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WIRELESS BRAIN-COMPUTER INTERFACE FOR ELECTRIC WHEELCHAIRS WITH EEG AND EYE-BLINKING SIGNALS

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Abstract. *This paper mainly proposed a wireless electroencephalogram (EEG)-based brain-computer interface (BCI) and a drive circuit for DC motors to control electric wheelchairs through a Bluetooth interface for paralyzed patients. Paralytic patients can not move freely and only use wheelchairs in their daily life. Especially, people getting motor neuron disease (MND) can only use the eyes and brain to exercise their willpower. Therefore, real-time EEG and eyes blinking signals can help these patients effectively. However, current BCI systems are usually complex and have to send the brain waves to a personal computer to process the EEG signals. In this paper, a simple BCI system and a drive circuit for DC motor can help paralytic patients easily drive the electric wheelchairs. The proposed BCI system consists of a wireless physiological signal-acquisition module and a signal processing unit. Here, the physiological signal acquisition module and signal processing unit were designed for extracting EEG and eyes blinking signals from brain waves which can be directly transformed into control signals to drive the electric wheelchairs. The advantages of the proposed BCI system are low power consumption and compact size so that the system can be suitable for the paralytic patients. The experimental results showed feasible action for the proposed BCI system and drive circuit with a practical operating in electric wheelchair applications.*

Keywords: EEG, BCI, Electric wheelchairs

1. **Introduction.** Electric wheelchairs have been considered as one of important mobility aids for the elderly as well as the physically impaired patients. Clinicians pointed out that approximately 50% of patients including paralyzed patients cannot be able to control an electric wheelchair by conventional methods. Especially, people getting MND can only use the eyes and brain to exercise their willpower. In the context, EEG-controlled wheelchairs are a mobility aid especially suitable for the paralyzed patients that are unable to operate the electric wheelchair completely. The motivation of the EEG-controlled wheelchairs is to facilitate assistance in mobility in order to accomplish complex navigational tasks in realistic environments for the paralyzed patients. It includes the development of automatic navigation strategies and personalized interactive assistance to enable the patients to move wheelchairs efficiently and easily.

When the patients have suffered from MND, their muscle does be gradually wasting and weakness and then their body is frozen. The main type of MND is named Amyotrophic Lateral Sclerosis (ALS). Because of the famous American baseball star Lou Gehrig died of this disease, it is also called Lou Gehrig's disease. Their words, swallowing and respiration are dysfunctional until respiratory failure and death. The disease can infringe upon anyone, but more common in age 40-70 years old. The development of the disease is rapid and ruthless. Generally, the average life expectancy of survival is between 2-5 years after onset. Because sensory nerves have not been violated, it does not affect the patients' intelligence, memory or feeling.

There are numerous interfaces between human and machines to utilize input devices such as a mouse, keyboards, or joysticks. Recently, a number of biological signals have been utilized as hand-free interfaces, named brain-computer interface (BCI) to machines like electromyogram (EMG) and electroencephalogram (EEG). The paralyzed patients can not operate objects or communicate their needs, even though their mental capabilities are integral. Therefore, the previous reason promoted us to design a BCI system and a drive circuit by using the paralytic patients' brain waves to control electric wheelchairs and to help them move freely in their daily life. Electric wheelchairs have been identified as a primary mobility aid for the elderly as well as the physically impaired. In [1], Montesano et al. proposed an electric wheelchair system towards an intelligent manner for cerebral palsy users. They supported a visual display by a hand-interface with a touching screen to select a command to force the wheelchair action.

There is a rising tendency in the growing recognition requirements of BCI systems [2-15]. These existing BCI systems focus on developing new superior control and communication technologies for those with strict neuromuscular disorders. Three BCI approaches have been implemented at Aalborg University SS-VEP, MI, and NMI and discussed in [5]. A subject-independent BCI based on motor imagery was discussed by Lotte et al. [6]. In [7], Soraghan et al. proposed optical brain-computer interfaces to drive triple wavelength LED. Liu and Zhao [8] demonstrated a semi-supervised learning algorithm for BCI based on combining features to aim at reducing the training process. In [15], Prof. Lin et al. proposed a real-time wireless BCI for drowsiness detection. Their system consists of a wireless physiological signal-acquisition module and an embedded signal-processing module to monitor the drivers' long-term EEG signals and drowsiness status respectively.

There have been several studies using the signals of brain activity to control machines without any manual control. For example, EEG signals and small facial muscular movements were used to control speed and direction of a small mobile robot that was proposed by Amai et al. [14]. In their research, beta wave in EEG, electrooculogram (EOG), and jaw clench are used to control the speed, the direction, and forward/backward switching. Additionally, several BCI systems were constructed to control electric wheelchairs [1-4].

Several portable BCI systems have been proposed with a complex manner and having to transmit an EEG signal to a back-end computer to process the EEG signals. Montesano et al. [1] proposed a wheelchair system for cerebral palsy users. They supported a visual display by a handy-interface with a touchscreen to select a command to force the electric wheelchair action. It cannot be used by a paralyzed patient completely. In [2], Tanaka et al. used 15 electrodes to acquire EEG signals and a computer to access and analyze the brainwaves through wired cables. Their system cannot be suitable in practical use. Additionally, the electrodes in their system were not easily to wear for a paralyzed patient. Galan et al. [3] proposed a brain-actuated wheelchair in an asynchronous and non-invasive BCI by using a complex EEG acquisition system with 64 channels. This resulted in a useless practice for a paralyzed patient. An electric wheelchair towards a BCI-based control was proposed by Cho et al. [4]. They utilized a software named ACQUIRE and a complex acquiring system for the data acquisition process. For the electric wheelchairs in [1-4], they did not use any wireless interface in their system. This paper describes EEG-controlled wheelchairs through a Bluetooth interface. The study focused on paralyzed patients who can only use eyes and brain to exercise their willpower.

In this paper, we proposed a novel and simple technology to incorporate interactivity value in a wireless BCI system and a drive circuit to control electric wheelchairs. In the proposed BCI system, it has a compact size with low-power consumption. And, the proposed BCI system allows human and machine to communicate easily and supplies real-time to translate brain and eye-blinking waves to the commands of the drive circuit like "turn to a direction", "moving forward", or "stop" to control electric wheelchairs.

