Human Factors in the Design of BCI-Controlled Wheelchairs

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Abstract. In this paper, we synthesize research on the type of cognitive commands that have been examined for controlling Brain Computer Interface (BCI) wheelchairs and the human factors that have been reported for the selection of different protocols of BCI commands for an individual user. Moreover, we investigate how different researchers have considered the necessity of sustained movement from a single thought/command, having an emergency stop, and the commands necessary for assisting users with a particular disability. We then highlight how these human factors and ergonomics' considerations were applied in the design and development of an EEG-controlled motorized wheelchair, aiming to emphasize users' requirements for people with severe physical disabilities. In this case study, we propose a brain controlled wheelchair navigation system that can help the user travel to a desired destination, without having to personally drive the wheelchair and frequently change the movement directions along the path to the destination. The user can choose the desired destination from a map of the environment, using his/her brain signals only. The user can navigate through the map using BCI cognitive commands. The system processes the brain signals, determines the required destination on the map, and constructs an optimized movement path from the source to the intended destination. To construct an obstacle-free path with the shortest possible distance and minimum number of turns, a path planning optimization problem is solved using a simple Simulated Annealing (SA) algorithm. The resulting optimized path will be translated into movement directions that are sent to the microcontroller to move the wheelchair to the desired destination.

Keywords: Brain Computer Interaction (BCI), electroencephalography (EEG), Path Planning Optimization, Simulated Annealing, Wheelchair.

1 Introduction

Human factors in the design of assistive technologies are essential to the successful adoption and utilization of devices that provide alternatives to functional limitations imposed by users' physical disabilities. Recent advances in technologies have made it possible for a person to interact with and control devices using only his/her brain

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waves or Brain Computer Interaction (BCI). Brain–computer interactions/interfaces (BCIs), brain–machine interfaces (BMIs), Direct Brain Interfaces (DBIs), and neuroprostheses, all refer to the same concept. According to [1], a BCI interface was defined formally in the first international meeting for BCI research in June 1999 as: “A communication system that does not depend on the brain’s normal output pathways of peripheral nerves and muscles” [1].

There are some available techniques to detect the brain activity such as electroencephalography (EEG) and magnetoencephalography (MEG), where EEG is considered to be the most common way to detect the electrical activity in the brain for the context of wheelchair designs [2]. In EEG systems, the sensors are placed on the brain scalp without surgical intervention. Nowadays, unobtrusive wireless headsets are available that can be used to detect EEG signals (e.g. Emotiv's EPOC and Neurosky's Mindwave [5-6]). The available EEG headsets are relatively inexpensive, easy to wear and control. Furthermore, the temporal resolution of EEG which represents the ability to detect changes within a certain time interval is relatively good; a millisecond or even better. However, the spatial resolution - a measurement of the accuracy of a graphic display - and the frequency range are limited, This consequently limits the amount of information that can be extracted [3-4]. One of the popular EEG headsets is EPOC which is made by Emotiv Systems.

The proliferation of BCI-oriented assistive technologies have the potential to improve the quality of life of people with severe motor disabilities with increased independence and less reliance on caregivers. Among the promising devices that have been developed for this purpose, is an EEG based brain controlled wheelchair, which the user can move using his/her brain signals only; hence, alleviating the need for any physical movement to control the device [7]. This wheelchair can be used to serve people who cannot move their limbs or people living with spinal cord injury. Nevertheless, a person with a disability may face difficulty in controlling the brain controlled-wheelchair for long periods of time, since the procedure usually requires non-trivial concentration by the person with a disability throughout the navigation process from the source to the destination. Accuracy of BCI-controlled systems remains a concern and using brainwaves to drive a wheelchair may not effectively lead the user to the required destination.

