin, J.K., et al., Real-time control of a robot arm using simultaneously recorded neurons in the motor cortex”, *Nat Neurosci.*, vol. 2, no. 7: pp. 664-670, 1999.

[8] A.P. Georgopoulos, A.B. Schwartz, R.E. Kettner, “Neuronal population coding of movement direction”, *Science*, vol. 233, no. 4771, pp. 1416–1419, Septemberr 26, 1986.

[9] J.M. Carmena, et al., “Learning to control a brain-machine interface for reaching and grasping by primates”, *PLoS Biol*., vol. 1, no. 2, E42, October 13, 2003.

[10] Paulo S. Motta and Jack W. Judy, “Multielectrode Microprobes for Deep Brain Stimulation Fabricated with a Customizable 3-D Electroplating Process”, *IEEE Transactions on Biomedical Engineering*, vol. 52, no. 5, pp. 923–933, May, 2005.

[11] Pedro I. Pastor, Istvan Mody, and Jack W. Judy, “Transcutaneous RF-powered neural recording device” *Proc. of the 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society EMBS/BMES Conference*, vol. 3, pp. 2105–2106 (October 23-26, 2002).

[12] I. Obeid, M. A. L. Nicolelis, and P. D. Wolf, “A multichannel telemetry system for single unit neural recordings” *Journal of Neuroscience Methods*, vol. 133, pp. 123–135, 2004.

[13] Shahin Farshchi, Istvan Mody, and Jack W. Judy, “A TinyOS-Based Wireless Neural Interface”, *26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, San Francisco, CA (Sep 1-5, 2004).

[14] Shahin Farshchi, Paul H. Nuyujukian, Aleksey Pesterev, Istvan Mody, and Jack W. Judy, “A TinyOS-Based Wireless Neural Sensing, Archiving, and Hosting System”, *2nd International IEEE EMBS Conference on Neural Engineering*, Washington, DC (March 16-19, 2005).