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Review of Wireless and Wearable Electroencephalogram Systems and Brain-Computer Interfaces – A Mini-Review

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Key Words

Brain-computer interface · Wireless data transmission · Wearable signal monitoring systems · Real-time data analysis · Electroencephalogram

Abstract

Biomedical signal monitoring systems have rapidly advanced in recent years, propelled by significant advances in electronic and information technologies. Brain-computer interface (BCI) is one of the important research branches and has become a hot topic in the study of neural engineering, rehabilitation, and brain science. Traditionally, most BCI systems use bulky, wired laboratory-oriented sensing equipments to measure brain activity under well-controlled conditions within a confined space. Using bulky sensing equipments not only is uncomfortable and inconvenient for users, but also impedes their ability to perform routine tasks in daily operational environments. Furthermore, owing to large data volumes, signal processing of BCI systems is often performed off-line using high-end personal computers, hindering the applications of BCI in real-world environments. To be practical for routine use by unconstrained, freely-moving users, BCI systems must be noninvasive, nonintrusive, lightweight and capable of online signal processing. This work reviews recent online BCI systems, focusing especially on wearable, wireless and real-time systems.

Introduction

Brain-computer interface (BCI) is a relatively new field of research that has been growing rapidly over the past 15 years [see 29]. A BCI system comprises a set of sensing and signal-processing components that enables the acquisition and analysis of brain activities in order to establish a reliable, direct communication channel between the brain and an external device such as a computer or a neuroprosthesis system, etc. Figure 1 shows the basic design and functioning blocks of a typical BCI system [see 29], which consists of 3 main parts: signal acquisition, signal processing and applications. The brain signal is recorded by electrodes placed on the scalp (noninvasive BCI systems) or implanted in the brain (invasive BCI systems). The signals obtained by these electrodes are generally obscured by noises and other artifacts including power line interference, electrode displacement, subject

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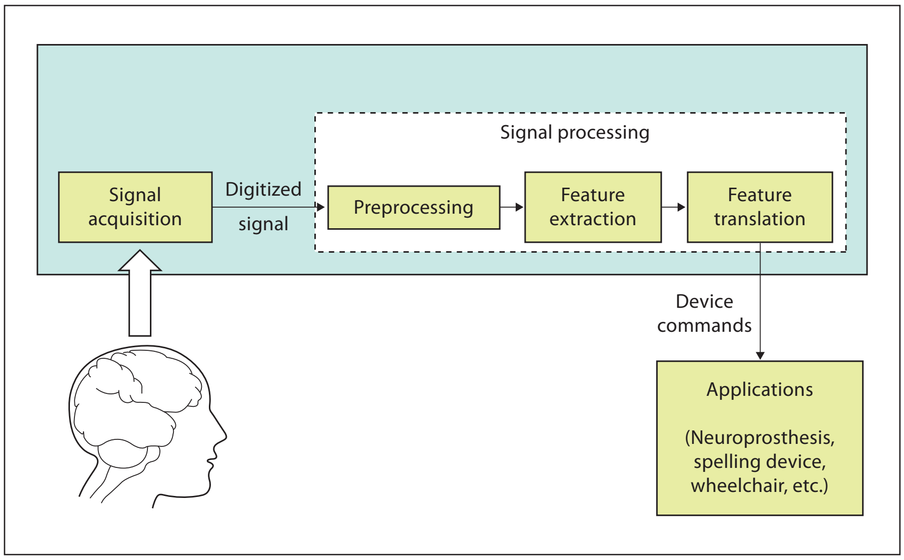


Fig. 1. Basic design and operation of the BCI system. Reproduced with permission from the Institute of Electrical and Electronics Engineers [29].

movements, electrode/wire contact, and physiological interference from ocular, muscular, respiratory, and cardiac activities. To eliminate these undesirable noises and artifacts is a required preprocessing step. The feature extraction and translation components (fig. 1) are to translate the acquired brain signals into measures indicative of some neurological effects of interest. The output of the feature extraction component is so-called 'feature vector' by the pattern recognition community. The informative features are further translated into some control signals such as visual feedback to the user, a sequence of electric pulses to control external devices, etc.

