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Coordinated control of an intelligent wheelchair based on a brain-computer interface and speech recognition*

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Abstract: An intelligent wheelchair is devised, which is controlled by a coordinated mechanism based on a brain-computer interface (BCI) and speech recognition. By performing appropriate activities, users can navigate the wheelchair with four steering behaviors (start, stop, turn left, and turn right). Five healthy subjects participated in an indoor experiment. The results demonstrate the efficiency of the coordinated control mechanism with satisfactory path and time optimality ratios, and show that speech recognition is a fast and accurate supplement for BCI-based control systems. The proposed intelligent wheelchair is especially suitable for patients suffering from paralysis (especially those with aphasia) who can learn to pronounce only a single sound (e.g., 'ah').

Key words: Brain-computer interface, Speech recognition, Coordinated control, Intelligent wheelchair
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1 Introduction

A brain-computer interface (BCI) provides a communication method to convey brain messages independently from the brain's normal output pathway (Panicker *et al.*, 2011). For people suffering from severe motor disabilities, such as amyotrophic lateral sclerosis (ALS) and even paralysis, brain-controlled wheelchairs (BCW) have emerged as a feasible type of human-computer interface (HCI) that can allow them to interact with the world and help to improve their quality of life (Bromberg, 2008). The idea of moving robots by mere 'thinking' has attracted the interest of researchers for the past 40 years. Recently, experiments have shown the feasibility of using a BCI for the control of simulated or real wheelchairs. For example, the BCI-based real wheelchair developed by Millán *et al.* (2009) can realize three wheelchair steering behaviors: turning left, turning right, and moving forward. Another 2D virtual wheelchair was designed by Huang *et al.* (2012). This wheelchair is controlled by event-related desynchronization/synchronization resulting in four control commands. Rebsamen *et al.* (2006) designed a real wheelchair based on a P300 visual paradigm combined with motor imagery. In our previous study (Long *et al.*, 2012), we designed a hybrid BCI to control the direction and speed of a real wheelchair. However, a fast and accurate design for the stop command has not been achieved.

Cerebrovascular disease is common and is one of three main causes of death. 50%–70% of

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survivors are left with paralysis, aphasia, or other severe disabilities, which create a heavy burden on society and families. For paralyzed and aphasic patients, communication is often reduced to poor physical signals (e.g., electrooculograms, electromyograms, and electroencephalograms) or even a single sound (e.g., 'ah') (Abraham and Ormrod, 1999). In this paper, we propose a coordinated control mechanism that combines a brain-computer interface and speech recognition. For navigation, start is determined by a P300-based BCI, turning left and turning right by a left/right motor imagery-based BCI, and stop by speech recognition. Therefore, the users (especially paralyzed and aphasic patients) can control the wheelchair spontaneously by only visual attention, speech, and left/right-hand movement imagery. The effectiveness of the proposed wheelchair was confirmed by five subjects in an indoor environment.

2 System overview

The intelligent wheelchair consists mainly of five components: a host computer, an electroencephalogram (EEG) acquisition device, a communication module, an embedded speech recognition module with a microphone, and a robotic wheelchair (Fig. 1). The EEG acquisition device is a commercial Neuroscan EEG system (SynAmps EEG System, Neuroscan Co., Ltd.), digitized at a sampling rate of 250 Hz. The host computer is installed onboard with an LCD screen as a visual stimulation interface which displays six buttons to evoke P300 potentials. When in operation, all six buttons are randomly intensified for 100 ms and the time interval between each intensification is 120 ms. Construction of the intelligent wheelchair is based on the SHOPRIDER-TE-UL8WFE wheelchair made by Shoprider Mobility Products, that receives control commands from a host computer via a communication module.

Fig. 1 Image of the proposed intelligent wheelchair

2.1 EEG data acquisition

In the data acquisition procedure, a NuAmps device from Compumedics is used to measure scalp EEG signals. Each user wears an EEG cap. Fifteen channels of Ag/AgCl electrodes are employed including 'FC3', 'FCz', 'FC4', 'C3', 'Cz', 'C4', 'CP3', 'CPz', 'CP4', 'P3', 'Pz', 'P4', 'O1', 'Oz', and 'O2' for motor imagery and P300 potentials detection. The EEG signals are referenced to the right ear, amplified and sampled at a rate of 250 Hz, then band-pass filtered between 0.5 and 100 Hz.

