Wearable and Wireless Brain-Computer Interface and Its Applications

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Abstract. This study extends our previous work on mobile & wireless EEG acquisition to a truly wearable and wireless human-machine interface, NCTU Brain-Computer-Interface-headband (BCI-headband), featuring: (1) dry Micro-Electro-Mechanical System (MEMS) EEG electrodes with 400 ganged contacts for acquiring signals from non-hairy sites without use of gel or skin preparation; (2) a miniature data acquisition circuitry; (3) wireless telemetry; and (4) online signal processing on a commercially available cell phone or a lightweight, wearable digital signal processing module. The applicability of the NCTU BCI-headband to EEG monitoring in real-world environments was demonstrated in a sample study: cognitive-state monitoring and management of participants performing normal tasks.

Keywords: Dry electrodes, brain computer interface, mobile and wireless EEG.

1 Introduction

Electroencephalogram (EEG) is a powerful non-invasive tool widely used by for both medical diagnosis and neurobiological research as it provides high temporal resolution in milliseconds. Another important advantage of EEG is that it involves sensors light enough to allow near-complete freedom of movement of the head and body, making EEG the clear choice for brain imaging of humans performing normal tasks in real-world environments [1]. However, the lack of portable and user-acceptable (e.g., comfortably wearable) sensors and miniaturized supporting hardware/software to continuously acquire and process EEG has long thwarted the applications of EEG

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monitoring in the workplace [2]. Recently, we developed and tested a prototype four-channel mobile and wireless EEG system incorporating a miniature data acquisition (DAQ) circuitry and dry Micro-Electro-Mechanical System (MEMS) electrodes with 400 ganged contacts for acquiring signals from non-hairy sites without use of gel or skin preparation [2-4]. This study extends our previous work, NCTU BCI-cap [2-4], to a smaller, lighter, wearable & wireless brain-computer interface (BCI), **NCTU BCI-headband**. The NCTU BCI-headband features: (1) disposable dry MEMS electrodes; (2) an 8-channel DAQ unit; (3) wireless telemetry and (4) real-time digital signal processing (DSP) implemented on a commercially available cell phone or a digital signal processing module. The applicability of the NCTU BCI-headband to EEG monitoring in operational environments was demonstrated by a sample study: cognitive-state monitoring and management of participants performing normal tasks in real-world environments.

2 Wearable and Wireless Brain-Computer Interface

Figure 1 shows the system diagram of the mobile and wireless brain-computer interface. The front-end unit integrates (1) clip-on electrode holders for dry MEMS or commercially available wet EEG electrodes, (2) a DAQ unit, and (3) wireless-transmission circuitry, into a quickly and easily donned and doffed **headband** that can acquire and transmit EEG signals from up to eight channels. The back-end unit integrates a wireless signal receiver and on-line DSP. EEG signals are first acquired by dry MEMS or commercially available electrodes, amplified by the preamplifier, converted to digital signals, and then wirelessly transmitted to the data receiver. The DSP unit processes the EEG data and displays the results. The raw EEG data can also be wirelessly transmitted to a remote PC for further offline analysis and/or database collection.