Two key issues related to BCI systems are data transmission and signal processing. Data transmission can be classified as wired or wireless. Many existing BCI systems have been constructed using wired connection to link all the building blocks. As a result, wired BCI systems are generally bulky and heavy; more importantly, they often limit the users' movement in ordinary working or living environments. Such systems are thus impractical for real-world use (for example at work). On the other hand, wireless transmission technology including Bluetooth, radio frequency (RF) or other protocols can largely eliminate the limitations associated with traditional wired BCI systems. Today, wireless transmission capability is embedded in numerous electrical products such as PDAs, cell phones and laptop computers. Such a ubiquitous technology has already improved the feasibility of integrating acquisition, transmission, and recording of neurophysiological signals into commercially available electronic portable devices. Furthermore, given the recent development of real-time embedded systems and signal processing techniques, it is now practical to implement and perform sophisticated signal processing in (near) real time. As a result, next-generation BCI systems will be small, lightweight, noninvasive, nonintrusive, nontethered and easily and comfortably worn. This study reviews current BCI systems and particularly wireless, wearable and real-time systems.

Taxonomy of Current BCI Systems

BCI systems can be classified in many different ways. Table 1 summarizes the results of a survey of 32 BCI systems. The references in the third column of the table represent published systems that possess the listed attributes. The presented taxonomy of BCI systems was inspired by recent comprehensive surveys [33, 34] and is based on technologies and transmission protocols they employ.

Seven attributes are used to characterize these systems (as shown in table 1).

Transmission Medium

Transmission medium refers to the material substance used to exchange information between different components (i.e. between signal acquisition and signal processing, or signal processing and application) shown in figure 1 [29]. The transmission media used by the listed BCI

Table 1. Classification of BCI systems

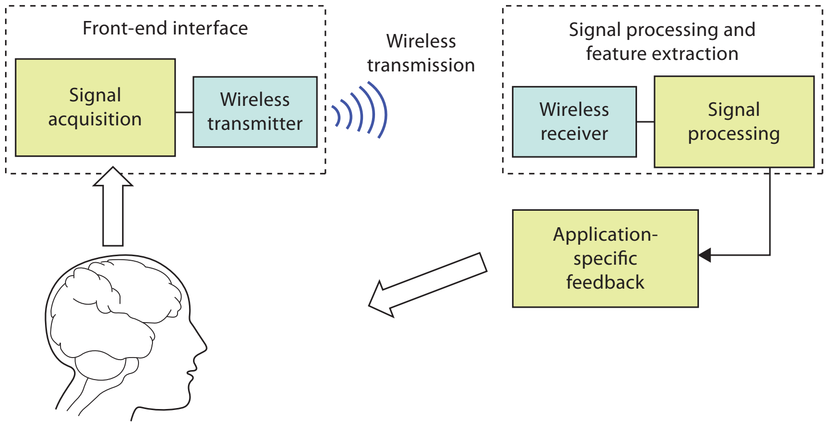
Design attribute	Attribute subclass	Papers with attribute subclass	Group counts
Transmission	Wire	3–7, 9–24, 27–30	25
	Wireless	1, 2, 8, 25, 26, 31, 32	7
Subjects	Healthy	2, 10, 13–15, 17, 21, 23–25, 27, 28, 30–32	15
	Patient	1, 3, 7, 12, 16, 18, 20, 22	8
	Animal	4, 5, 8, 19	4
	Including healthy and patient subjects	26	1
	Not reported	6, 9, 11, 29	4
Sensor placement	Invasive	4, 5, 8, 18, 19	5
	Noninvasive	1–3, 6, 7, 10, 12–17, 20–28, 30–32	24
	Not reported	9, 11, 29	3
Number of channels	Single channel	18, 22	2
	2 channels	2, 3, 6, 7	4
	3 channels	4, 12, 14, 23	4
	Multiple (>3) channels	1, 8, 10, 13, 15–17, 19–21, 24–28, 30–32	18
	Not reported	5, 9, 11, 29	4
Training time	No (or less) training time	2, 4, 6, 10, 12, 15, 17	7
	Training time required	3, 5, 7, 13, 14, 16, 18–24, 26–28, 30–32	19
	Not reported	1, 8, 9, 11, 25, 29	6
Target activity	General communication or control (nonspecific)	1, 3, 13, 16, 20, 21, 24, 25, 27, 28	10
	Control of		
	Appliances/devices (e.g. TV, phone, computer, cursor, bed)	2, 6, 9, 10, 14, 15, 17, 26, 30	9
	Objects/avatar in virtual environment (VR)	19, 23, 31, 32	4
	Paralyzed limbs (for body positioning or object manipulation)	5, 7, 12, 18	4
	Personal mobility (e.g. operating a wheelchair)	22	1
	Not reported	4, 8, 11, 29	4
Neurological phenomenon	Changes in cell firing rate		
	Related to imagined movement	18	1
	Related to cognitive task	5, 19	2
	Mu, alpha, beta or other rhythm power	1, 7, 10, 13, 21–25, 31, 32	11
	ERD or ERS	3, 12, 13, 15	4
	P300 (or N100) response	11, 20, 30	3
	Response to basic cognitive tasks	14	1
	SSVEP response to visual stimulus	2, 6, 17	3
	Multiple phenomena	9, 16, 26–29	6
	Not reported	4, 8	2