2.2 Communication module

A conventional electric wheelchair is controlled by a joystick. To achieve communication between the robotic wheelchair and the host computer, we designed a communication module to replace the conventional joystick. The hardware architecture of the communication module is based mainly on an ATmega8L microchip and PL2303, which can receive commands via a USB interface from the host computer and output two analog voltages as the joystick control signals.

The control method of the communication module for controlling the direction and speed of the wheelchair looks like 2D signals which can be represented on an X-Y graph. The X-axis denotes the rotation speed of the motor and the Y-axis denotes the forward and backward speed. The driving speed and steering direction required by the user is represented by vector $\boldsymbol{F}$ (Fig. 2).

$F_{\max}$ is the maximum value (measured by norm) of vector $\boldsymbol{F}$ obtainable from the communication module. $S_{\max}$ is the maximum value of motor rotation speed, which is preset by the program. The speed of the left and right motors, S_{l} and S_{r}, are obtained from the following formulas, respectively:

$$S_{\mathrm{l}}=\begin{cases}C_xF_x+C_yF_y,\ |S_{\mathrm{l}}|\le|S_{\max}|,\\ \pm S_{\max},\ |S_{\mathrm{l}}|>|S_{\max}|,\end{cases}$$
$$S_{\mathrm{r}}=\begin{cases}C_xF_x+C_yF_y,\ |S_{\mathrm{r}}|\le|S_{\max}|,\\ \pm S_{\max},\ |S_{\mathrm{r}}|>|S_{\max}|.\end{cases} \quad (1)$$

C_x determines the rotation characteristic of the wheelchair steering and C_y determines the speed characteristic of the wheelchair. If calculation results are greater than the maximum motor rotation speed, the system reverts to the maximum motor rotation speed. In our wheelchair system, the start speed is set to 0.3 m/s, and the rotational speed to 7°/command. As the communication module is programmable on a chip, it is convenient for users to update these parameters.

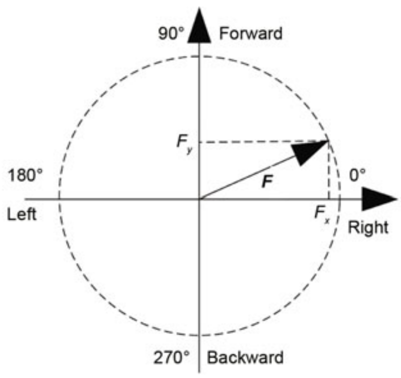

Fig. 2 Communication module vector graph

2.3 Graphical user interface

The graphical user interface (GUI) was developed using Microsoft C++, running at the user level of a Windows XP system with a real-time Matlab algorithm. The GUI for the wheelchair is displayed on the LCD screen of the host computer with six flashing buttons (Fig. 3). When in operation, the 'S' button and the other five buttons are randomly intensified for 100 ms with white color, and the time interval between each intensification is 120 ms.

2.4 Coordinated control mechanism

The proposed coordinated control mechanism includes a brain-computer interface and speech recognition, where the start is determined by P300 potentials, the direction by left/right-hand motor imagery, and stop by speech ('ah'). The four steering behavior commands and their corresponding activities are shown in Table 1. The user is instructed to navigate the wheelchair by performing four appropriate activities. A flowchart of the coordinated control mechanism is shown in Fig. 4.

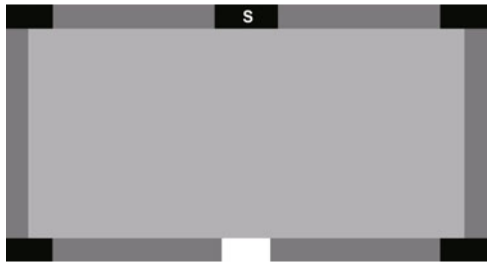

Fig. 3 GUI for the proposed wheelchair. When in operation, the six buttons flash in a random sequence. If the user wants to start the wheelchair, he/she simply makes a selection by staring the 'S' button

Table 1 The control commands and their corresponding activities

Control command	Corresponding activity
Start	P300
Stop	Speech 'ah'
Turn left	Left-hand motor imagery
Turn right	Right-hand motor imagery
No control command	Otherwise (Idle)

2.4.1 P300 potentials for start

Firstly, the EEG signals are filtered within the range of 0.1–20 Hz. Then we extract a segment (0–600 ms after a button flash) of EEG signal from each channel for each flash of the specific button. For each flash of the specific button, a new data vector with 375 dimensions (25 time points×15 channels) is obtained. The feature vector denoted in each trial is obtained by averaging four data vectors obtained in four repeats of button flash. Finally, a support vector machine (SVM) is employed for classification. If the 'S' button is recognized, a start command is sent out and the wheelchair moves forward at a speed of 0.3 m/s.

