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Design of the Multi-channel Electroencephalography-based Brain-Computer Interface with Novel Dry Sensors

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***Abstract*—The traditional brain-computer interface (BCI) system measures the electroencephalography (EEG) signals by the wet sensors with the conductive gel and skin preparation processes. To overcome the limitations of traditional BCI system with conventional wet sensors, a wireless and wearable multi-channel EEG-based BCI system is proposed in this study, including the wireless EEG data acquisition device, dry spring-loaded sensors, a size-adjustable soft cap. The dry spring-loaded sensors are made of metal conductors, which can measure the EEG signals without skin preparation and conductive gel. In addition, the proposed system provides a size-adjustable soft cap that can be used to fit user's head properly. Indeed, the results are shown that the proposed system can properly and effectively measure the EEG signals with the developed cap and sensors, even under movement. In words, the developed wireless and wearable BCI system is able to be used in cognitive neuroscience applications.**

Keywords: Electroencephalography (EEG); Brain-computer interface (BCI); Dry sensor; Data acquisition device; Size-adjustable soft cap.

I. INTRODUCTION

Electroencephalography (EEG) is one of important imaging tools for probing the brain activations, providing valuable insights to both basic neuroscience researches [1-4] and clinical applications [5, 6]. Indeed, the EEG-based brain-computer interface (BCI) is used to translate signals from brain activities into machine commands. This technique has recently rapid raised for the neuroscience and rehabilitation engineering [7], such as motor imagery [8-11], drowsiness detection [12-19] and sleeping analysis [17, 18, 20-22]. Indeed, it provides a reliable and efficient way to communicate between users and computers. However, their bulky size has made the range of BCI experiments and corresponding application restricted. Recently, many EEG-based BCIs have been proposed, but with the use of traditional wet sensors. For the long period of cognitive experiment, wet sensors with the use of conductive gel would result in affecting the signals quality, due to that the gel dried. Gradually, many dry sensors have been proposed that have the same security and acceptable signal quality. It is also important to reduce time of skin preparation processes which are the factors of experiment. However, until now, no dry sensors integrated with the wearable and wireless EEG-based BCI system has been proposed.

Conventional wet sensors requires preparation of the skin or the application of conductive electrolytes at the skin-sensor interface, which can be time consuming and uncomfortable for the users. Preparation of the EEG channels involves abrading the scalp and risk of infection if the sensors are not clean between users. Likewise, if conductive gel leaves part of gel on the scalp, it may result in an electrical short between two sensors closely. In order to improve these limitations of conventional EEG-based BCI system with wet sensors, there

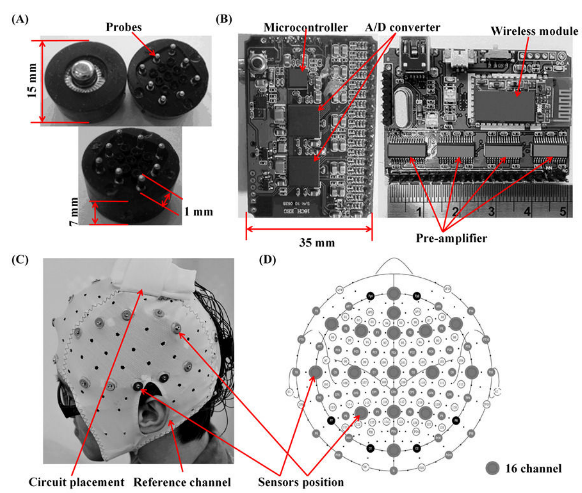

Figure 1. The proposed 16-channel EEG-based BCI system is designed with dry sensors. (A) The proposed dry EEG sensor with 15 mm of diameter, 7 mm depth and 8 probes. Each probe is 1 mm length. (B) The wireless EEG acquisition system with pre-amplifier, ADC converter, microcontroller and wireless module. (C) A size-adjustable soft cap with 16 dry EEG sensors, the placement of each sensors are compared with the (D) standard 10-20 EEG measurement system.

