An Intelligent Wheelchair Based on Automated Navigation And BCI Techniques

Rui Zhang, Yuanqing Li*, Yongyong Yan, Hao Zhang and Shaoyu Wu

***Abstract*— In this paper, we propose an intelligent wheelchair system that relies on a brain computer interface (BCI) and automatic navigation. When in operation, candidate destinations and waypoints are automatically generated on the basis of the current environment. Then, the user selects a destination using a P300-based BCI. Finally, the navigation system plans a path and navigates the wheelchair to the determined destination. While the wheelchair is in motion, the user can issue a stop command with the BCI. Using our system, the mental burden of the user can be alleviated to a large degree. Furthermore, our system can adapt to changes in the environment. The experimental results demonstrated the effectiveness of our system.**

I. INTRODUCTION

One important application of Electroencephalogram (EEG)-based brain computer interfaces (BCIs) is wheelchair control, which has attracted a great deal of attention because brain-controlled wheelchairs have the potentials to improve the quality of life and self-independence of the disabled users [1]. There have been several challenges for a brain-controlled wheelchair. For example, multiple commands are required to control start and stop, direction and speed of a wheelchair [2]. However, it is difficult to produce so many control commands for an EEG-based BCI. Although we may obtain multiple control commands using a P300 or steady-state visual evoked potentials (SSVEPs)-based BCI, it is generally time-consuming. In addition, controlling a wheelchair for a long time may produce a large mental workload for the user, especially for disabled people [3]. These challenges may be solved by integrating automated navigation techniques into brain-controlled wheelchairs [3], [4], [5]. For instance, Millán *et al.* proposed a shared control method for a wheelchair [4]. Specifically, a dynamical system was designed for navigation that could generate naturally smooth trajectories by integrating the BCI commands from the user along with obstacle information from the vision sensor. This wheelchair would go straight until a left or right command was received. For this system, the BCI commands were from the user's motor imageries. In [5], multiple stages of shared control were implemented for a wheelchair. At each stage, a 3-D environmental map was constructed using a laser ranger finder (LRF). A set of candidate destinations were set/distributed in an environmental map and then presented to the user. Next, the user selected a destination using the P300-based BCI. Finally, the wheelchair autonomously moved to the selected destination. Through a series of destination selections and navigations, the final goal destination could be reached. The main advantages for these systems are: (i) no priori information on the environment is needed; (ii) the trajectories are determined in real time, rather than being predefined; and (iii) the two systems can automatically avoid obstacles when necessary. However, many BCI commands were required to reach a destination, which might exhaust the user. In a previous study [3], a semi-automatic wheelchair was proposed. Specifically, the user selected one of several predetermined destinations using a P300-based BCI. Next, the autonomous system took control to navigate the wheelchair to the selected destination along a predefined path. This system alleviated the workload of the user to the highest degree. However, because these candidate destinations and their corresponding paths were predefined, a change in the environment might result in the failure of the strategy, and redevelopment of the system might be required.

This paper proposes an intelligent wheelchair combining a P300-based BCI and an autonomous navigation system. Using the system, the candidate destinations and paths are first automatically generated on the basis of the current environment. The user then selects a destination with the P300-based BCI. According to the selected destination, the autonomous navigation system plans a path and drives the wheelchair to the destination. The main advantages for our system are: (i) the mental burden of the user can be alleviated to a large degree; (ii) our system is adaptive to the changes in the environment; (iii) the user can issue a stop command through the BCI when they want to stop or change the destination.

II. AUTONOMOUS NAVIGATION SYSTEM

As illustrated in Fig.1, our intelligent wheelchair consists two parts: an autonomous navigation system and a BCI. In this section, the autonomous navigation system is described and structured in following five modules.

A. Obstacle Localization

To acquire enough information from the webcams to accurately locate the obstacles, the webcams should be placed at a relatively high position on the wall. Additionally, the number of webcams can be increased with the size of the space. The processes for obstacle localization are described as follows. First, we obtain the pictures (Pic_1, Pic_2, $\cdots$

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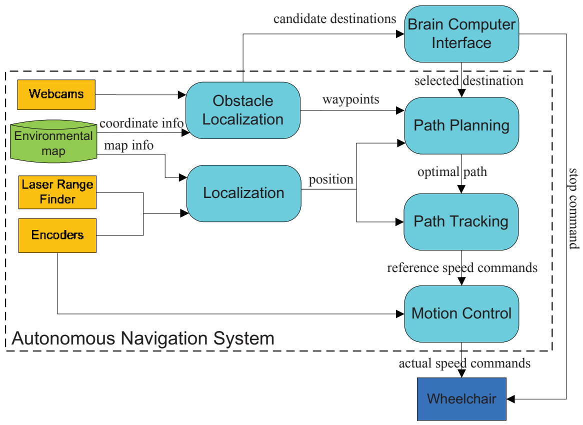

Fig. 1. System architecture.