2.4.2 Motor imagery for turning left/right

EEG signals are spatially filtered with common average reference (CAR) (Blanchard and Blankertz, 2004) and band-pass filtered in a specific band (8–12 Hz) to extract mu rhythm. Then a common spatial pattern (CSP) transformation matrix $\boldsymbol{W}$ for one class against others can be calculated by the well-known joint diagonalization method to extract the

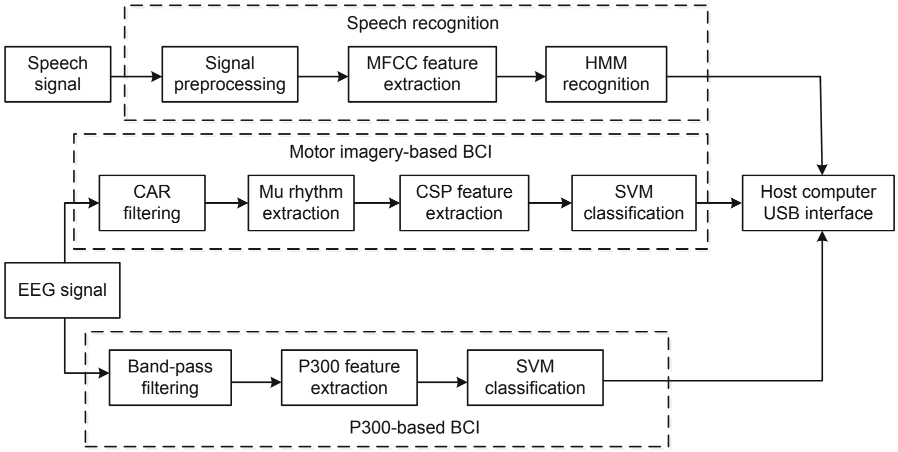

Fig. 4 A flowchart of the coordinated control mechanism, which consists of three parts: a speech recognition algorithm, a motor imagery based BCI algorithm, and a P300 based BCI algorithm

feature (Li and Guan, 2008), which is learned during 90 trials of guided mental tasks for left- and right-hand motor imagery. Finally, the feature vector is fed into a trained SVM classifier and outputs corresponding to the turning left/right command for 200 ms. Each command is set to a rotational speed of 7°. The topographies of two CSP filters, i.e., the first and last rows of the CSP transformation matrix $\boldsymbol{W}$, are shown in Fig. 5. The CSP transformation matrix $\boldsymbol{W}$ is obtained from the calibration data set for CSP feature extraction. More details about motor imagery EEG signal processing and calibration can be found in Li *et al.* (2010) and Long *et al.* (2012).

2.4.3 Speech recognition for stop

First, the user's speech signals from the microphone are digitized at a sampling rate of 8000 Hz by a 12-bit A/D converter, and then processed by a signal preprocessing method. The method includes a

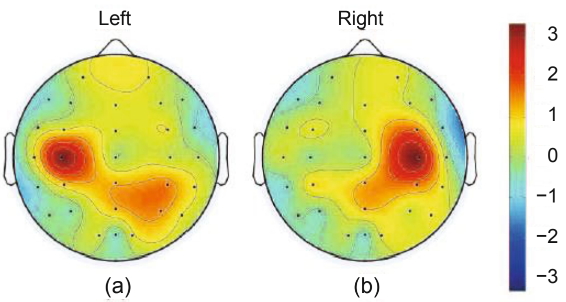

Fig. 5 For each subject, two selected CSP filters (the first (a) and last (b) rows of $\boldsymbol{W}$) are displayed as scalp maps

logarithm domain energy change algorithm for start point detection, and a window frame of 40 ms shifting to 10 ms for further processing. Second, we extract the mel-frequency cepstrum coefficient (MFCC) of the window frame. Finally, continuous mixing Gaussian hidden Markov modeling (HMM) (Eddy, 1996) is used for speech recognition. The details of the recognition procedure can be found in Rabiner *et al.* (1983), Furui (1986), and Lee and Hon (1989). If the sound 'ah' is detected, a stop command is sent out. As we adopted speaker-independent isolated word speech recognition technology, no extra training of the users is needed.