ERD = Event-related desynchronization; ERS = event-related synchronization.

systems can be classified into 2 categories: wireless and wired transmission.

Target Users

'Users' refers to the group of people expected to use the technology. Most surveyed BCI systems are in the laboratory demonstration stage, using healthy volunteers or animals as subjects. However, some studies focused on clinical applications. Patient groups included in these studies were severely disabled individuals who have little or no usable voluntary muscle control such as amyotrophic lateral sclerosis, epilepsy, spinal cord injury, brainstem stroke, severe cerebral palsy, muscular dystrophy, and other serious disorders.



Color version available online

Fig. 2. Block diagram of a wireless BCI system.

Sensor Placement

In this taxonomy, sensor placement is divided into 2 categories: noninvasive electroencephalogram (EEG) and invasive electrocorticogram (ECoG). In general, the EEG signals have a lower signal-to-noise ratio in comparison with the ECoG signals. However, it is still more preferable especially for normal healthy humans in daily applications because of its noninvasiveness.

Number of Channels

Channel number can be classified into single channel, 2 channels, 3 channels and multiple channels according to the applications.

Training Time

Before using the BCI system, training may be required in order for the users to effectively control their brain activities. However, recent studies have demonstrated that the need for subject training can be minimized or even eliminated (table 1).

Target Activity

This consists of activities that the target population wishes to perform with the assistive technology.

Neurological Phenomenon

This attribute describes the phenomenon (phenomena) used as a feature(s) to control the BCI system. For example, many BCI systems detect and employ a positive 300 event-related potential (P300 ERP) in EEG in response to a less frequent stimulus. Another commonly used phenomenon is the increase in neural firing rates measured by microelectrodes placed on the cortical surface.

Of the 32 articles summarized in table 1, 5 BCI systems described in the 7 articles [1, 2, 8, 25, 26, 31, 32] feature wireless transmissions and are further discussed below.

Wearable and Wireless EEG Monitoring

A physiological signal monitoring system would be extremely useful in many areas, provided it was portable, wearable, and capable of monitoring target physiological signals remotely via wireless transmission protocol. First, a wireless BCI system can dramatically reduce installation complexity, wire weight, and trouble-shooting effort associated with traditional wired BCI systems. Second, a wireless BCI system would provide users with more freedom of posture and movement so that they can perform their routine tasks in real-world environments. Third, when built with low-power, miniature signal acquisition and conditioning circuits, the front-end of a BCI system can be integrated into a truly wearable device such as a baseball cap, a headband, or a pair of sunglasses to maximize portability and wearability. If wearable and wireless EEG monitoring proves feasible, a much wider range of applications for BCI will emerge. In addition, the low-power integrated circuit design can also fulfill the requirements for long-term field operations. Figure 2 illustrates a general wireless BCI system in which the wires/cables connecting the front-end signal-sensing circuit and the back-end data analysis unit are completely replaced by wireless transmission protocols such as Bluetooth or wireless local area network (WLAN). The following section reviews the systems listed in table 1 that feature wearable and wireless physiological signal monitoring.