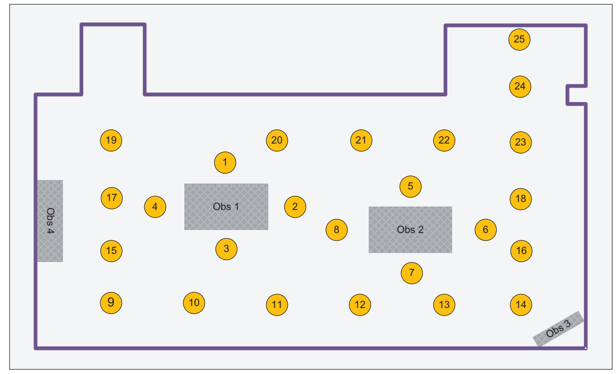

Fig. 2. The graphical user interface (GUI) is a two-dimensional geometrical representation of the environment. The environmental map (slate blue line), candidate destinations (yellow circle), and obstacle locations (gray rectangles) are arranged at their corresponding positions in the GUI according to their actual locations and sizes.

, Pic_n) from the calibrated webcams via the wireless internet. Next, we perform the following processing steps for each picture: (i) obstacles are separated using the threshold segmentation method; (ii) the morphological operations are used to remove noise; (iii) contours are retrieved from each segmented image, and then approximated with convex hulls; and (v) the vertices of the convex hulls on to the ground plane coordinate are mapped according to the homography matrix. The homography matrix, which represents the correspondences between the pixel and ground plane coordinates, is calculated using the homography technique [6]. Finally, we calculate the intersection of the regions corresponding to the convex hulls in $Pic_i (i = 1, \cdots, n)$ on the ground plane coordinate; subsequently, the regions of the obstacles on the ground plane can then be approximated using these intersection regions.

B. Generation of Candidate Destinations and Waypoints

To offer the user more candidate destinations to choose and let our wheelchair can reach to more places, some predefined destinations are uniformly scattered in the map with a certain distance. Additionally, after obstacle localization is completed, some additional destinations are distributed around the obstacles, and the predefined destinations that are within the coverage of the obstacles are cleared (see Fig.2).

A sequence of waypoints forms a complete path. In our system, we used an approach based on the generalized Voronoi diagram [7] for a planar region with specified obstacles. The process followed is described below. First, the distance between two obstacles is checked to determine if it is larger than the safe distance through which the wheelchair can go. If not, the regions of these obstacles are merged. Second, the regions of obstacles are expanded with a certain safe distance. Then, the boundaries of the polygonal obstacles are approximated with the large number of points that result from subdividing each side of the original polygon into smaller segments. Next, a Voronoi diagram is constructed for this collection of approximating points, and Voronoi edges are then obtained. Finally, a waypoint every 0.2 m from each Voronoi edge is determined.

C. Self-Localization of the Wheelchair

Two types of localization, global localization and process localization, are used in our system.

1) Global Localization: Global localization is used to accurately estimate the wheelchair's initial position without any prior position information. The corresponding global localization algorithm was proposed previously [8].

2) Process Localization: Process localization that is based on an LRF and two encoders is used to track the position of the wheelchair in real-time after the initial position of the wheelchair is known. The process localization algorithm is similar to a process described previously [9]. First, the local line segments, which are extracted from the LRF data, are transformed to the global coordinates according to the estimated pose by dead reckoning. Next, we compare the transformed local line segments with the global line segments in the environmental map to find matching pairs. Finally, the pose of the wheelchair is calculated.

D. Path Planning and Path Tracking

Selecting an optimal path from several candidate paths contributes to reducing the navigation time. A^* algorithm [10], which uses a best-first search and finds the least-cost path from a given initial node to one goal node, is responsible for determining the global least-cost path. Specifically, according to some points and the adjacency relationship between these points, this algorithm is implemented online and determines an optimal path. These points consist of the current position of the wheelchair (start point), the destination (end point) selected by the BCI, and a sequence of waypoints based on Voronoi edges.