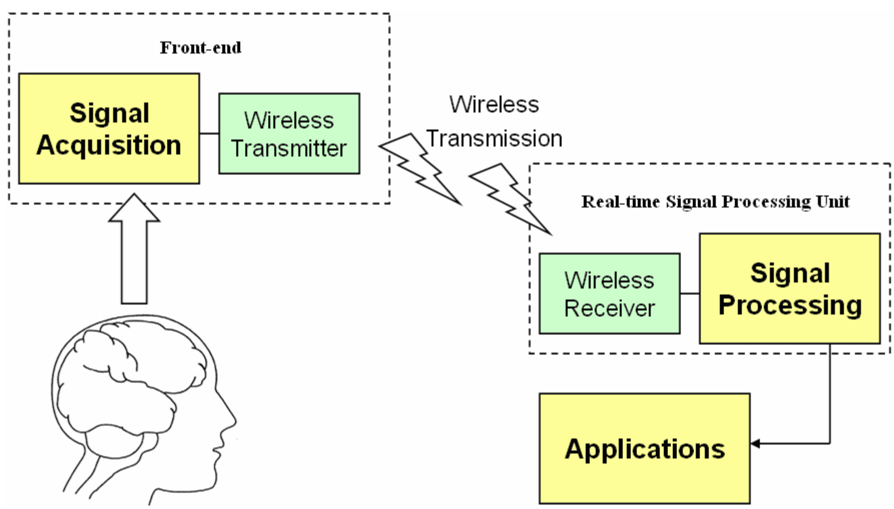


Fig. 1. System diagram of a wearable and wireless brain-computer interface

2.1 Dry MEMS Electrodes and Electrode Holders

We previously explored the use of MEMS technology to build a silicon-based spiked electrode array or so-called dry electrode, to enable EEG, EOG, ECG, and EMG monitoring without conductive paste or scalp preparation [2-4]. However, the connectors between the dry sensors and DAQ board were not very robust in the BCI-cap. This study incorporated snap-on electrode holders to house dry electrodes or commercially available EEG sensors. Fig. 2B shows the snap-on connector.

2.2 Data Acquisition Unit

The data acquisition unit integrated an analog preamplifier, a filter, and an analog-to-digital converter (ADC) into a small, lightweight, battery-powered DAQ. EEG signals are sampled at 512Hz with 12-bit precision, amplified by 6000 times, and band-pass filtered between 1 and 50 Hz. Fig. 2A shows the block diagram of the DAQ unit. Fig. 2B shows the DAQ unit for each electrode (20mm x 18mm PCB 'node'). To reduce the number of wires for high-density recordings, the power, clocks, and measured signals are daisy-chained from one node to another with bit-serial output. That is, adjacent nodes (electrodes) are connected together to (1) share the power, reference voltage, and ADC clocks, and (2) daisy chain the digital outputs.

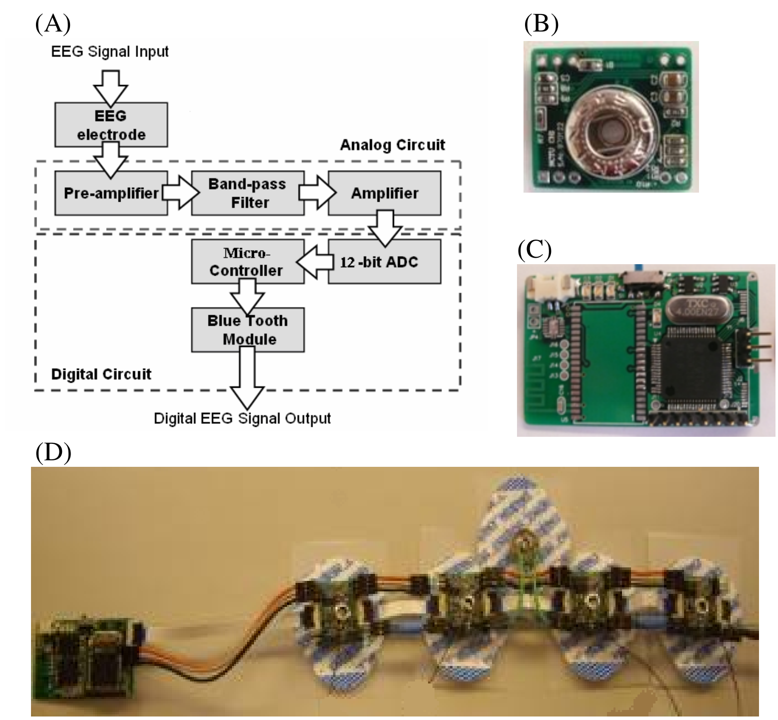


Fig. 2. (A) Block diagram of the data acquisition unit, (B) the DAQ unit for each electrode, (C) the wireless transmission unit, and (D) the integrated circuits of the NCTU BCI-headband

2.3 Wireless Transmission Unit

The wireless-transmission unit consisted of a wireless module and a micro-controller. It used a Bluetooth module to send the acquired EEG signals to a custom real-time DSP unit described below or a Bluetooth-enable cell phone which was used as a real-time signal-processing unit. The dimension of the wireless transmission circuit was 40 x 25 mm^2 (as shown in Figure 2C). Figure 2D shows a picture of the integrated 4-channel wireless EEG system. A reference and a ground channels were also included in the system (not shown). The integrated circuitry can be embedded into a headband, NCTU BCI-headband, as shown in Figure 3. The power-consumption of the NCTU BCI-headband is very low (a 1100 mAh Li-ion battery can last over 33 hours).