This paper is divided as follows. Section 2 introduces the architecture of BCIs. Section 3 demonstrates the structure of the proposed BCU for electric wheelchairs. Section 4 explains real-time EEG detecting algorithm in the proposed system. The experimental results are described in Section 5; and Section 6 shows the conclusions.

2. Architecture of BCIs.

A BCI is a novel communication system which enables users to translate brain activity, measured by Electroencephalography (EEG), into a control signal and sending to computers. BCIs have been exposed as a promising tool for paralyzed people and healthy people in several computer applications such as medical assistant devices [8] and video games [9].

BCI is a system in order to acquire and analyze brain waves in which a communication channel with high-range bandwidth has been created between the brain and the machine. Recently, the research field on BCI provides a new direction to construct an interactive system which can translate human brainwave into control signals for computer-application devices. BCI provides a communication channel not based on nerves and muscles to allow users to communicate without movement with the external world. BCIs are the only means to infer user intent through direct measures of brain activity usually via EEG signals. A BCI system is just to translate EEG signals from a reflection of brain activity into user action through system's hardware and software. BCI approaches are based on a variety of strategies to generate control signals which may be the result of visual stimulation or of imaginary motor tasks.

Figure 1 shows a block diagram of a wireless based BCI system. The system involves EEG acquisition, signal processing, wireless interface, and an application interface together with several applications. The block of signal processing includes preprocessing, feature extraction and classification.

3. Structure of the Proposed BCI for Electric Wheelchairs.

As shown in Figure 2, the proposed framework for the signal processing of EEGs with Bluetooth interface is expressed. The EEG signal was extracted from EEG acquisition module. In this system, we used the NeuroSky's ASIC chip to capture EEG and eye-blinking signals. With the

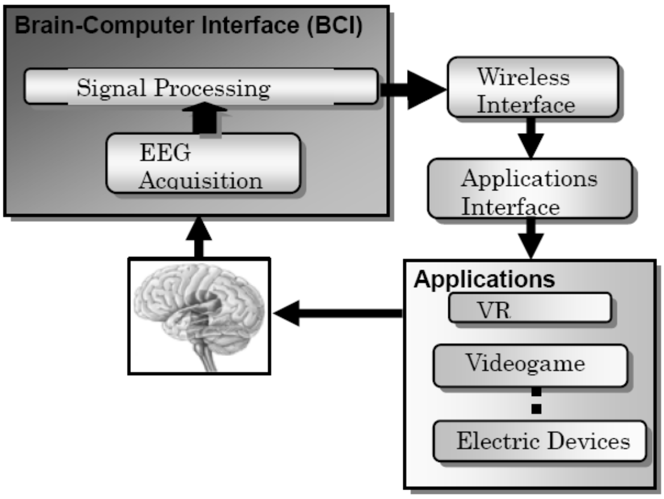


Figure 1. The brain-computer interface system with wireless interface

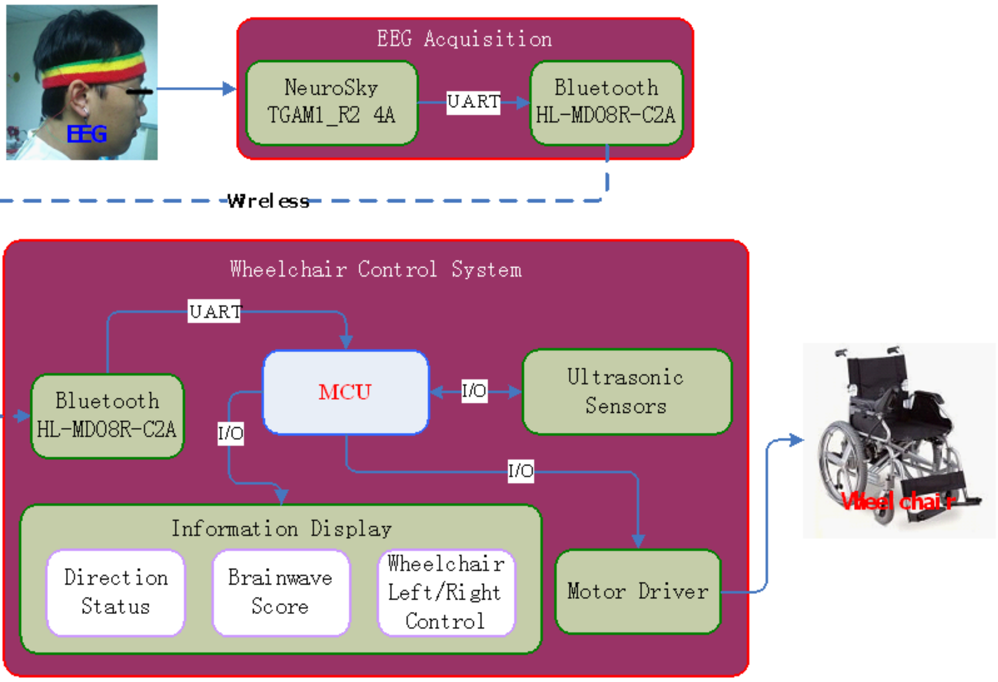


FIGURE 2. System architecture of the proposed BCI for electric wheelchair

sensor on headband to read brain waves, the brainwaves raw EEG were transmitted by the Bluetooth wireless module HL-MR08R-C2A in the EEG acquisition module. In the receiving part, we also integrated the Bluetooth module HL-MR08R-C2A in the wheelchair control system. The raw EEG signals, received from Bluetooth, were processed by the MCU, SunPlus SPCE61A, with a DSP algorithm to extract the Attention signal. The MCU also displayed the operation signals on information display unit. The direction-status unit, controlled and determined by the eye-blinking signal, is an LED array used to show the moving direction of turning for the wheelchair. The brainwave-score unit shows the intensity of Attention signal as well as the action status of electric wheelchair is displayed on the wheelchair left/right control unit. The Attention signals can be transformed as analog signals with a D/A converter to control the electric wheelchair through the motor driver circuit. The ultrasonic sensors with four directions are also designed to detect the obstacles around wheelchair.

