Robotic rehabilitation devices based on Brain-Computer Interfaces: wheelchair and teleoperated robot

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Abstract

This paper describes two innovative brain-actuated applications for rehabilitation developed in the University of Zaragoza: the first one is a brain-actuated wheelchair with automated navigation, and the second one is a brain-actuated robot to carry out teleoperation tasks between remote places. Briefly, the subject faces a real-time virtual reconstruction of the scenario (wheelchair) or video captured by a camera merged with augmented reality items (robot) and concentrates on the area of the space to reach. First, a visual stimulation process elicits the neurological phenomenon (evoked P300 response), the EEG signal processing detects the target, and given then to the autonomous navigation system that drives the device to the desired place while avoiding collisions with every obstacle detected. These systems have been validated with ten healthy users (five for each application). The overall result is that all the users successfully used the device with relative ease and adaptability.

1. Introduction

Nowadays, it exists different degenerative diseases that gradually provoke the incapacity of use of any kind of muscular activity, as amyotrophic lateral sclerosis (ALS). So, common interaction between patients with these diseases and machines become impossible, making the brain the unique communication channel available. Furthermore, this idea is also applicable to patients without an arm or a leg, to whom it may be possible to implant a robotic arm or leg.

Brain-Computer Interfaces (BCI from now on) are those interfaces that allow an interaction with the user using only cerebral signals of him/her. In other words, it allows the control of applications with the thoughts, avoiding any use of muscular activity from the user. In this way, recently a new field of research has emerged.

One of the aspects that makes the difference in this field is the type of technique used to measure the cerebral activity. In United States, research is dominated by invasive techniques in animals, where a sensor is introduced directly into the brain. The advantage is the purity of the signal, at the expense of the ethic problems that this entails. Because of this reason, researchers in Europe tend to use techniques denominated non-invasive (concretely the electroencephalogram or EEG), which are based on the collocation of several electrodes on a cap situated on the head of the user. The principal disadvantage is that the signal measured is much worse, however, it can be used without risk in humans.

In this context, emerges the idea of the development of applications that make use of this technology, developed for users with several physical diseases. Nowadays, it exist numerous interfaces that these people can use in order to control assisted devices. However, all of these approximations requires, in one way or another, some kind of muscular activity. The advantage of BCI technologies is, as explained before, the elimination of that requirement, offering the user the possibility of controlling these devices only with their mind. The range of applications that merges with this idea is vast, from a wheelchair control to a prosthetic robotic arm controlled in a natural way. So far, systems based on human's EEG have been used to control a mouse on the screen [1], for communication like an speller [2], an internet browser [3], etc. Regarding brain-actuated robots, the first control was demonstrated in 2004 [4], and since then, the research has focused on manipulators

[5], small-size humanoids [6] and wheelchairs [7], [8], [9].

From this base, the University of Zaragoza has developed two systems that present applications with different improvements: the first one, a new approximation of a wheelchair controlled by thought; the second one, a robot controlled by thought and situated remotely, i.e. a teleoperation. A rigorous methodology of experiments' design and a exhaustive evaluation of posterior results obtained with five healthy users has been followed for both applications. The overall result is that every user was able to use correctly and efficiently the prototypes designed, demonstrating also a great adaptation against changes in the environment, and also a great robustness of developed systems.

2. Design of wheelchair's system

The research on brain-machine devices applied to the human control of physical devices has been broadly directed mainly in two directions: neuroprosthetics and brain-actuated wheelchairs. Wheelchairs focus on the facilitation of assistance in mobility to accomplish complex navigational tasks. These devices have been demonstrated to improve the quality of life and the independence and self-esteem of the users.

Here we describe a new brain-actuated wheelchair concept that relies on a synchronous P300 neurophysiological protocol integrated in a real-time graphical scenario builder, and that incorporates advanced autonomous navigation capabilities (Figure 1). In operation, the subject faces on a screen a real-time virtual reconstruction of the scenario constructed using a laser scanner. Over the base of this representation, the user concentrates on the area of the space to reach. A visual stimulation process elicits the neurological phenomenon and the signal processing detects the target area. Then, this location is given to the autonomous navigation system that drives the wheelchair to the desired place while avoiding collisions with the obstacles detected by the laser scanner.