After the optimal path is obtained, the position error between the actual position of the wheelchair and the path is calculated and is used as the feedback of a PID tracking algorithm (as described previously [11]). Then, the reference angular speed is obtained based on this algorithm. In our setup, the linear velocity is considered as constant (0.18 m/s), and the angular speed is restricted to a maximum of 0.6 rad/s to guarantee the safety and comfort.

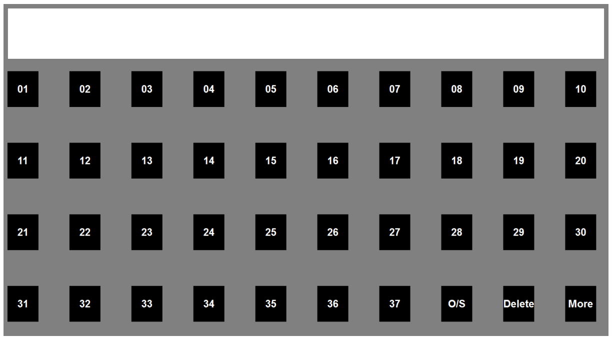

Fig. 3. GUI of the P300-based BCI is used for destination selection. Forty buttons arranged in a 10×4 stimuli matrix. Thirty-seven Arabic number buttons were mapped onto 37 different destinations. 'O/S': 'O' represents validating the selected destination, navigating the wheelchair to the final destination while 'S' represents stopping the wheelchair. 'Delete': represents deletion of the last input destination. 'More': opens the next stimuli interface with additional and different destinations.

E. Motion Control

The obtained reference speed commands and the odometry data from the two encoders are transmitted to the PID controller. The actual linear and angular velocities are calculated in real-time based on the odometry data. These velocity values are used as the feedback of the PID motion controller, which regulates the wheelchair control signals.

III. Brain computer interface

In this section, a P300-based BCI is used to select a destination and to issue a stop command during the motion of the wheelchair.

A. Destination Selection

To select a desired destination, the user first determines the number of this destination in 20 seconds, according to Fig.2. Then a P300 GUI shown in Fig.3 is activated and covers last GUI (Fig.2) on the screen. Using this P300-based BCI, the user can select the intended destination by focusing on the corresponding number button. If the desired destination is selected, the user needs to focus on the 'O/S' button for validation. Otherwise, the subject can focus on the 'Delete' button to reject this selection and reselect the desired destination. Once a P300 potential is detected at the 'O/S' button, the wheelchair automatically moves to the selected destination. When the wheelchair reaches it, the GUI in Fig. 2 is shown to the subject for selection of a new destination.

B. Stop Command

While the wheelchair is in motion, a stop command for the wheelchair is issued if and only if P300 is detected at the 'O/S' button. In this way, the user can stop the wheelchair in motion by focusing on the 'O/S' button.

C. P300 Detection

When the wheelchair is stationary, the P300 detection algorithm used for the destination selection works as follows. The EEG signals are first bandpass-filtered between 0.1 and 20Hz and are then downsampled at a rate of 5Hz. Next, a segment (0-600 ms after a button flashes) of EEG signals is extracted from each channel to form a vector. Then, a feature vector corresponding to a button flash is constructed by concatenating the vectors from the 15 channels used in our system. After one round (one round is defined as a complete cycle in which all of the buttons are flashed once in a random order), an SVM classifier is applied to these feature vectors, and forty scores corresponding to forty buttons are obtained. Finally, we calculate the sum of the SVM scores for each button obtained from l accumulated rounds ($l \geq 4$) and determine the maximum and second maximum among these summed scores. The button with the highest score is selected only if the ratio between the maximum and the second maximum summed scores is higher than a threshold. Here, the detection is performed per round of flashes using the previous l rounds of data, until an output is obtained.

While the wheelchair is in motion, the following P300 detection for stopping is performed. When at least 3 accumulated rounds of data is collected and if the score of 'O/S' button is the highest, the system issues stop command. Otherwise, no control command is generated. The rest of buttons function as pseudo-keys, which are useful for differentiating the control and the idle states, as explained in [12].