3.1. **Wireless EEG signal-acquisition module.** The wireless EEG acquisition module, shown as in Figure 3, mainly consists of the NeuroSky ASIC chip and wireless transmission unit. This chip passes signals through an A/D converter. It also uses DSP circuit and an MCU to get high-quality EEG signals and reduce the noisy interference. Additionally, the chip has an active electrode to extract EEG signals and two reference electrodes. It, working on a voltage level of 3.3V, can send signals to peripherals by series manner with a baud rate of 57600 bps. Here, the Bluetooth module HL-MD08R-C2A is used as the wireless transmission unit.

In Figure 3, Active Electrode Port is an I/O port to acquire the EEG signals. The Active Electrode Port is connected an electrode to attach on the forehead as well as two Reference Electrode Ports are affixed on ears as reference points. Then the analog EEG signals have to be amplified, filtered, and converted to digital manner through TGAM1_R24A to form raw EEG signals. These raw EEG signals can then be fed foreword into the Bluetooth module HL-MR08R-C2A on the port TXD with the UART port. The Bluetooth module was used to transmit/receive the EEG signals. The principle of Bluetooth uses spread

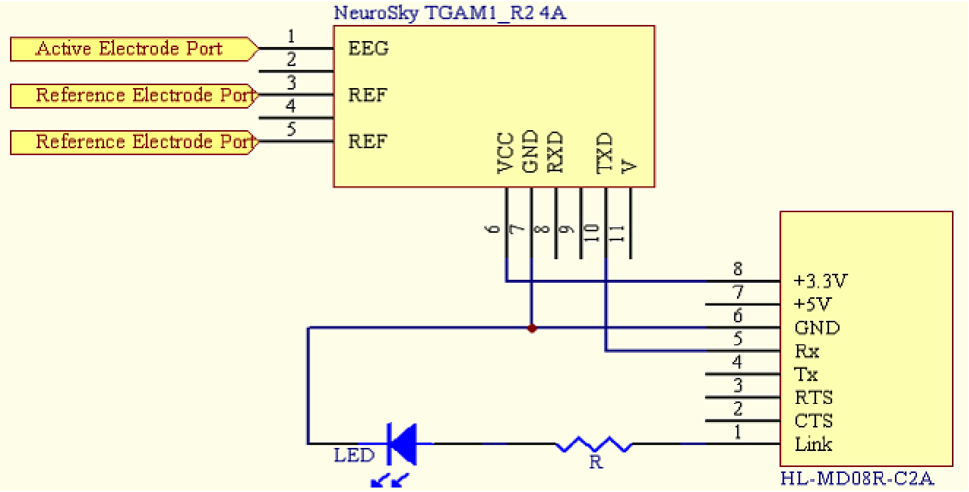


Figure 3. The hardware diagram of EEG acquisition


(a) (b) (c)

Figure 4. Photographs of (a) the proposed wireless EEG signal-acquisition module, (b) EEG headband with electrodes, and (c) the PCBs of EEG signal acquisition module TGAM1_R24A and Bluetooth module HL-MR08R-C2A

spectrum frequency hopping technology (FHSS) switching on 79 channels with a frequency of 1MHz so that both ends of a Bluetooth chip can synchronously transmit and receive signals with a specific narrowband-carrier manner in a 2.4GHz frequency band.

The Bluetooth module HL-MR08R-C2A was selected because it has low-power consumption, supports many interface protocols (SPP, SDP, GAP, L2CAP and RFCOMM), and can be designed a wireless interface with a simple manner. The LED in Figure 3 is used to show the linking status between TGAM1_R24A and HL-MR08R-C2A. The photograph of the proposed EEG acquisition module is shown as in Figure 4. Figure 4(a) is the proposed EEG acquisition module as well as the EEG headband with electrodes to acquire the EEG signals demonstrated in Figure 4(b). Figure 4(c) displays the PCBs of EEG signal acquisition module TGAM1_R24A and Bluetooth transmitting module HL-MR08R-C2A.

3.2. **Wheelchair control system.** Figure 5 shows the circuit diagram of the wheelchair control system. In the MCU SunPlus SPCE61A, we embedded a DSP algorithm to extract the Attention signal. There are 32 I/O ports on the MCU such as IOA0∼IOA15 and IOB0∼IOB15. IOA, working as output ports, were used for information-display module. Those 13 LEDs, placed on upper right corner in Figure 5, are used to exhibit the 13 moving directions in the direction mode. The direction angle between two adjacent LEDs