Fig. 3. A picture of the wearable & wireless EEG system, NCTU BCI-headband. It comprises 4- or 8-channel snap-on electrode holders (plus a reference and a ground channels), miniature bio-amplifier, a bandpass filter, an ADC and a Bluetooth module. All channels were referred to the left mastoid.

2.4 Real-Time Digital Signal Processing Unit

To be practical used in operational environments, the signal processing unit must be light-weight, portable, low-power, and have on-line data receiving and real-time signal processing function. Therefore, this study designed and developed a real-time digital signal processing unit which used a Bluetooth module to receive the acquired EEG signals from the NCTU BCI-headband and process the EEG signals via its core processor in near real-time. The core processor is the Blackfin processor (Analog Device Incorporation, ADSP-BF533) which provided a high performance, power-efficient processor choice for demanding signal processing applications. The dimension of the miniature DSP unit is about 65 x 45 mm^2 (as shown in Figure 4).

The maximum high processing performance of the BF533 core processor can reach 600MHz. Furthermore, the following peripheral modules were also incorporated in the unit.

- SD RAM and FLASH memory
- RS-232 serial interface
- Six keypads and a LCD panel (240 by 320 pixels)
- JTAG interface for debug and FLASH programming

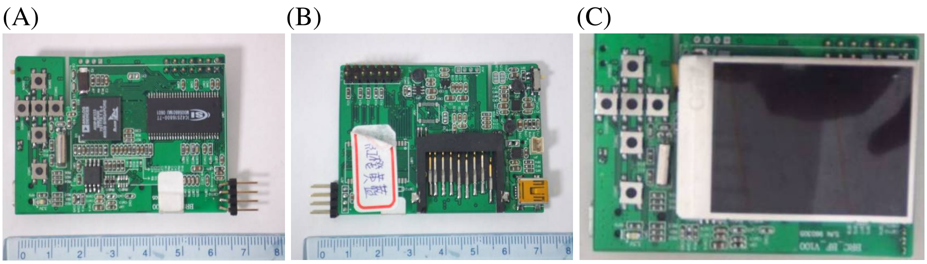


Fig. 4. Real-time digital signal processing unit. (A) Front panel houses an ADI BF533 processor and six keypads, (B) Back panel houses a SD card adapter, a Bluetooth module and a USB module, (C) A LCD is mounted on the frontal panel of the DSP unit to display the received raw data or the results of DSP.

- Bluetooth module
- USB chargeable and programming module

2.5 Data-Logging and Digital Signal Processing on a Cell Phone

To demonstrate the application of the wearable & wireless BCI during long and routine recording in operational environments, we have developed and installed a data-logging Java graphical user interface (GUI) on a Bluetooth-enable cell phone. The Java program receives EEG signals from the NCTU BCI-headband and plots them on the LCD screen. We have also implemented power spectrum density (PSD) estimation using a 512-point Fast Fourier Transform (FFT) on the cell phone.

3 Testing of Nctu Bci-Headband

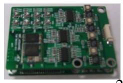
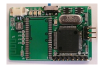
3.1 Comparison between the NCTU BCI-Cap and BCI-Headband

Lin et al. [2] reported a 4-channel BCI-cap which measured EEG and transmitted it to a commercially available DSP kit by Texas Instruments. This study extended the EEG recording system into a truly mobile brain-computer interface which acquired and processed EEG signals in near real-time. Table 1 compares the specifications and features of the BCI-cap and those of the BCI-headband. It is evident that, compared to BCI-cap, BCI-headband is lighter, smaller, more power-efficient and accommodates more channels with higher sampling rate and digitization precision.