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are different kinds of dry sensors have been developed [23-32]. Some of these dry sensors are made by the microelectromechanical systems (MEMS) technique [25, 28-30]. The dry MEMS EEG sensors techniques acquire the EEG signals on the forehead [28]. There still exist some disadvantages by using the MEMS sensors, such as high cost for the manufacture procedure of MEMS sensors and the MEMS sensors with the hard substrate will lead to uncomfortable. Some kinds of these dry sensors are made by the fabric-based sensors [33-35]. Compared to dry MEMS sensors, signals measurement using fabric-based sensors are in a comfortable way. However, fabric-based sensors measurements are not suitable on hairy site (i.e., parietal and occipital).

In this study, a wearable and wireless 16-channel EEG-based BCI system with dry EEG sensors is proposed, which is consisted of the dry sensors and the wireless acquisition system. The dry sensors can be performed without the application of conductive gel; they were able to provide good electrical conductivity to acquire an EEG signals effectively. In contrast to the traditional BCI systems, using the dry sensors, users can reduce the skin preparation processes and have highly accuracy of EEG signals. Because of the comfortableness, the EEG-based BCI system can make preparation time of experiment quickly and have feasible applications in cognitive neuroscience research .

II. System Architecture and Material

The fundamental components of proposed system is shown in Figures 1(A-D), including the dry sensors, a wireless/wearable EEG acquisition system, a size-adjustable soft cap and international 10-20 system of sensor placements.

A. Design of Dry Sensor

The proposed dry EEG sensors were designed with eight "probes," as shown in Figure 1(A). Each of the probes has four components: probe, spring, plunger and barrel. The top of the probe is made as a spheroid shape, which is coated with gold for enhancing the conductivity. The chemical properties of gold are stable, which are not easily react with other substances. Besides, its high conductivity and high resistance to oxidation, resistance to environmental degradation (i.e., resist other non-chlorinated acids), so gold are widely used in the electronics industry. The spring force is about 18 gram, which is mainly dependent on measuring EEG signals of the scalp. In addition, according to the location of the contact with

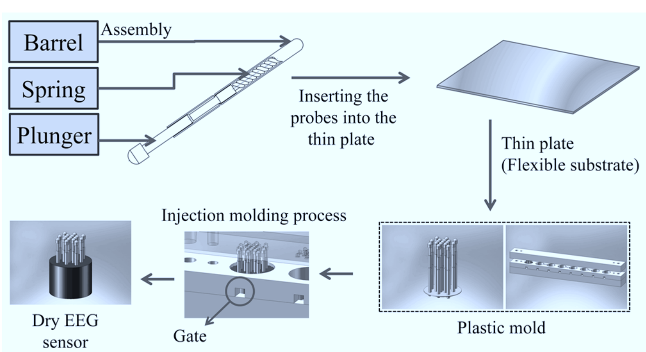

Figure 2. The manufacture processes of developed dry sensors, including the injection-molding and package processes.

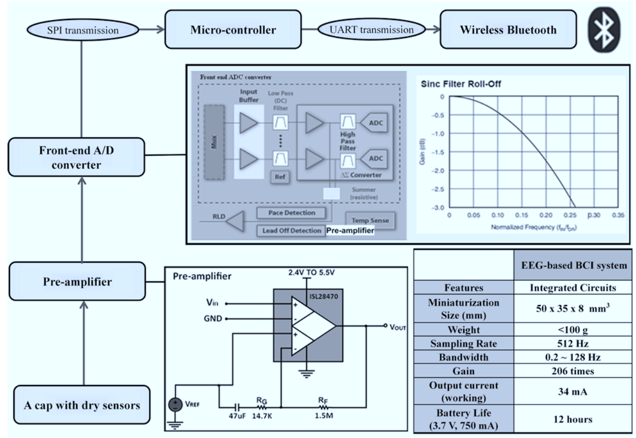

Figure 3. The fundamental concept of wireless and wearable 16-channel EEG-based system is designed with dry sensors.

the scalp, spring would increase/decrease the spring length.

B. Manufacture of Dry Sensors

The manufacturing process for the developed dry EEG sensors was shown in Figure 2. Eight probes are inserted into the thin Cu plate which applied to the flexible base of the sensor. After insertion, eight probes on the thin Cu plate are all conductive. When force applied on the sensor, the flexible substrate can be flexible to fit to the scalp surface. The spring provides buffering effects, which enables the dry EEG sensor to contact the scalp well when force is applied. After fabricating and inserting probe into the flexible substrate, injection-molding process is used to the flexible base to several probes. The probes with the elastic base are fixed in the plastic mold. With the thin plate and spring contact probes, the sensors also have flexible benefits after the injection molding process [36].