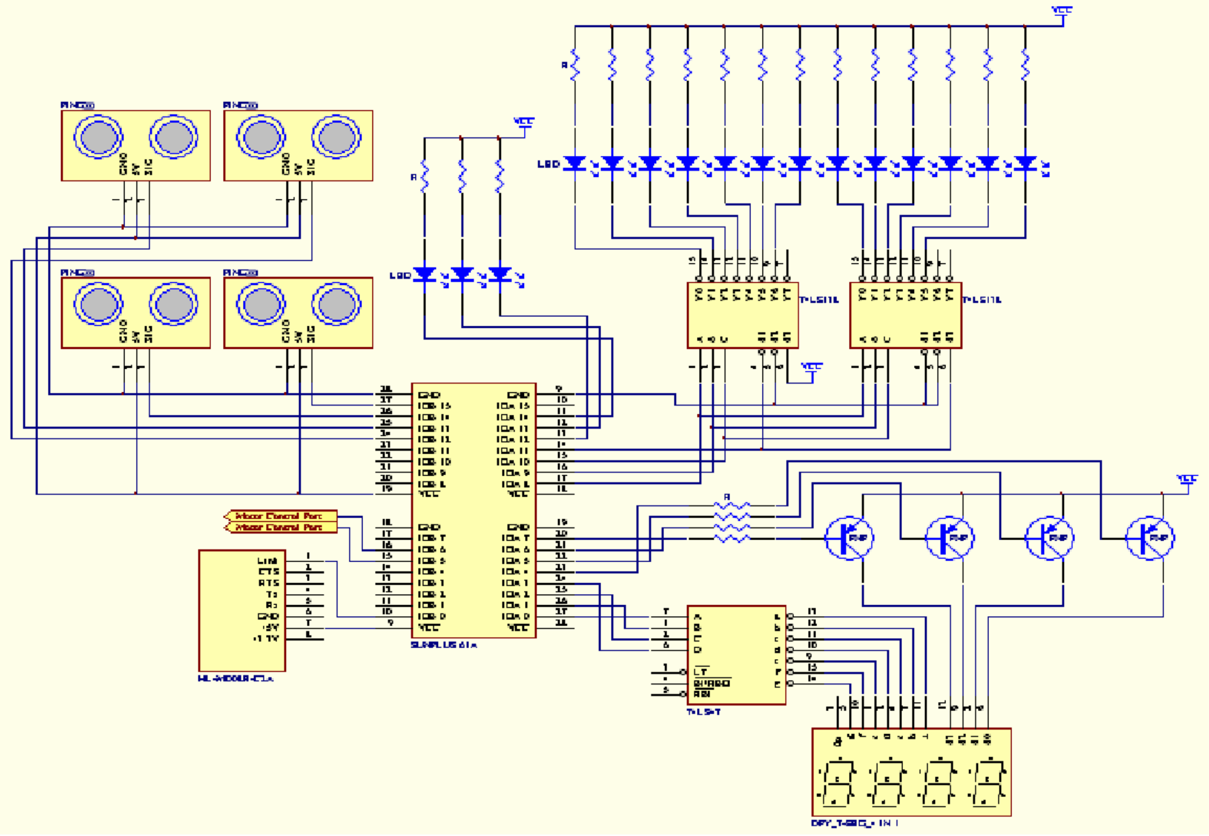


FIGURE 5. The circuit diagram of the wheelchair control system

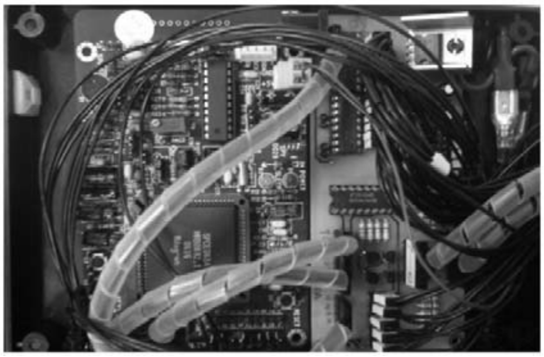


FIGURE 6. The photograph of MCU module

is 15°. The upper left on the figure, we utilized 4-set ultrasonic modules and tied to port IOB to detect the obstacles beside the left and right sides and the front of the electric wheelchair. The intensity of the EEG signals are normalized and displayed on the seven-segment display. The control signals of Bluetooth HL-MR08R-C2A and motor drivers are also bounded on the I/O ports IOB. Figure 6 shows the photograph of MCU module.

The wheelchair is controlled through two motor drivers to operate two DC motors providing both of steering and propulsion. The electric wheelchair has two 12-Volt batteries with 31-50 Amp-hr to support 24 V for the whole system motors. The 24-Volt battery is directly connected to the motor driver to provide the main power. They have a continuously variable speed from 0 to 4 MPH. Two drivers provide control power to the two DC motors. The block diagram of the proposed electric wheelchair system is shown as in Figure 7, in which the Sunplus SPCE61A is used as a microprocessor control unit (MCU)

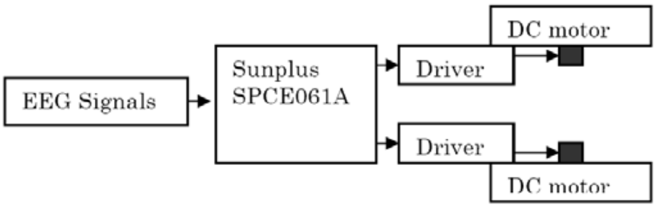


Figure 7. The block diagram of the proposed electric wheelchair

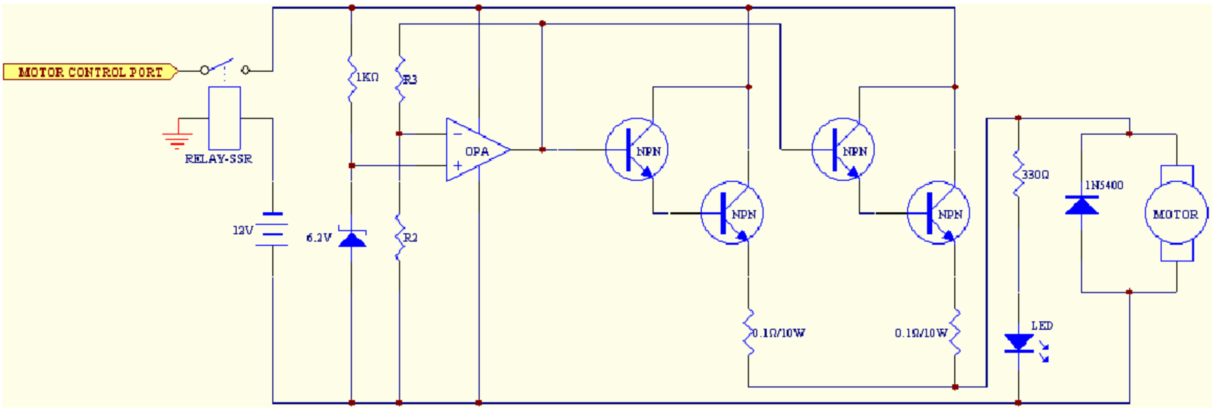


Figure 8. The schematic of the proposed DC-motor drivers

platform that contains all algorithms and functions for electric wheelchair. The MCU accepted commands signal and converted the digital value to analog voltage to provide the speed and torque.