3 Experiments and results

3.1 Indoor experiment

To evaluate the performance of the proposed intelligent wheelchair, five healthy subjects from South China University of Technology (four males and one female aged from 24 to 33) participated in an indoor experiment. The technical metrics proposed in Iturrate *et al.* (2009) and Rebsamen *et al.* (2010) were followed to evaluate the performance of the wheelchair:

Path length: the distance traveled, in meters, to accomplish a task.

Path length optimality ratio: the ratio of the path length to the optimal path (the optimal path was approximated by measurement as (3.0+1.3+1.5+1.3+2.4)×2=19 m (in length)).

Time: the time taken in seconds to accomplish the task.

Time optimality ratio: the ratio of the time taken to the optimal time (the optimal time was approximated assuming a speed of 0.3 m/s and a rotational speed of 7° per command controlled by a joystick, resulting in 66 s).

Collisions: the number of collisions (hitting the desk). The subject navigated the wheelchair from the start line to the destination, following a guide of ideal trajectories.

Response time (RT): the interval from the time the user initiates a stop to the time the stop command is issued.

False activation rate (FAR): the number of times per minute that a stop command is issued when the subject is not intending to stop (an important metric to evaluate in an asynchronous system, also called the false triggering rate).

The task of the indoor experiment was to navigate the wheelchair from the initial position and back to the initial position (destination) along a guide of ideal trajectories. Each trial contained the following steps: start the wheelchair with a constant speed of 0.3 m/s, turn right, turn right, stop and turn round, and go back and stop at the initial position (Fig. 6). Each subject performed 10 trials. In addition, we needed to evaluate the RT of a stop. In each trial, there were two positions where the subject needed to stop: a stop to turn round, and a stop on returning to the initial position (destination). When the wheelchair was near either of these two positions, we sent a 'stop' order. Once the user received the 'stop' order, he/she tried to stop the wheelchair by uttering the sound 'ah' and we recorded the response time. To evaluate the FAR of stop, we also recorded the numbers of times a stop command was issued when the user was not intending to stop during the moving period.

The results are summarized in Table 2. All five users were able to complete the task successfully without collisions. The metric path length optimality ratio was satisfied and the time optimality ratio was remarkable because of fast and accurate decision making. The average response time was 1.2 s and the false positive rate was 0.0 per minute for stop by speech recognition in the indoor environment (the signal-to-noise ratio was 40–50 dB).

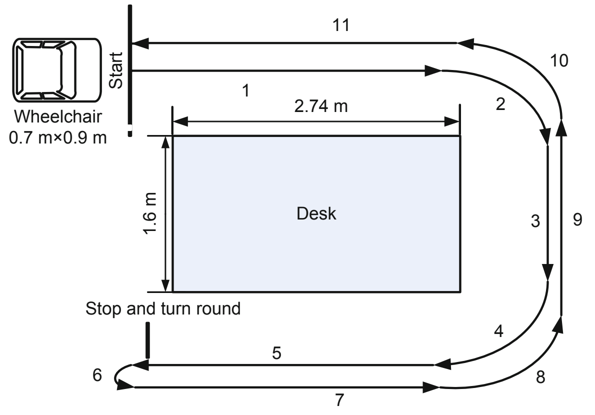

Fig. 6 The indoor environment experiment. The figure shows the initial position and ideal trajectories for the navigation task

3.2 Comparison of different intelligent wheelchairs

Recent experiments have shown the feasibility of using a BCI to control simulated or real wheelchairs. In this section, we compare our proposed intelligent wheelchair with brain controlled wheelchairs (BCW) and speech controlled wheelchairs .

There are mainly two types of brain controlled wheelchair based on a BCI approach: (1) single mode BCI and (2) hybrid BCI. For example, a single mode BCI was developed by Rebsamen *et al.* (2010), which realized navigation from a start zone to a goal zone with four commands based on steady-state visual evoked potentials (SSVEP). Another single-mode 2D virtual wheelchair was designed by Huang *et al.* (2012). This wheelchair was controlled by event-related desynchronization/synchronization, resulting in four control commands. In our previous study (Long *et al.*, 2012), we used a hybrid BCI to control the direction and speed of a real wheelchair. However, effective control of a BCW is still a big challenge, especially the stop command.