C. EEG Measurement Module

The EEG signal is ranging from 10 to 100 μV when measured from the scalp. It is difficult to measure the EEG signals because the weak signals and with noise. According to the EEG properties, the 16-channel EEG acquisition module was designed to measure the EEG signals, as shown in Figure 1(B). This acquisition module consists of four major units: 1) pre-amplifier unit, 2) front-end ADC converter unit, 3) microcontroller unit and 4) wireless unit. The size of the proposed wireless 16-channel IC-based acquisition module was about 50 × 35 × 8 mm^3. It can be embedded into our system. The EEG signals measured by the dry EEG sensors are first amplified by pre-amplifier unit. In pre-amplifier stage, the instrumentation amplifier was used for its extremely high input impedance and high common-mode rejection ratio (CMRR). Instrumentation amplifier has ability to improve CMRR and amplify the EEG signals such that mini voltage level signals can be detected successfully.

The gain of the pre-amplifier unit is set to 103 V/V and the cut-off frequency using the high pass filter was regulated to 0.2 Hz. The transfer function of this designed pre-amplifier circuit is as follow:

$$V_{out} = (1 + \frac{R_F}{R_G + 1/sC})V_{in} + V_{REF} \quad , \quad (1)$$

$$\frac{V_{out}}{V_{in}} = (1 + \frac{R_F}{R_G + 1/sC}) + \frac{V_{REF}}{V_{in}} \quad , \quad (2)$$

$$\frac{V_{out}}{V_{in}} = (1 + \frac{R_F}{R_G}) = (1 + \frac{1.5\times10^6}{14.7\times10^3 + 1/j\omega\times47\times10^{-6}}) \quad . \quad (3)$$

Using the ADC is in the following stage: front-end ADC converter unit. Because the simplified designed, the quite large space and power consumption are saved. Analog front-end for EEG was used to digitize the EEG signals with the sampling rate of 512 Hz, and the sinc filter removed the frequency higher than 128 Hz, as shown in Figure 3. In microcontroller unit, it deals with the signals sampled rate, magnification and noise reduction. The processed EEG signals from ADC, which through the microcontroller to reduce the noise by moving average. The microcontroller unit sets the gain of the ADC unit to 2 V/V. Therefore, the total gain of the EEG signals is set to 206 V/V (i.e., 103 x 2 V/V). After removing the noise and amplify the EEG signals, the EEG signal is transmitted to the computer interface by the wireless module. In the wireless unit, Bluetooth module is used for data transmission. A Bluetooth module supports the transfer baud rate (i.e., 921,600 bps) to provide high band-width, which is properly compliant with the Bluetooth v2.1+ EDR spec. More importantly, it can be continuously operated over 12 hours with a commercial 750 mAh Li-ion battery.

D. *Brain-Computer Interface System*

Standard EEG-based BCI system has multi-channel (i.e., 256 channels) for measuring brain activity. The sensors locations are according to the international 10-20 [37] EEG system on an elastic head cap. This cap is suitable only for the sensors are covered with conductive gel. Therefore, an easy-of-use size-adjustable soft with the dry sensors is proposed. The designed EEG cap are placed with 16 dry sensors sites. The designed size-adjustable soft cap is shown in Figure 1(C). It is composed of elastic fiber, providing more comfortable and flexible performance, which can be more fit in user's head. It makes the sensor closer to contact user's scalp. The inner layer holds and fixes the universal joints, which can connect the dry sensors on the scalp. The outer layer is also made up of elastic fiber which provides much more flexibility for covering the head from different users. By using the Velcro, which can be more suitable for different kinds of head shape for measuring the EEG signals. Those 16 dry sensors are located on the cap according to international 10-20 system as shown in Figure 1(D). The dry sensors can easily be placed onto the designed cap and contact with the scalp of the subject.