Wireless System for Long-Term EEG Monitoring of Absence Epilepsy

Absence epilepsy is a form of epilepsy that occurs most frequently in children. Due to the subtle nature of its symptoms, episodes of absence epilepsy may often go unrecognized or misdiagnosed [1]. Since EEG is an effective means of detecting subtle abnormalities, it is desirable to continuously monitor the EEG of epileptic patients. Whitchurch et al. [1] recently developed and reported an EEG monitoring system for patients with absence epilepsy. The system utilized a Bluetooth personal area network that linked the front-end (an EEG acquisition system) and a data analysis system. This wireless monitoring system allowed EEG monitoring of freely moving patients as they performed their daily activities.

High-Rate Steady-State Visual Evoked Potential-Based BCI

Cheng et al. [2] recently developed an online BCI that detected and classified steady-state visual evoked potential (SSVEP) measured with as few as 2 active electrodes. Twelve buttons illuminated at different refresh rates were displayed on a computer monitor. The buttons constituted a virtual telephone keypad, representing the ten digits 0–9, BACKSPACE, and ENTER. Users could input phone numbers by looking at these buttons. The induced frequency-coded SSVEP was used to determine user button selection. Eight of the 13 subjects succeeded in dialing the desired number using brain activity. The average transfer rate over all subjects was 27.15 bits/min – one of the fastest communication rates described in the BCI literature. The BCI system also employed a wireless transmitter to allow users more freedom of movement.

Multichannel Telemetry System for Signal-Unit Neural Recordings

Obeid et al. [8] used WLAN to link the front-end data acquisition circuit and the data analysis system. A multichannel neural telemetry system capable of continuously transmitting 12 of 16 channels was demonstrated in their study. The system comprised: (1) a 16-channel analog front-end circuit to condition and acquire signals from implanted electrodes, (2) a digital circuit to process and buffer the digitized signals, and (3) a miniature 486 PC equipped with an IEEE 802.11b wireless Ethernet card to transmit digitized signals. Digitized data (up to 12 bits of resolution at 31,250 samples/s per channel) were transferred to the PC and sent to a nearby host computer on a wireless local area network. The device successfully recorded neural signals from awake-behaving macaque and owl monkeys.

Hybrid Bioelectrodes for Ambulatory EEG Measurements Using Multi-Channel Wireless EEG System

Matthews et al. [25] recently developed a wireless multi-channel system for EEG measurements in operational settings. The EEG sensors were based on a hybrid (capacitive/resistive) bioelectrode technology that required no modification to the outer layer of the skin. In addition, the EEG system [25] featured a miniature, ultra-low power microprocessor-controlled data acquisition system and a miniaturized wireless transceiver that can operate for over 72 h from 2 AAA batteries. The system acted as a wearable and wireless EEG recording system rather than a complete BCI system since it did not incorporate any specific data-processing capabilities or applications.

Vibrotactile Feedback for BCI Operation

Cincotti et al. [26] developed several hardware and software technologies to explore the advantages and disadvantages of using vibrotactile feedback and visual feedback to control an EEG-based BCI system during user training. The designed system used Bluetooth to send commands wirelessly from the host PC to the vibrotactile device. Advantages of using vibrotactile feedback became apparent when the visual channel was heavily loaded by a complex task [26]. Their study showed that users felt, after some training, more natural to interact with the BCI.

Table 2 summarizes the BCI systems mentioned above [1, 2, 8, 25, 26, 31, 32]. Except for the BCI system developed by Cincotti et al. [26], whose wireless transmission lies between the host PC (intermediate stage) and the vibrotactile feedback device (back end), other BCI systems employed a wireless transmission module between the signal acquisition (front end) and signal analysis units (intermediate stage). Notably, all 5 wearable and wireless BCI systems mentioned above [1, 2, 8, 25, 26] focused on