In order to drive the left and right DC-motors in the electric wheelchair, we designed a couple of DC-motor driving circuits as shown as in Figure 8. We use two Darlington circuits to amplify current to increase the torque of the motors and let both sides of the rear wheel can easily drive electric wheelchair. In the motor drivers, we used an operation amplifier OPA to adjust speed of electric wheelchairs. In Figure 8, the output voltage can be adjusted by R_2 and R_3 and shown as in Equation (1). The higher the output voltage the faster wheelchair moves. The motor can carry a maximum voltage of 24 V.

$$V_o = V_i \times \left(1 + \frac{R_3}{R_2}\right) \tag{1}$$

Additionally, we added an LED on each driver circuit to indicate the activity of right (R) or left (L) motor shown as in Figure 8.

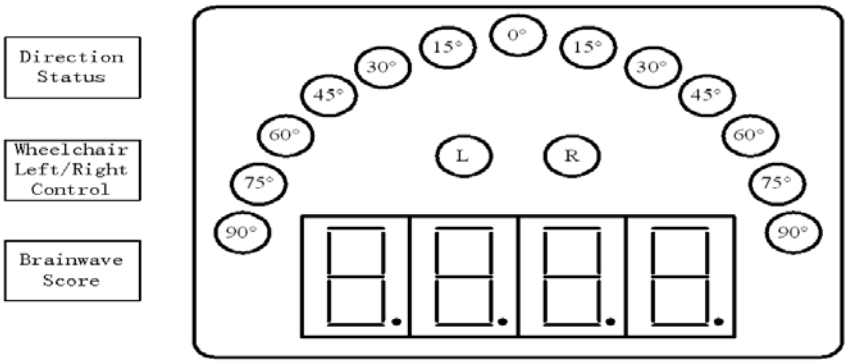


Figure 9. Information display for electric wheelchair

In Figure 9, 13 directions on angle-movement module, scanned from 0° to 90° from right to left, can then be selected by the users with their eye-blinking signals. If the direction was confirmed, the corresponding DC-motor would be turned on and the LED of the direction status R or L would also be displayed. Then, the electric wheelchair can be controlled to move to the matched direction. Finally, the users can use their Attention signals extracted from EEG signals to move the electric wheelchair forward. The intensity of Attention signals are normalized and shown on the seven-segment LEDs. But the electric wheelchair cannot move forward if the users' Attention signals do not be greater than a defined threshold. The users can also use eye-blinking signals to force the electric wheelchair to stop suddenly on the way forward.

4. Real-time EEG Detecting Algorithm.

The frequency features and conditions of EEG signals can be coincided with the five low frequencies as shown in Table 1. So we can analyze the EEG spectrum of waves δ, θ, α, β and γ. The condition is drowsy and sleeping if θ wave has a high intensity. When a person is rest and relaxing, his α wave shows high amplitude as well as β wave is high strength if he is waking. In this paper, we selected α wave to transfer as Attention signal.

TABLE 1. Classification of EEG signals

Frequency Band	Frequency (Hz)
δ	0.5 – 4 Hz
θ	4 – 8 Hz
α	8 – 14 Hz
β	14 – 30 Hz
γ	> 30 Hz

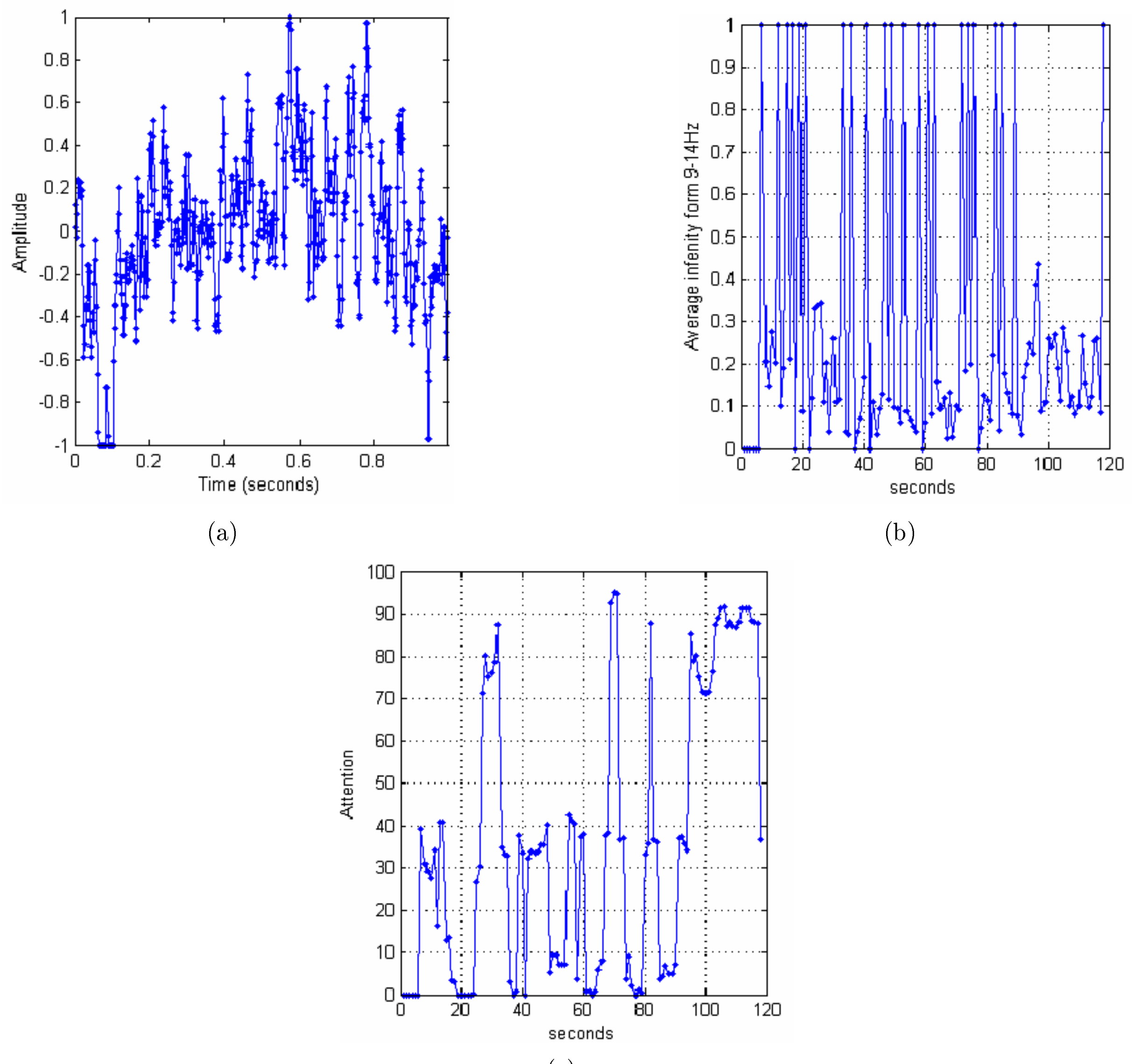
4.1. DSP algorithm.