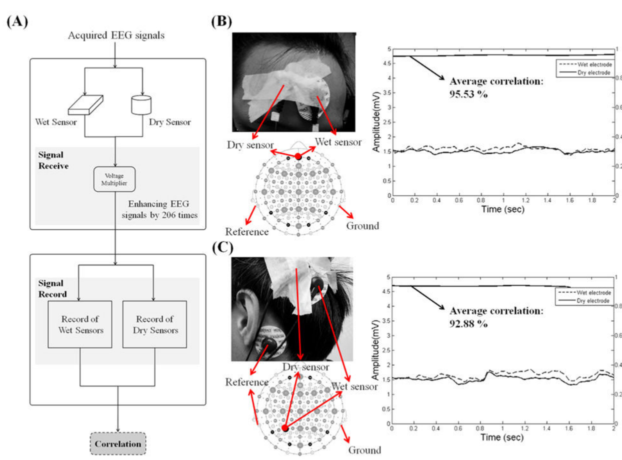

Figure 4. (A) Testing flow of the signal quality between the dry sensors and wet sensors. (B) The EEG measurements on the frontal (Fpz) and (C) the hairy site (P3) are presented.

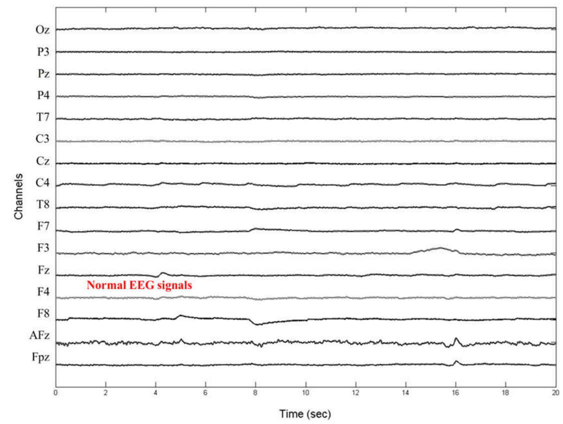

Figure 5. The normal EEG signals are measured by the proposed EEG-based BCI system with dry sensors.

III. Results and Discussion

Figure 4(A) shows the testing flow of the signal quality between the dry and wet sensors. Measuring the EEG signals with dry and wet sensors is the first step. Then, the EEG signals are transmitted to the data acquisition and amplified EEG signals by 206 times. Both EEG records are saved with using dry and wet sensors measurement. Finally, the signals correlation is compared between dry and wet sensors.

Figures 4(B) shows the results of EEG measurements using dry sensor and wet sensors on the forehead location (Fpz). Figure 4(B) shows the recorded by wet sensors signals and the recorded signals from our proposed dry EEG sensor. The recorded EEG signals by the wet sensor and the signals that are obtained using the dry EEG sensor were highly

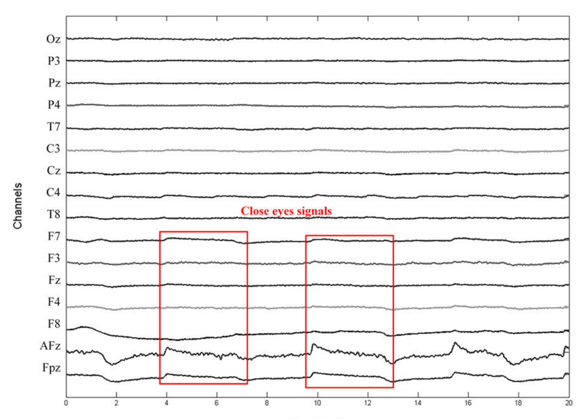

Figure 6. The EEG signals during the eye closing are measured by the proposed EEG-based BCI system with dry sensors.

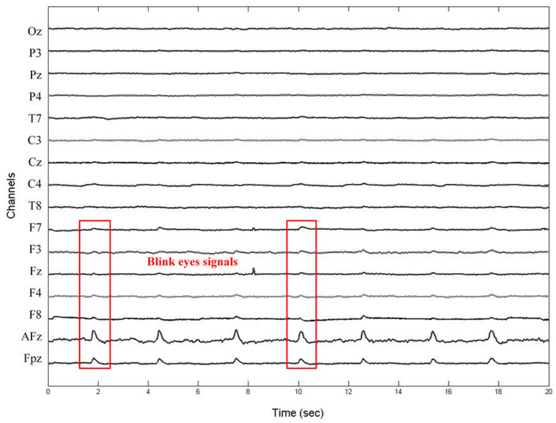

Figure 7. The blink eye signals are measured by the proposed EEG-based BCI system with dry sensors.

correlation of 95.53%. The dry sensor is proved that the signal quality is stable for the EEG measurement, comparing with wet sensors, after checking the correlation between the conventional wet sensor and the dry sensor. Figure 4(C) shows the results of EEG measurements using dry sensor and wet sensors on the hairy site (P3). The signal correlations are over 92.88% on hairy site location.