IV. Experimental Results

Three subjects participated in our navigation experiment. Before the navigation experiment began, one data set was collected, which took about 15 minutes. Each subject performed 30 trials with the GUI shown in Fig. 3. Specifically, in each trial, all 40 buttons flashed in a random order, and each button flashed ten times. Each flash lasted 100 ms, and a flash started 30ms after the onset of the previous one. Thus one round of button flashes lasted 1.2s. Simultaneously, the subject was instructed to focus his attention on a given button according to the cue. The collected training data were used to train an SVM classifier for P300 detection.

A. Experiment For Wheelchair Control

In the navigation experiment, each subject was requested to consecutively complete the following three tasks. The environment for experiment is shown in Fig.4. For Task 1, each subject was instructed to select a given destination using the P300-based BCI. The wheelchair then automatically moved to it. Next, the subject performed Task 2, which was the same as Task 1 except a new destination was given. For Task 3, each subject selected a given destination such that the wheelchair automatically moved to it; however, during the movement of the wheelchair, a beep tone delivered at a random time reminded the subject to stop the wheelchair. The subject were then required to stop the wheelchair as quickly as possible by P300-based BCI. After the wheelchair stopped, the subject reselected the given destination and allowed the wheelchair to reach it. At the beginning of each task, a traffic cone (marked as red dot in Fig.4) was placed at a position in the room to indicate the given destination for the subject.

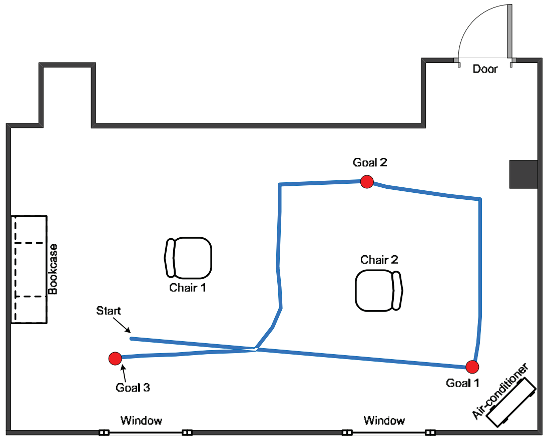

Fig. 4. Experimental Environment

Before the navigation experiment began, several pieces of moveable furniture (two chairs in our experiment) were first placed randomly in the room. Then, our wheelchair system performed obstacle localization and the self-localization of the wheelchair. Finally, the subject performed the three tasks listed above one by one. In addition, the three destination positions (corresponding to the three respective tasks) and the starting position of the wheelchair were set randomly. To facilitate the experimental data analysis, the three destination positions and the starting position of the wheelchair were fixed in the remaining experiments for all of the subjects, but the subjects did not know these positions beforehand.

B. Performance Evaluation

To evaluate our intelligent wheelchair system, we adopted the following metrics, according to the related references [3].

1) Concentration time: The time spent selecting a destination and the validation of it.

2) Response time (RT): The time from the moment the user is instructed to stop the wheelchair to the moment the stop command is issued.

3) False activation rate (FA): The number of times per minute that a stop command is wrongly issued when the subject does not intend to stop the wheelchair.

C. Results

Table I illustrates the performance results for destination selection and stop command generation based on the P300 paradigm. The subjects took an average of 12 seconds to complete a destination selection using the P300-based BCI. On average, the subjects issued stop commands with the P300-based BCIs in 5.6 seconds. Furthermore, the FA rates for wheelchair stopping were zero.

TABLE I
METRICS TO EVALUATE THE PERFORMANCE OF BCIS

	Concentration time (*s*)			RT (*s*)	FA (*event/min*)
	Task 1	Task 2	Task 3		
Subject 1	13.2	12.0	13.2	4.8	0
Subject 2	9.6	14.4	13.2	7.2	0
Subject 3	8.4	12.0	12.0	4.8	0
Average	10.4	12.8	12.8	5.6	0

V. CONCLUSIONS

In this paper, we presented an intelligent wheelchair combining a P300-based BCI and an automated navigation system. Three subjects attended our experiment. The experimental results demonstrated the effectiveness of our system. In our wheelchair system, the candidate destinations and paths are automatically generated on the basis of the current environment, which indicates that our system can adapt to change in the environment. Once the user selects a destination with the BCI, our wheelchair automatically navigates to it. Thus, the workload for the user is alleviated to a large degree. Furthermore, during the motion of the wheelchair, the user can issue a stop command through the BCI. It is our future work to extend our system for use in the outdoor environment.

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