3.2 Real-Time Alertness Monitoring Using NCTU BCI-Headband and a Cell Phone

Lin et al. [2, 5] recently demonstrated the feasibility of using dry MEMS EEG electrodes, supporting hardware and commercially available TI DSP kit to continuously and accurately estimate the driving performance (putative drowsiness level) based on EEG data from four frontal non-hairy positions in a realistic VR-based dynamic driving simulator. This study implemented the cognitive-state monitoring algorithm on a

Table 1. Comparison between the NCTU BCI-cap [2] and BCI-headband

	NCTU BCI-cap [2] 	NCTU BCI-headband 
Dimension (mm)	 46 x 66 mm^2	 DAQ: 20 x 18 mm^2 (4 pieces)  Wireless Unit: 40 x 25 mm^2
Weight	185 g	< 100 g
Precision	8 bit	12 bit
Sampling Rate	200Hz	512Hz
Bandpass Filter	1 - 50 Hz	
Gain	5000 times	6000 times
Output Current	480 mA	31.58 mA
Battery Life (3.7V, 1100mAh)	**3-4 hours**	**33-34 hours**

Bluetooth-enable cell phone that received EEG signals and processed them with the on-board processor. The cell phone delivered arousing feedback when the participants were drowsy. Figure 5A shows the flowchart of the signal processing implemented on the cell phone. Figure 5B shows the evident alpha activities when the subject was drowsy. We have also developed a user-friendly GUI (the pie chart in Figure 5C) to

(A) (B)

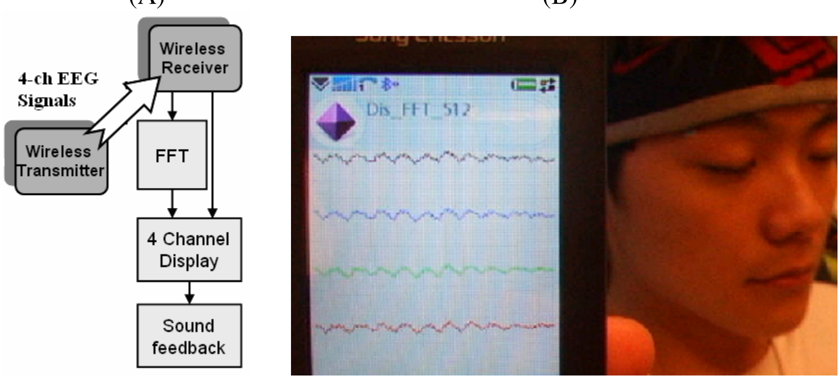


Fig. 5. (A) The flowchart of signal processing on a cell phone, (B) Four-channel EEG signals were displayed on the cell phone. Alpha rhythm became evident when the subject was drowsy. (C) A custom GUI of BCI-based cognitive-state monitoring on a cell phone.

(C)

Fig. 5. (*continued*)

continuously track and display the cognitive states of the subject. When the subject was alert, the whole pie chart was blue. As the subjects became more and more drowsy, wedges of the pie chart changed from blue to red, increasing the red area as the subject became drowsier. When the subject became very drowsy, the whole pie chart became red and the warning set off.

4 Conclusions

This study demonstrated a truly portable, lightweight, and readily wearable brain-computer interface that featured dry MEMS electrodes and a miniaturized DAQ, wireless telemetry and online signal processing. The main goal of the design and development of wearable and wireless BCI is to maximize their wearability, unconstrained mobility, usability and reliability in operational environments. In this study, the signal-processing module and the Bluetooth-enable cell phone were programmed to assess fluctuations in individuals' alertness and capacity for cognitive performance based on the EEG signals. The BCI delivered arousing feedback to the driver to maintain optimal performance. The cell phone and DSP unit, however, can be programmed for many other brain-system interface applications. We expect that a truly portable and user-acceptable BCI will have enormous future impacts on clinical research and practice in neurology, psychiatry, gerontology, and rehabilitation medicine.

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