Table 2. Comparison of wireless BCI systems

	Reference					
	[1]	[2]	[8]	[25]	[26]	[31, 32]
Signal	EEG	SSVEP	single unit	EEG	EEG	EEG/EMG ECG/EOG
Channels	6	2	16	multi-channel	multi-channel	4
Transmission	Bluetooth	wireless	WLAN IEEE802.11b	–	Bluetooth (between computer and vibrotactile device)	Bluetooth/RF
Resolution of A/D	12	–	8	16	–	8
Sampling rate	–	200	244	–	500	457
Gain	10,000	–	500/1,000	–	–	1,000/5,000
Filter	60 Hz low pass	4–35 Hz band pass	211 Hz high pass	–	–	1~100 Hz band-pass 60 Hz notch
Signal processing unit	notebook	computer	66 MHz AMD processor	computer or PDA	computer	custom dual-core DSP
Analysis procedures implemented in the portable device	–	FFT	–	–	FFT Gabor filter feature selection	down sample Hanning windowed FFT normalization moving average PCA linear regression model

EMG = Electromyography; ECG = electrocardiogram; EOG = electro-oculogram; FFT = fast Fourier transform; PCA = principal component analysis.

custom hardware and software for EEG/ECoG monitoring rather than on hardware for performing online signal processing. The acquired data were either recorded on a portable device or transmitted wirelessly to a host PC located within a confined space or on a WLAN. Analysis of acquired signals was carried out either online or offline using personal computers (PCs), meaning that the data acquisition units were wearable, while the BCI systems as a whole were not. The lack of completely stand-alone wearable and wireless BCI that is capable of high-fidelity recording and online signal processing could hinder the portability and practical usefulness of such systems in real operational environments. Given the recent development of embedded system and signal processing techniques, it seems practical to implement sophisticated algorithms in embedded systems for online BCI systems. Recently, Lin et al. [31, 32] developed and demonstrated a wearable and wireless EEG acquisition and real-time data analysis module based on an embedded system for maximizing the usability, portability and wearability of BCI. The details are presented in the next section.

Real-World Applications of Wearable and Wireless BCI

The wearable and wireless BCI system developed and published by Lin et al. [31] featured dry micro-electro-mechanical system EEG sensors, low-power signal acquisition, amplification and digitization, wireless telemetry, and online signal processing. Figure 3 shows the pictures and the system architecture of the BCI system, which comprises 5 major units: (A) signal acquisition and amplification units, (B) wireless data transmission unit, (C) dual-core signal processing unit, (D) host system for data storage and real-time display and (E) warning device for providing feedback to the user. EEG signals were obtained using dry EEG sensors that did not require skin preparation and gel application to ensure good electrical conductivity between the sensor and skin. The acquired signals were first amplified by the signal acquisition and amplification unit. The wireless data transmission unit comprised an A/D converter, a complex programmable logic device and a wireless module. The wireless module could be either an RF module (RF3100/3105) or a Bluetooth module depending on transmission range require-

