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Effective Brain-Computer Interfacing Using BCI2000

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***Abstract*— To facilitate research and development in Brain-Computer Interface (BCI) research, we have been developing a general-purpose BCI system, called BCI2000, over the past nine years. This system has enjoyed a growing adoption in BCI and related areas and has been the basis for some of the most impressive studies reported to date. This paper gives an update on the status of this project by describing the principles of the BCI2000 system, its benefits, and impact on the field to date.**

I. INTRODUCTION

Development and implementation of a Brain-Computer Interface (BCI) system is complex and time consuming. In response to this problem, we have been developing a general-purpose system for BCI research, called BCI2000. BCI2000 has been in development since 2000 in a project led by the Brain-Computer Interface R&D Program at the Wadsworth Center of the New York State Department of Health in Albany, New York, USA, with substantial contributions by the Institute of Medical Psychology and Behavioral Neurobiology at the University of Tübingen, Germany. In addition, many laboratories world-wide have also played an important role in the project's development. These laboratories include the BrainLab at Georgia State University in Atlanta, Georgia, and Fondazione Santa Lucia in Rome, Italy.

The goals of the BCI2000 project are 1) to create a software system that facilitates the implementation of a wide range of experiments that rely on data acquisition, real-time processing, and stimulus presentation; 2) to incorporate into this system support for the most commonly used BCI methods; and 3) to disseminate the system and associated documentation to other laboratories. Thus, BCI2000 should facilitate research and clinical applications of BCI technology by reducing the time, effort, and expense of testing new BCI methods, by providing a standardized data format for offline analyses, and by allowing groups lacking high-level software expertise to engage in BCI research. To achieve these three goals, BCI2000 decomposes a BCI into four modules that represent the four critical functions of any BCI system: signal acquisition, signal processing, stimulus presentation and feedback, and operating protocol. These four modules, their components, and the interfaces between them, are designed such that a change in a module or a component requires little or no change in other modules or components. This feature facilitates evaluation of different BCI methods.

As described in more detail in Section IV, BCI2000 has enjoyed a substantial impact on the field. It has been used to implement BCI methods that can use a variety of data acquisition devices, that can use different types of brain signals recorded with non-invasive or invasive sensors, and that can provide different types of output. The BCI2000 system can run on standard PC hardware and supports many different data acquisition devices that are listed on `www.bci2000.org`. It also makes efficient use of computational resources and can satisfy the real-time requirements of BCI operation.

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II. BCI2000 PRINCIPLES

As mentioned above, BCI2000 is based on a system model that consists of four modules (see Fig. 1). These modules are Source (which consists of a data acquisition and storage component), Signal Processing (which consists of several components that extract signal features and translate them into device commands), User Application (which presents stimuli and feedback), and Operator Interface. At present, the implementations of these modules support fifteen data acquisition devices from different manufacturers; support feature extraction and translation needed for processing of movement/movement imagery related mu/beta rhythms or gamma activity, and evoked potentials (such as the P300); and implements a cursor task (similar to the "center-out" task commonly used in motor control studies), a matrix-based speller, and a general-purpose auditory-visual stimulation program.

These modules communicate through a network-capable protocol, may be written in any programming language, and can be run on any machine on a network. Importantly, the protocol does not need to be changed when changes are made in a module. Brain signals are processed in blocks that contain a fixed number of samples that are acquired by the Source module. Each time a new block of data are acquired, the Source module submits it to Signal Processing, which extracts signal features, translates those features into device control signals, and sends them on to the Application module. Finally, the Application module sends event markers that indicate relevant states of system operation (e.g., which stimulus is presented on the computer screen) back to the Source module where they are associated with the raw signals, and are stored to disk. The contents of the data file thus allow for full reconstruction of an experimental session during offline analyses.

BCI2000 also facilitates interactions with other software, both for real-time operation as well as for offline analyses. This includes interfaces that allow software written in Matlab^{TM}, Fieldtrip using the Fieldtrip buffer component (maintained by Robert Oostenveld), and Python using the

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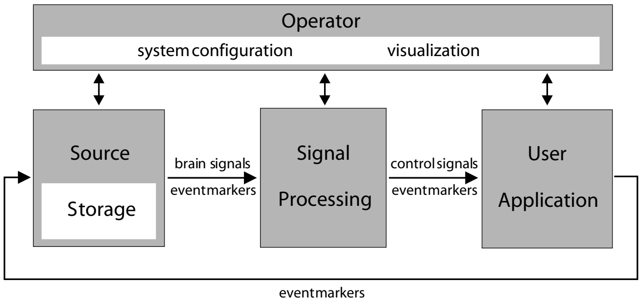

Fig. 1. BCI2000 System Model. Acquired data are processed by three *core* modules in sequence, controlled from an additional Operator module. (Modified from [1].)

Fig. 2. Yellow circles indicates sites of laboratories using BCI2000.

BCPy2000 framework (maintained by Jeremy Hill) to execute within or parallel to BCI2000. In addition, offline analyses are facilitated through Matlab scripts that can directly load or save BCI2000 data files, and through a utility that converts data into ASCII.

III. BENEFITS

Implementation of a real-time system that integrates data acquisition, signal processing, and feedback, is complex and difficult. BCI2000 provides a platform in which many of these technical difficulties have been resolved. In addition, BCI2000 includes a number of standardized system components and data structures, such as a common file format[1], which can be used the same way regardless of the details of the experiments. Thus, BCI2000 allows a scientist or engineer to spend more time on research than on worrying about the underlying technology.