We defined Attention signal is the average intensity of the EEG signals in frequencies from 9 to 14 Hz. In a time interval, the more stable the extracted frequencies the higher the intensity of Attention signal. In this paper, we used Fast Fourier Transform (FFT) to extract Attention signal from raw EEG. FFT is an efficient processing algorithm to compute the discrete Fourier transform (DFT) of a digital signal and its inverse. FFT reduces the number of computations needed for N points from $2N^2$ to $2N\log_2 N$. The functions FFT and its inverse implement the transform and inverse transform pair given for vectors of length N by:

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{2\pi ink/N} \tag{2}$$

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) e^{-2\pi ink/N} \tag{3}$$

Figure 10(a) is a part of EEG raw data received from IOB port in one second. Figure 10(b) is the average intensity of EEG signals in a range from 9 to 14 Hz through a band pass filter and transformed by FFT algorithm with a sampling frequency 512 Hz in the MCU during 120 seconds. Finally, the 120-second average intensity of EEG signals are passed through a 6-point running average filter in Equation (4) and normalized them as Attention grades from 0 to 100 shown as in Figure 10(c). Then we can use the Attention



(a) (b)

(c)

Figure 10. Extracted EEG signals: (a) EEG raw data, (b) average intensity in a range from 9 to 14 Hz, (c) normalized signal for the Attention signal from the output of a 6-point running average filter

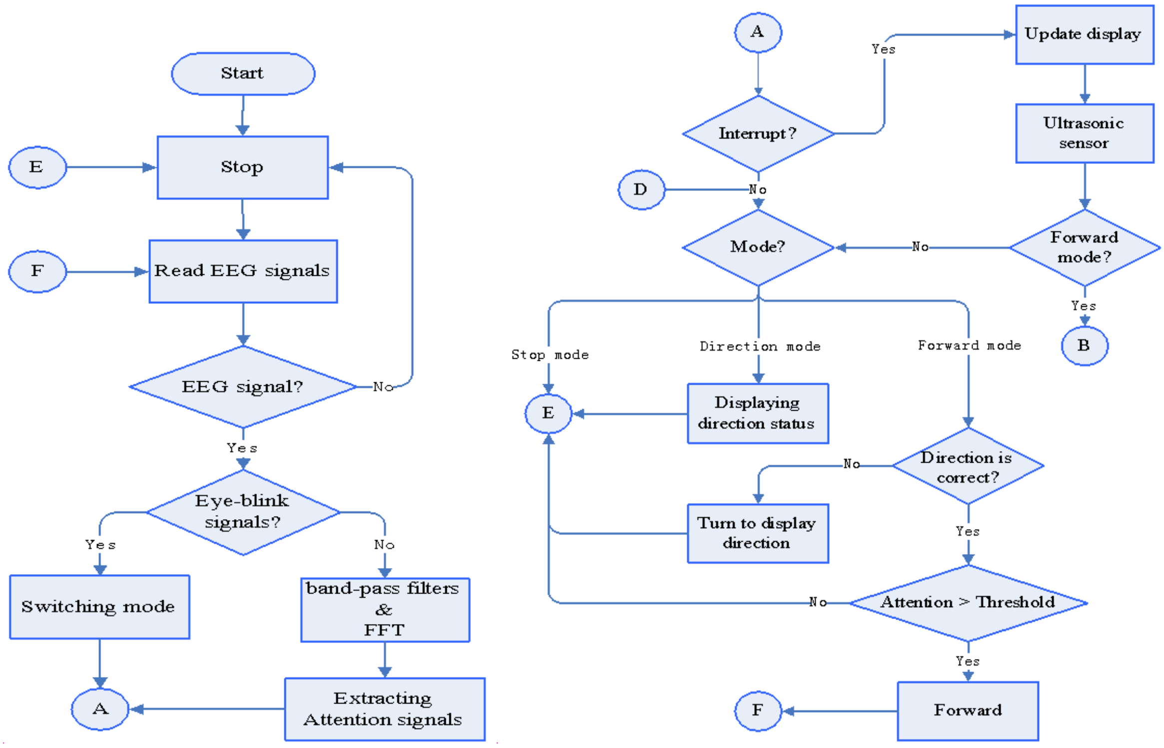
grades to control the electric wheelchair turn to forward.

$$y_{M+1}[n] = \frac{1}{M+1}\sum_{k=0}^{M} x[n-k], \tag{4}$$

where n is an integer.