The normal EEG signals measured by the proposed system are shown in Figure 5. The EEG signals can be significant observed from frontal (i.e., Fpz, AFz, F8, F4, Fz, F3 and F7), temporal (i.e., T7 and T8), central (i.e., C4, Cz and C3), parietal (i.e., P4, Pz and P3) and occipital (i.e., Oz). Due to the scale issue, the signals variations would be relatively smaller. The EEG signals of during the eyes closed can be indeed measured by the proposed system, as shown in Figure 6. It is significant on the frontal sites (i.e., Fpz, AFz, F8, F4, Fz, F3 and F7). During the signal measurement of eyes closed, because the eyes are relatively close to the frontal place, the signal of Fpz, AFz, F8, F4, Fz, F3 and F7 sites are more significant than temporal (i.e., T7 and T8), central (i.e., C4, Cz and C3), parietal (i.e., P4, Pz and P3) and occipital (i.e., Oz). Figure 7 is shown that the 16-channel EEG-based BCI system measures the blink signals. Because the motion of blink is near the frontal, the signals of blink eyes are significant on frontal (i.e., Fpz, AFz, F8, F4, Fz, F3 and F7). Indeed, the eyes are relatively approaching to the Fpz, AFz, F8, F4, Fz, F3 and F7 sites. So, during the blink of eyes signals would be more obvious on frontal than other sites (i.e., central, temporal, parietal and occipital). The signal of teeth-clamping was shown in Figure 8, showing that the whole head (i.e., frontal, central, temporal, parietal and occipital) have significant signal variations.

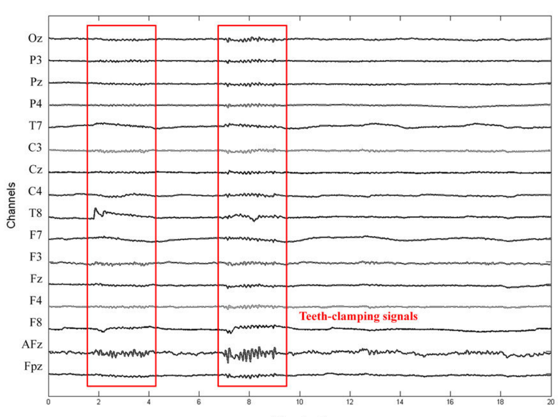

Figure 8. The EEG signals during the teeth-clamping are measured by the proposed EEG-based BCI system with dry sensors.

According to the experimental results, the 16-channel EEG-based BCI system would be used for measuring the EEG signals especially on the hair sites. On the other hand, the proposed system has good signals quality by using the dry sensors. From the above experimental data, the proposed EEG-based BCI system is able to measure the EEG signals, blink of eyes signals, closed eyes signals and signals of teeth-clamping.

IV. Conclusion

In this study, a wearable electroencephalography (EEG)-based brain-computer interface (BCI) system with dry spring-loaded sensors can transfer the EEG signals to the computer wirelessly. The developed system contains a size-adjustable soft cap, developed dry EEG sensors and 16-channel acquisition circuit. Comparing with the conventional BCI system with wet sensors, the proposed system with dry sensors can be used to measure the EEG signals without the use of conductive gel and skin preparation processes. Because of the soft substrate of the dry sensors and spring-loaded probes, dry sensors ensure the force fixing the sensors on the scalp tightly. Moreover, the proposed system with dry EEG sensors can be reliable for measuring the clean 16-channel EEG signal. On the other hand, the developed soft cap is suitable for general size of heads (i.e., large, medium and small sizes) for the basic cognitive experiments. Besides, the 16-channel acquisition circuit provides more powerful operation, proving a high sample rate, low-power, light weight and small size performances. In words, users can use the developed EEG-based BCI system with dry sensors to investigate the human cognitive states.

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