Taking such difficulty into account, we developed a brain controlled wheelchair system, which we called Brain-Wheel, in a way that will relieve users from the task of planning the path to the destination. To avoid the inaccuracy of existing BCI tools, we are restricting the use of BCI to the selection of the destination. Hence, BCI is not utilized in this context for guiding the wheelchair step-by-step as the user is navigating to the destination. The system was designed so that users of this system can choose a target destination, which they would like to navigate to, from the 2-D environment map using their brain signals. In the system, Emotiv's Epoc is used to detect the brain signals for selecting the required destination from the presented room map. In the Brain-Wheel system, we used the Emotiv cognitive suite, where the headset can understand the user’s intent to perform specific actions. Based on the user’s intention to move, the detected brain signals will determine whether or not to start the navigation system. The navigation system will then decide the optimal path that the wheelchair should follow using a metaheuristic algorithm, which has been specifically designed for this problem. The output of the algorithm will be fed back to the micro-controller where we used an Arduino UNO Rev3 [8]. The circuit, which the Arduino controls, consists of two servos [9]. Once the signals from the software are received, the Arduino directs the two servos to rotate accordingly, to push the wheelchair's joystick shaft forward, backward, left, or right. Thus, allowing the wheelchair to move to the desired location via the user's command. Insights from this project and reflections on the design of related systems are discussed in this paper.

In this paper, a review of related work is presented in the next two sections. Then, we discuss the Brain-Wheel system that we developed with an emphasis on the human factors related to BCI control and motion modules.

2 Human Factors in the Design of Powered Wheelchairs

In this section, we describe the human factors in the design of wheelchairs that support independent movement of users with a range of disabilities. Innovative designs for wheelchairs have emerged in recent years that address a wide spectrum of ergonomics ranging from the seats, motor controls, and head support to the interaction modalities that facilitate freedom of navigation and movement with configurable controls.

Innovations in wheelchair design are intended to improve the ergonomics of wheelchairs and independence of wheelchair users, thereby saving the cost of additional treatment or assistance in daily living. Complexities in the interaction between wheelchairs and their users have risen in recent years that are in-line with advancements in computing power, decrease in cost of microcontrollers, and the emergence of a variety of sensors. Human factors in the design of wheelchairs have been examined extensively with regards to the mechanical components such as the seats, foot rests, hand rims, castors, head supports and arm rests [16]. Several factors influence the energy needed to propel wheelchairs; most notably are as the users' position and the control modules for navigating in the space. Human factors related to the control components of electrical powered BCI wheelchairs have been recognized as key design issues due to the inaccuracy of sensors in BCI modules but have been inadequately examined [e.g. 10]. BCI-controlled wheelchairs have been designed with wired and wireless EEG headsets. Wireless headsets have the advantage of increased freedom of head movement but with less accuracy in interaction/control. On the other hand, wired headsets provide more accuracy but in a more obtrusive setting using the EEG caps and constrained movements. Navigation interfaces have facilitated controlling the movement commands and the selection of destinations in gradual navigation through physical spaces. Virtual environments have been proposed to train users in a safe context-of-use before engaging in the real-time control of the BCI wheelchair in the actual environment [10]. Minimizing the cognitive load of users in interacting with BCI wheelchairs is a key design factor and different control mechanisms have been examined where some interfaces allow users to select the navigation path phase-by-phase while other interfaces facilitate selecting only the destination and handover the path-planning and maneuvering task to the computing and mechanical modules of the wheelchair [10-11, 14]. Computational intelligence has potential for contribution in such scenarios of Human-Computer Interaction (HCI) contexts of research and development to alleviate the cognitive load of users; however, very few attempts been reported in the literature to address this interaction design problem for BCI-controlled wheelchairs. Reducing the mental effort and concentration of users that is required for BCI-controlled wheelchairs has been examined for selection components in [10] and in stopping controls in [11] and [14]. In user acceptance evaluations of BCI-controlled wheelchairs, human factors of response time of BCI, training time of the systems to recognize patterns of user thoughts and interpreting them into commands, and the thresholds of mental effort required to trigger controls (e.g. selection, navigation, sustained attention for recognition of evoked potentials) are key in the effective design of such assistive technologies.

3 BCI-Controlled Wheelchair Designs

BCI-controlled wheelchair prototypes have been developed to provide un-aided control of wheelcahairs for people with disabilities. In this section we present some of the existing BCI applications designed for powered wheelchairs.