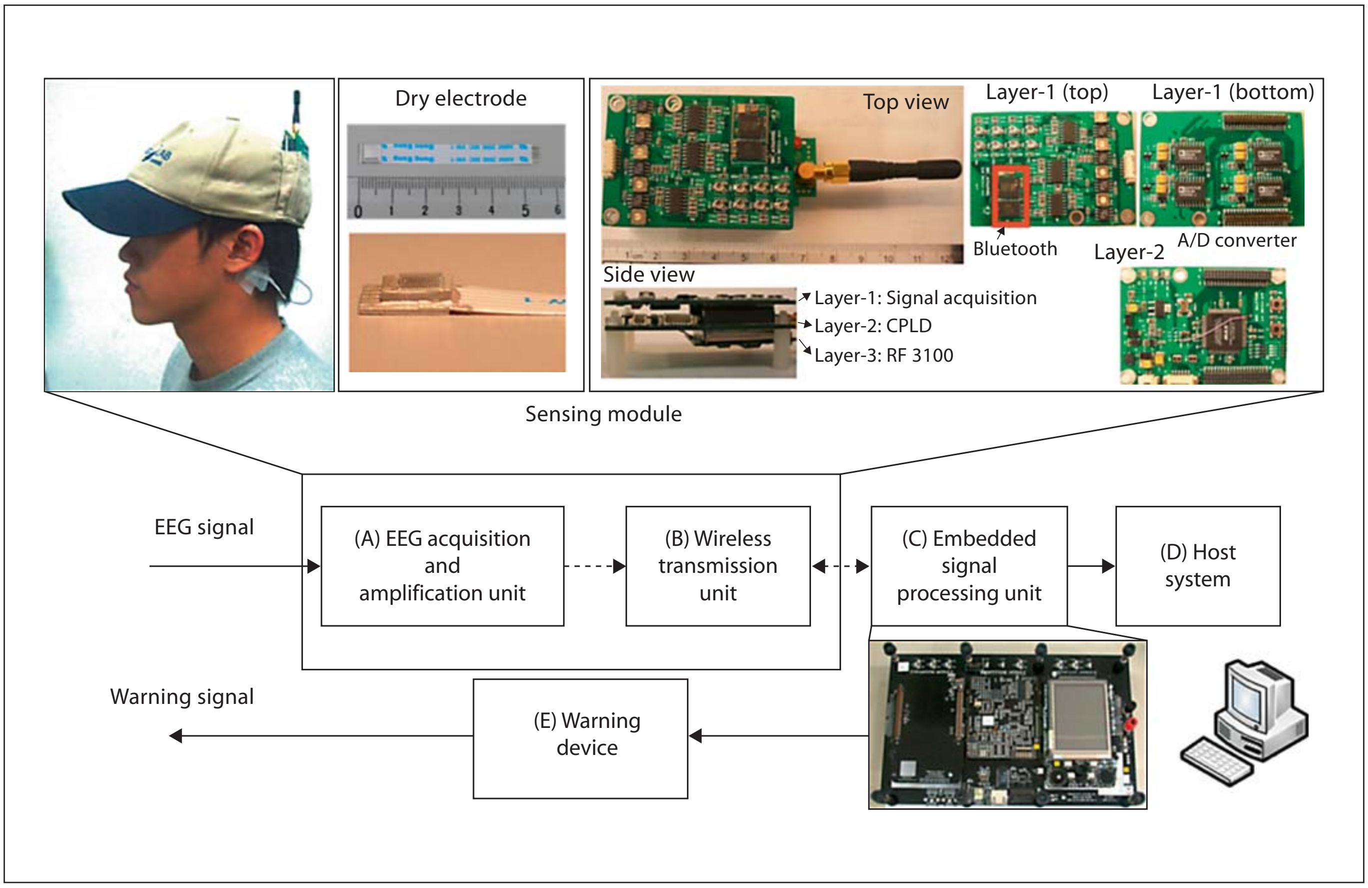


Fig. 3. Photos and block diagram of the BCI system proposed by Lin et al. [31, 32]. (A) EEG acquisition and amplifying unit. (B) Wireless transmission. (C) Dual-core signal processing unit. (D) Remote host system for data storage and real-time display. (E) Warning device provides feedback to the user. Adapted with permission from the Institute of Electrical and Electronics Engineers [31]. CPLD = Complex programmable logic device.

ments. The custom-designed DSP module comprising Bluetooth receiver, data processing and display circuits served as a development platform for general-purpose EEG signal processing. The analytical procedures implemented in the investigation included: (1) downsampling, (2) Hanning windowed fast Fourier transform, (3) normalization, (4) moving average, (5) independent/principal component analysis, and (6) linear regression model. The procedures were designed to estimate subject performance and putative level of drowsiness (or potentially other attributes) based on the EEG power spectra. The BCI delivers arousing warning tones to the subject to maintain optimal performance in the study of Lin et al. [31]. Notably, the BCI system actually serves as a platform that can be programmed and extended to many other BCI applications.

Conclusions

BCI has recently attracted increasing attention. This study reviewed recent developments of online BCI systems, particularly focusing on the wearable, wireless and real-time systems. The main goal of designing and developing wearable and wireless BCI systems is to maximize their usability, wearability, portability and reliability in operational environments. Recently, several wearable and wireless BCI systems have been proposed and developed. In the future, an increasing number of BCI systems capable of high-fidelity data acquisition, wireless telemetry and online signal processing are widely expected. These systems will provide further insight into the complex brain functions of users performing ordinary tasks in natural body positions in real operational environments. These systems will potentially have an enormous impact on clinical research and practice in gerontology, neurology, psychiatry and rehabilitation medicine.

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