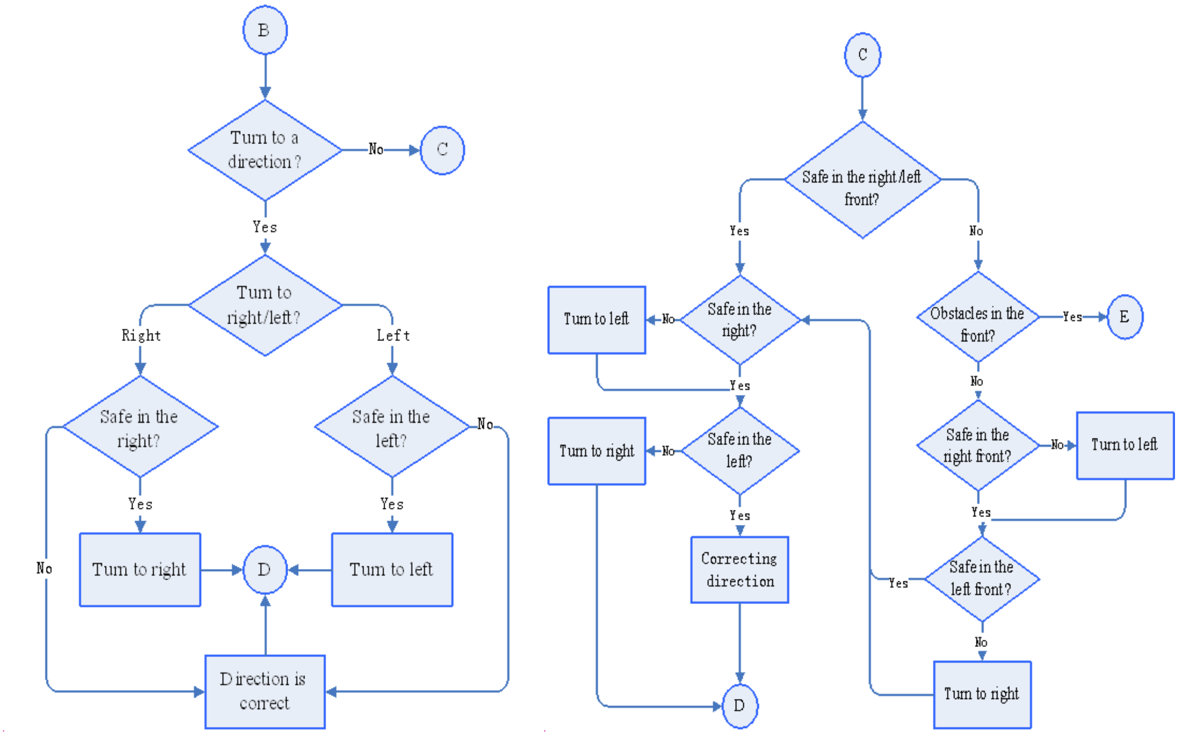
Table 2. Commands for the proposed electric wheelchair

Commands	**Extracted Signals**
Switching mode	1 eye-blinking
Moving forward	Attention signal
Stop	1 eye-blinking or Low Attention



(a) Extracting eye-blinking and attention signals

(b) Operations of stop, direction and forward modes



(c) Turning to right/left

(d) Flowchart of forward control

FIGURE 11. The algorithms for extracting attention signals and wheelchair control

The control commands for the proposed electric wheelchair are listed in Table 2. By using one pulse of eye blinking, the switching modes such as stop, direction and forward, are selected. The time interval between two modes is about 0.25 second. The flowcharts of extracting Attention signal algorithm used to control electric wheelchair are shown as in Figure 11. We used eye-blinking signal to switch the operation modes such as stop, direction, and forward modes. In the forward mode, the next mode could be changed to stop mode if a low Attention signal is detected. On the other hand, the electric wheelchair was also forced stop when it detects obstacles. In Figure 11(a), eye-blinking signal was used to select the operation modes as well as EEG signals were received to pass through a band-pass filter and FFT algorithm to obtain Attention signals with a frequency range from 9 to 14 Hz. Then, the normalized Attention grades were used to control the electric wheelchair. Initially, the electric wheelchair stays on the stop mode with no any action. The operation mode is changed from stop mode to direction mode when eye-blinking is detected. At the same time, the LEDs of direction status are displayed with scanning manner. And, user can use eye-blinking signal again to select the desired direction. In forward mode, the wheelchair control system recognizes whether it turns to the correct direction. If the selected direction is matched, the wheelchair can be controlled forward if the Attention signal is greater than a threshold. Otherwise, the wheelchair turns to the displayed direction.

In the forward mode, the electric wheelchair was operated with the flow as shown in Figures 11(c) and 11(d) by means of ultrasonic sensors to avoid the obstacles. In Figure 11(c), the electric wheelchair was decided to turn left or right when the direction had been selected. If there were not obstacles in the front of left or right, the electric wheelchair can then be controlled turn to left or right in accordance with the selected direction. The obstacles are detected by Figure 11(d). The ultrasonic sensors can be used to detect obstacles to avoid the obstacles in this flowchart.

5. Experimental Results.

The experimental scenario for the proposed electric wheelchair is displayed on Figure 12. The traveling path length from start point and bypassing two tables then back to original point is about 24 meters. In order to test the proposed electric wheelchair, we selected seven healthy young men divided 2 groups with 3 experienced users and 4 inexperienced users respectively. Every subject must be tested 4 times with one training phase and three testing phases. The experimental results are shown as in Table 3 with the consuming time. The average consuming time was calculated from the time of one training phase and three testing phases. The experimental results are shown as in Table 3 with the consuming time. The average consuming time were calculated from the time of one training phase and three testing phases. In the training phase, every subject wasted much time to complete the marked traveling path. For each subject, the time wasted in the three testing phases is less than the time wasted in the training phase at least once. The maximum wasted average time is 7 minutes and 58 seconds for the experienced users as well as the maximum wasted average time is 13 minutes and 35 seconds for the inexperienced users. A special case is found for the subject 4. He wasted about 13 minutes and 5 seconds in training phase but all the wasted time were less than 5 minutes and 20 seconds for the three testing phases. From the experimental results, promising results can be obtained for the proposed electric wheelchair. Especially, the 4-set ultrasonic modules can perform their functions in avoiding obstacles for each subject.