A brain controlled wheelchair system was proposed in [10]. The proposed system is composed of three stages: detect the brain signals, classify them into actions, and interfacing to the wheelchair. Firstly, to detect the brain signals the authors used 16-channel 24-bit electroencephalogram (EEG). Sensorimotor rhythms (SMR), which can be produced by imagining the limbs or moving them, are used to produce the desired brain signal. To achieve the second step, which requires understanding and classifying the detected signals, the authors investigated several feature extraction algorithms, such as discrete Fourier transform (DFT) and common spatial patterns (CSP). CSP aims to facilitate the process of differentiating between the two classes of data by increasing the variation between them, which aids in the classification process. Different machine learning algorithms have been used as a classifier. Support Vector Machine (SVM) was used to predict the class of the given input. After the feature selection phase, the authors investigated the optimal sensors number and location. Over 60 sensors, the sensors that produce the most demanding signal that can serve both CPS and the classifier were chosen. The classification performance results show that when the number of sensors is increased, the classification results will be better. The system has been tested in a virtual 3D simulated environment and a modular controller was used as an interface to the wheelchair.

B. Rebsamen et al. [11] also develop a BCI-controlled wheelchair using a hybrid P300and mu-Beta interface. The authors used visual stimuli to invoke P300 signals where the items or destinations that the users can navigate to are presented and flashed sequentially. To select a destination from the presented list, the user needs to focus his/her attention on the destination image. P300 signals were used select the navigation item that the user focuses on. The authors of [11] represented the navigation environment as a graph, where a limited number of destinations through the environment can be selected to navigate to. These destinations are linked via virtual paths where the paths are stored in the memory, such that depending on the destination the required path will be retrieved. Thus, the paths to the destination are not calculated using computational intelligence. While this solution may resolve navigation problems in a relatively static environment, dynamic contexts-of-use would require human intervention to modify the paths for the BCI-controlled wheelchair.

4 Brain-Wheel: A Brain-Controlled Wheelchair

The design of "Brain-Wheel" combines BCI with an optimized wheelchair navigation path that takes into account the context-of-use and physical environment. This section reviews the developed Brain-Wheel system describing its main components, which are: detecting the brain signals, constructing the path which requires the room map to be processed first. Later, the path will be fed to the motion module or control box. The system design is shown in Figure 1.

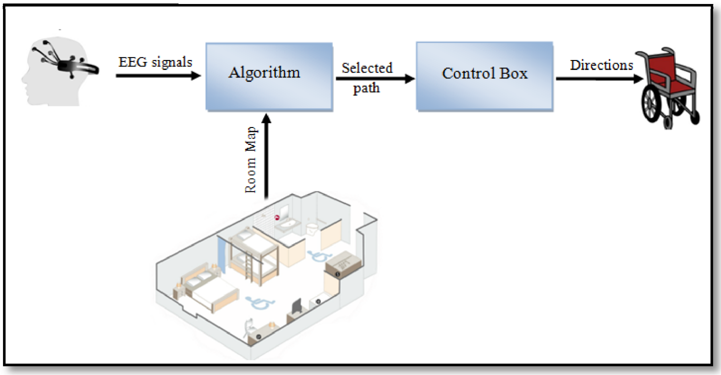

Fig. 1. System Architecture Design

4.1 Detecting Brain Signals

The main goal of the system is to help those who have lost their ability to move their four limbs by assisting them to navigate from one place to another. Thus we developed our system in a way that can respond to the user's cognitive actions using the Emotiv cognitive suite. The Emotiv Epoch headset was considered due to its wireless connection to the computer and its ability to detect different type of signals. A list of the cognitive actions can be found in the Emotiv cognitive suite such as: push, pull, right, left,...etc. The default action, which the user needs to train the Emotiv headset on first, is the neutral state of the user. While training, the user must be focused and avoid any distraction to enable the panel to detect the appropriate signals.

Two cognitive actions were considered in the design of the system: Push and Right. Push is used to simulate pressing the buttons, which in turn is translated to selecting a destination from the map, after reaching it through the Right cognitive command. The Right navigation command is used to move through the map from one cell to another. The user of Brain-wheel must train Emotiv first, before starting to use the system. This is to facilitate allowing the system to save his/her profile and thus recognize his/her brain signals for each cognitive action. After training, the system can respond to the user's push cognitive command, which will move the user from one window to another.