As far as we know, only two studies have used a stop command in a BCW. Rebsamen *et al.* (2010) designed a stop command using a fast P300 and mu/beta rhythm. The average RT and FAR for stop by fast P300 were 5.9±2.2 s and 1.4±0.8/min, respectively, and by mu/beta were 5.5±3.0 s and 0.0±0.0/min, respectively. Li *et al.* (2013) designed a go/stop command using P300 and SSVEP. The RT

Table 2 Metrics for evaluating the intelligent wheelchair

Technical metric	Value					Average*
	1	2	3	4	5	
Path length±std (m)	21.7±0.5	21.4±0.3	21.5±0.4	22.1±0.5	23.0±0.3	21.7±0.5
Path length optimality ratio	1.14	1.13	1.13	1.16	1.21	1.14
Time±std (s)	73.0±5.0	76.0±3.0	75.0±4.0	80.0±2.0	85.0±3.0	74.0±5.0
Time optimality ratio	1.11	1.16	1.14	1.21	1.29	1.12
Number of collisions	0	0	0	0	0	0
(Stop) RT±std (s)	1.3±0.3	1.1±0.3	1.4±0.4	1.2±0.5	1.0±0.2	1.2±0.4
(Stop) FAR±std (min^{-1})	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0

std: standard deviation. * Calculated by averaging all the subjects with their each experiment record

and FAR for stop were 5.28 s and 0.52/min, respectively. In this study, we designed an effective stop command using speech recognition with an average RT of 1.2 s and FAR of 0.0/min. Compared with the existing BCI-based wheelchair systems, our proposed intelligent wheelchair is superior in realizing a reliable stop command to ensure the safety of users without any other assistance (e.g., an automatic navigation system).

For speech controlled wheelchairs, Luo *et al.* (2011) proposed a short-term energy and cepstral distance combined endpoint detection method and realized speech control of an intelligent wheelchair by using five basic movement commands, including forward, backward, turn left, turn right, and stop. However, the users needed to make multiple control sounds. This is difficult or impossible for those suffering from paralysis (especially those with aphasia). In a recent study, Peixoto *et al.* (2013) implemented a voice controlled wheelchair and realized fine control by humming (a single sound). They also pointed out that previously published control methods for assistive technology, such as the tongue-computer interface (Huo *et al.*, 2008), inertial units (Raya *et al.*, 2010), and electrooculography-control (Barea *et al.*, 2002), may be seamlessly combined with humming for added functionality. This may indicate a future research direction. In this paper, we proposed an intelligent wheelchair controlled by a coordinated control mechanism, where the start was determined by P300 potentials, direction by left/right-hand motor imagery, and stop by only a single sound 'ah'.

4 Conclusions

An intelligent wheelchair controlled by a coordinated control mechanism based on a brain-computer interface (BCI) and speech recognition was devised, where the start was determined by P300 potentials, direction by left/right-hand motor imagery, and stop by speech recognition. The proposed coordinated control mechanism has two main advantages. Compared with speech controlled wheelchairs and existing BCI-based wheelchair systems, our proposed coordinated control mechanism is superior in realizing a reliable stop command to ensure the safety of users without any other assistance (e.g., an automatic navigation system). Compared with speech controlled wheelchair systems, we have realized an assistive technology (brain-computer interface) combined with speech for added functionality, which is especially suitable for patients suffering from paralysis (especially those with aphasia) who are able to utter only a single sound. The main deficiency, however, is that long-term use can cause mental fatigue.

The indoor experiment demonstrated not only the effectiveness of the coordinated control mechanism, but also the good performance of the intelligent wheelchair (satisfying path and time optimality ratios). The average response time (RT) and false activation rate (FAR) for stopping were 1.2 s and 0.0 per minute, respectively. Therefore, speech recognition is a fast and accurate supplement for a BCI-based control system. The proposed intelligent wheelchair is fit for our target users suffering from paralysis (especially those with aphasia) who can pronounce only a single sound. In a further study, we will equip this wheelchair with an obstacle avoidance system based on ultrasonic sensors as proposed in our previous study (Liu *et al.*, 2012), and invite disabled patients to participate in experiments.

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