There are several related articles having been proposed in the field of EEG-based electric wheelchair [2-4]. In Table 4, the proposed electric wheelchair was compared with [2-4]. For the number of electrodes used in the acquisition system, the proposed method just needed one electrode for acquiring EEG signals. In [2], their system was controlled by

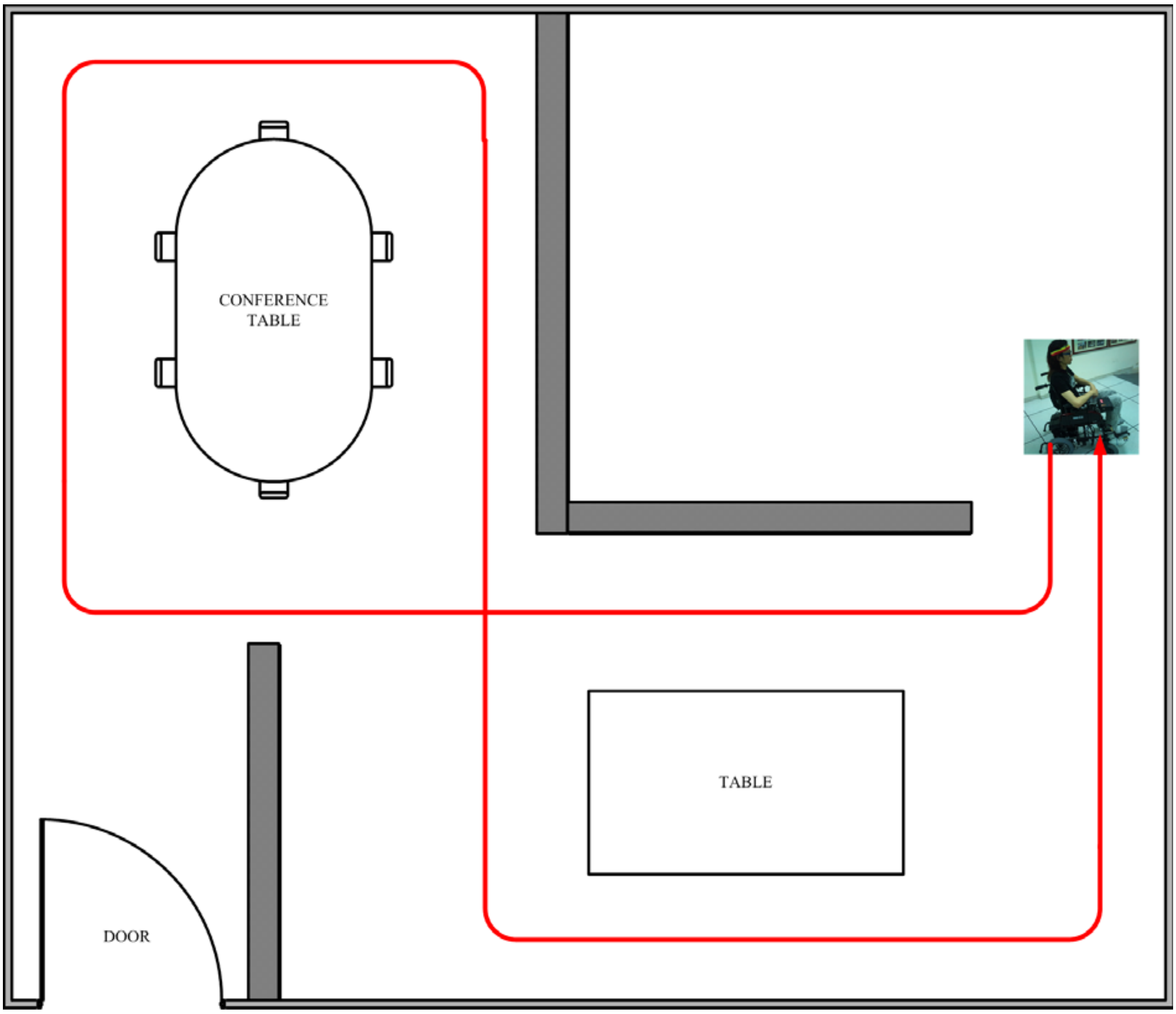


Figure 12. The experimental scenario

Table 3. Subject results in consuming time

Teams	Users	Training Phase	Test 1	Test 2	Test 3	Average time
Experienced Persons	Subject 1	04:15	04:08	03:48	04:50	04:15
	Subject 2	07:11	07:07	08:19	05:47	07:06
	Subject 3	10:43	07:59	06:31	06:42	07:58
Inexperienced Persons	Subject 4	13:05	04:46	03:42	05:16	06:42
	Subject 5	07:24	11:48	06:56	07:45	08:28
	Subject 6	10:25	08:48	07:28	11:40	09:35
	Subject 7	10:34	18:35	12:52	12:22	13:35

a personal computer so that it limits the practical application. For the control system, the proposed electric wheelchair was controlled by a microcomputer control unit which is similar to the central control unit designed by [3,4]. Except for [2,4], the proposed method use 4-set ultrasound unit while [3] used laser scanning to detect obstacles. Especially, the proposed method used a wireless manner in the interface between the BCI and wheelchair to simplify the operation of EEG-based electric wheelchair. From the comparison in Table 4, the proposed electric wheelchair is more suitable and easier for the paralyzed patients in the practical application.

TABLE 4. Summary of comparison for different methods

Methods	**# of electrodes***	**Control system**	**Obstacle avoidance**	**BCI-Wheelchair interface**
[2]	13	Personal computer	none	Wired
[3]	4 – 8	Central control unit	Laser scanning	Wired
[4]	3	Central control unit	none	Wired
Proposed method	1	Microcomputer control unit	Ultrasound	Wireless

* Except the reference electrodes

6. **Conclusions.**

In this paper, EEG and eye-blinking signals through a BCI interface based control for electric wheelchairs with wireless scheme is proposed. In a conventional wheelchair system, users require hand to control electric wheelchair. In the proposed system, a simple electrode was used to capture EEG and eye-blinking signals from the forehead and transmitted to an electric wheelchair control system through a Bluetooth interface. The proposed system is low cost and easy control with EEG and eye-blinking signals. The brain and eye-blinking signals were acquired from the acquisition system to composited raw-EEG package. The raw-EEG signals were calculated by the MCU and transformed the control signals to control the DC motors in the electric wheelchair. In the future, we will extend the bandwidth of the wireless tranceiver to suit more electrodes and acquire more EEG information in order to update the controlling performance for the electric wheelchair.

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