The room, where the user wants to navigate through, has been transformed to a digital 2-D image and has been divided in to cells, i.e., rows and columns that fit the wheelchair size. Figure 2 shows the 2-D map, where the initial location of the user is assumed to be at the location of the entrance.

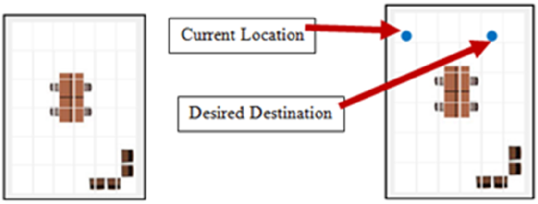

Fig. 2. Selecting a destination using push cognitive commands

4.2 Constructing the Path to the Destination

Optimizing the path for a robot or a vehicle movement is an interesting field of study. In the last decade, the path optimization problem has received the attention of many researchers, due to its close connection to robot movement applications. The path planning optimization problem can be defined as: trying to find a collision-free path that connects a specific starting location with a specific goal/destination. In the path planning optimization problem, each location in the path is represented as a state, and the transition between those states represents the actions [12]. The path is optimal when the sum of its transitions' costs is less than the cost of all possible paths that lead to the same target. There are several existing approaches for computing the optimal path. Heuristic and metaheuristic-based algorithms are among the common algorithms to solve the path planning problem [12].

Metaheuristics are general purpose algorithms that can be used to solve difficult problems. There are many metaheuristic-based algorithms that have been used to solve the path planning problem, such as Ant Colony Optimization, Genetic algorithms, Swarm optimization, etc. The metaheuristic that we selected to solve the path planning optimization problem is Simulated Annealing (SA) [15]. Using the detected signals and the chosen destination, the system processes the SA algorithm to optimize the path to be followed towards the destination. The path planning optimization process in our BCI wheelchair goes through two phases:

Map Processing

Before planning the path, the system processes a 2D map of the room to define the obstacles' locations so that the generated path would not intersect with them. To define the obstacles' locations, the map will be converted into a digital matrix that contains 0's and 1's using an image segmentation algorithm implemented in MATLAB. The output matrix is shown in Figure 3.

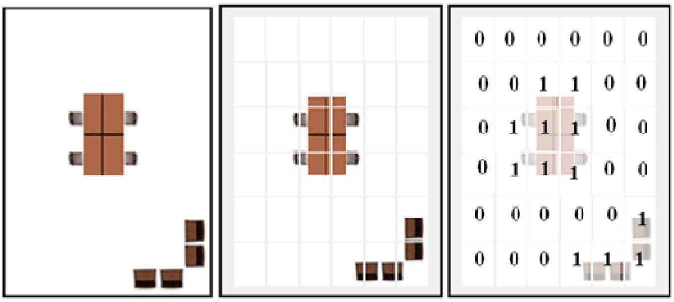

Fig. 3. Transform a map into a matrix

Optimization Using Simulated Annealing

The designed algorithm is based on a Simulated Annealing (SA) metaheuristic, where the advantage of using SA over other metaheuristics is that it can overcome the drawbacks of direct local search in terms of being trapped in a local optimum, and thus can produce better quality solutions. In addition, being a single solution based metaheuristic, simulated annealing is also simpler to implement and less expensive than population based methods (like evolutionary and swarm intelligence algorithms), in terms of both time and space, since it does not need to keep track of multiple solutions at the same time.

In a metaheuristic search, there are different solution representations that can be used according to the type of the optimization problem. In our design, we make some simplifying assumptions, such as representing the environment as a grid where the grid cells are numbered from 0 to N. To move from a node (cell) to another, four possible moves are allowed (horizontal and vertical), whereas diagonal movements are prohibited. This is meant to ease the wheelchair movement through horizontal and vertical directions only. For the path representation, a permutation representation is adopted where the path is represented as a sequence of integer numbers. Each number represents the cell number that the wheelchair will move through.

The objective function for our path optimization problem is concerned with the total path distance, the number of obstacles encountered, and the number of turns (twists) in the path. Due to the allowed movements, the path will add one of its adjacent cells at each movement. Thus, the number of nodes that the path passes through represents the total distance of the path. In addition, for every obstacle passed through in the path, i.e. a non-free cell, a penalty value will be imposed. Moreover, to avoid jerky movements of the wheelchair, the number of turns in the path will also be penalized, such that each change between horizontal and vertical movement will be considered as a turn.