Specifically, BCI2000 offers several important benefits:

- A Proven Solution: BCI2000 comes ready with proven support for different data acquisition hardware, signal processing routines, and experimental paradigms.
- Facilitates Operation of Research Programs: Different technical approaches can be used to prototype experimental paradigms (e.g., such as Matlab, LabView). However, no quickly designed prototype will have a common data format, software interfaces, or documenting protocols. In contrast, BCI2000 has been designed from the ground up and been developed over many years to support long-term research programs with many research projects.
- Facilitates Deployment in Multiple Sites: The BCI2000 system does not rely on third party software components for its operation. Even for compilation, the system only requires affordable or free C++ compilers. Thus, both development and deployment of BCI2000 on multiple computers in potentially multiple sites is very economical.
- Cross-Platform/Compiler Compatibility: BCI2000 currently requires Microsoft Windows to operate and Borland's/CodeGear's C++ Builder for compilation. In future versions, BCI2000 will also support Linux and Mac OS X, as well as compilation with other C++ compilers.
- Open License The use of BCI2000 is free and without restrictions for academic and research purposes.

[1]BCI2000 also supports EDF and GDF for data storage.

IV. IMPACT TO DATE

A. *Publications generated using BCI2000*

BCI2000 has already had a substantial impact on BCI research. As of June 2009, BCI2000 has been acquired by close to 400 laboratories around the world (see Fig. 2). It has been the basis for some of the most impressive BCI studies reported to date. These include: the first online brain-computer interface system using electrocorticographic (ECoG) signals [2], [3], [4], [5] or magnetoencephalographic (MEG) signals [6]; the first multi-dimensional BCI using ECoG signals [7]; the first exploration of BCI approaches for restoration of function in stroke patients [8], [9]; the first real-time BCI use of high-resolution EEG techniques [10]; control of a humanoid robot by a noninvasive BCI [11]; the use of BCI techniques to control assistive technologies [12]; the first demonstration that non-invasive BCI systems can support multi-dimensional cursor movements without [13] and with [14] click functionality; and the first demonstration that people severely paralyzed by amyotrophic lateral sclerosis (ALS) can operate a sensorimotor rhythm-based BCI [15]. BCI2000 has also been the basis for the first, and to date only, long-term in-home application of BCI technology to people who are totally paralyzed. In these ongoing studies led by Dr. Jonathan Wolpaw at the Wadsworth Center, BCI systems are placed in the homes of severely disabled patients. These BCI systems are operated by the patients and their caregivers. For the past couple of years, these patients have been using the BCI effectively for word processing, email, and environmental control.

Other studies have used BCI2000 in fields related to BCI research. This includes real-time mapping of cortical function using ECoG [16], [17], [18]; the first large-scale motor mapping studies using ECoG signals [19], [20]; the exploration of new BCI processing algorithms [21], [22], [23]; evaluation of steady-state visual evoked potentials (SSVEP) for the BCI purpose [24]; and the demonstration that two-dimensional hand movement trajectories can be decoded from ECoG signals with an accuracy similar to that achieved previously only with intracortical microelectrodes [25]. A number of these studies were performed as collaborations among several geographically widespread laboratories. These collaborations were facilitated by the common exchange of data and experimental paradigms supported by BCI2000. To our knowledge, there have been no comparable large-scale collaborative BCI studies that have not used BCI2000.

B. Impact on Scientific and Popular Media

BCI2000 has also received significant attention by scientific and popular media. For example, the initial article on the BCI2000 system [1], which received the *Best Paper Award* by *IEEE T Biomed Eng*, has already been cited more than 160 times. The system has also been: used in more than 120 peer-reviewed publications; referenced several hundred times, including in journal articles, media articles, and personal blogs; used or cited in dozens of Masters Theses or Doctoral Dissertations; mentioned as desirable experience in job postings; and listed as qualification in Curriculum Vitae. This large and increasing success of the adoption of the BCI2000 system provides strong evidence for the substantial demand for and utility of the software.

In summary, BCI2000 is strongly stimulating progress in the field of BCI research. As indicated by the above descriptions of its utility for different aspects of BCI research, by the growing success of its dissemination, and by its prominence in the scientific literature, BCI2000 is fast becoming, or perhaps has already become, the standard software platform for research in this area.

C. Dissemination

The BCI2000 system is available for free for non-profit research and educational purposes at http://www.bci2000.org. This web site contains comprehensive project-related information, such as additional documentation on a wiki and a bulletin board. In addition, the BCI2000 project has organized a number of workshops on the theory and application of the system: Albany, New York, June 2005; Beijing, China, July 2007; Rome, Italy, December 2007; Utrecht, The Netherlands, July 2008; Bolton Landing, New York, October 2009 (planned); Asilomar, California, June 2010 (planned).

D. Current and Future Plans

Over the past ten years, the BCI2000 system has steadily improved from a research-grade software to a highly capable and robust software platform with comprehensive and up-to-date documentation. Current and future efforts center on making the system less dependent on the operating system and compiler. (Large portions of the code already compile on other platforms and using other compilers.) Also, the current license that is used to disseminate BCI2000 is very open and does not place any restrictions (other than commercial use) on how the system may be used. However, this license is proprietary, and most people are more familiar with traditional open-source licenses, in particular the GPL and LGPL. We are currently evaluating transition to one of these more common open-source licenses. This effort may also benefit the ability to integrate extensions to BCI2000 written by the user community.

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