In the SA algorithm, the initial path is improved step by step by generating a neighboring path and comparing its quality with the current path. If the new path has a better quality, it replaces the current path. Otherwise, the new path is adopted with a certain probability. To generate a neighboring path, a special neighborhood move was designed to fit the constraints of the path optimization problem presented here.

4.3 Motion Module

After the path has been generated, the software would translate the path into commands of “forward”, “right”, or “left”. The commands are sent to the Arduino UNO microcontroller, the brain of the motion module, and are received as “F” for “forward”, “R” for “right”, and “L” for “left”. The Arduino is programmed to control two servos mounted over the wheelchair’s joystick’s shaft. Given a command signal, from the Arduino to the servo, the servo's motor will turn its own shaft to a specified angle. Each servo controls an axis (X, Y), and their initial setting is 90 degrees (middle value) each. When “F” is received, the Y-axis servo would turn to 180 degree, and the X-axis servo would be in its initial setting, thus moving the joystick forward. When “R” is received, The Y-axis servo would be given its initial setting value, and the other servo a 0 degree, same for when the “L” is received except now the x-axis servo is set to 180 degree. Each command is carried out for one second; then would lock back to its initial setting 90 degrees for each servo, for it to stop. This was made to help avoid collisions. Communication between the Arduino and PC/LAPTOP is made using serial communication, over a USB cable. Once the signals from the software are received, the Arduino will direct the two servos to rotate accordingly, to push the wheelchair’s joystick shaft forward, left, or right. Thus, allowing the wheelchair to move to the desired location given by the user’s command. Because our work was designed as an external component to the powered wheelchair, and we didn’t modify the mechanical components of the wheelchair, it is envisioned that similar power wheelchair models could integrate our system in their design. Our system allows the wheelchair driver to sit comfortably in his/her power wheelchair, only facing the laptop screen on their lap tray, and wearing the EEG headset. A USB cable is connected from the laptop to the motion module.

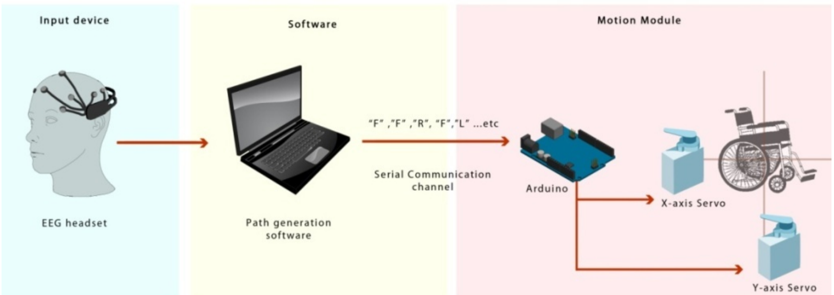

Fig. 4. Motion Module

5 Conclusion

Aiming to facilitate the navigation of the wheelchair and other brain controlled devices, we proposed in the Brain-Wheel project a navigation system that combines Brain Computer Interaction and Path Planning Optimization. Instead of guiding a device to the destination, an interface that contains the environment map will be presented to the user offering various destinations to be reached from the point of navigation. The user has to select a destination from the presented map using his/her brain signals. Two cognitive actions have been used in Brain-Wheel: push cognitive and right cognitive. Using right cognitive, the user can navigate from one cell to another. When the required destination cell is reached a push cognitive is required. The system will then construct a collision-free path to the desired destination using a Simulated Annealing metaheuristic. Finally, the path will be fed to wheelchair using a control box that will transform the path into directions of movements that are connected to the wheelchair's motor modules.

The current system is a prototype at this stage, but in future work, we wish to create an ergonomically designed enclosure for our wheelchair motion module. For example, the speed of the wheelchair was fixed during testing of the system, and cannot be changed. A more flexible system would allow the user to select the speed of their choice. As for safety measures, we plan to add sensors to prevent the wheelchair driver from colliding with unobserved objects in our system.

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