From the navigation point of view, in this system the user selects freely destinations of the environment (over the base of a real-time reconstruction), which are safely and autonomously reached by the navigation system. This concept gives great flexibility to the user since the wheelchair can autonomously navigate in unknown and evolving scenarios using the onboard sensors. Furthermore, once the user sets the location he can relax, which avoids exhausting mental processes.

System's design is composed by two main modules: (i) the brain-computer system that decodes the user intention, and (ii) the navigation system that executes the user's desired decisions. Finally, there is a communication system between them that performs all the exchange of data needed.

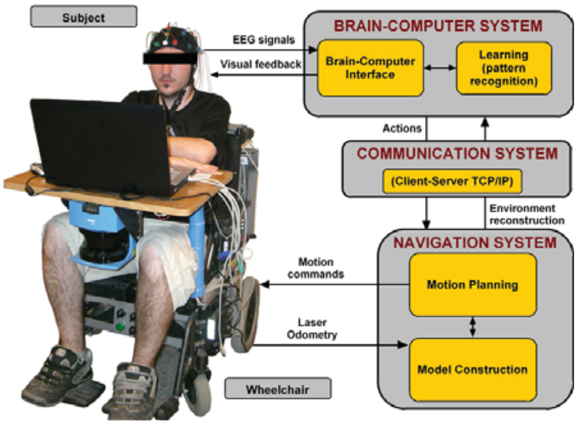

Figure 1: This figure displays the design of the brain-actuated wheelchair, the main modules and the information flow among them.

2.1. Brain-computer system

The neurophysiological protocol followed in our study is based on an event-related response, the P300 visually evoked potential [10]. This potential manifests itself as a positive deflection in voltage at latency of roughly 300 msec in the EEG after the target stimulus is presented (within a random sequence of non-target stimuli) (see Figure 2).

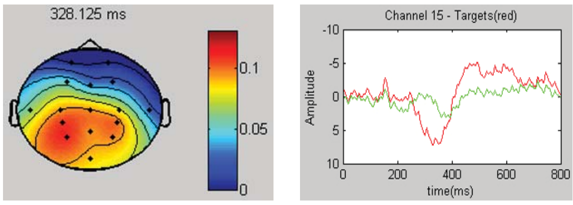

Figure 2. (Left) Topographical plot of the EEG distribution in the scalp at 300 msec. The area with more activity (mid-low part of the scalp) is in the parietal lobe, where the P300 potential is elicited. (Right) Typical P300 response. The red line shows the EEG activity on one channel (elicited by the target stimulus), and the green line corresponds to the non-target one.

Apart from the signal processing unit, it includes a graphical interface. In order to command the wheelchair, the user selects destinations or motion primitives by concentrating on the possibilities displayed on the computer screen (Figure 3). The graphical interface has two functionalities: displays information of the real-time reconstruction of the environment and additional information for the order selection; and develops the stimulation process to elicit the P300 visually-evoked potential. The graphical aspects of this module are based on a previous study involving a robotic wheelchair adapted for cerebral palsy users [11] with a tactile screen.

The information displayed on the screen is a reconstruction of the real scenario for the user's command selection. The environment 3D visualization is built from the 2D map constructed in real-time by the autonomous navigation technology. In other words, the visual information of the screen is a simplified reconstruction of the user's perception. The use of an online map instead of an a priori one endows the system with the flexibility to work in unknown scenarios. This is because online maps rapidly reflect changes in the environment, such as moving people or unpredictable obstacles like tables or chairs. The rest of the displayed information is used for command selection: the obstacles are depicted by walls; the grid over the floor maps the possible goal locations, where the first grid row is the one that has the farthest destinations. The walls hide the unreachable destinations of the grid. The arrow buttons turn the vehicle around ±90º its current position; the traffic light buttons (i) validate the user's commands or (ii) stop the vehicle; and the rubber represents the "remove selection" option. In the current version of the interface the stop and "remove selection" options are not used, but they have been taken into account for the next interface prototype. All the elements of the visual display can be customized in terms of color, texture, shape, size and location. This was important in the screening sessions to equilibrate the user capabilities and preferences with the performance of the system (recall that the elicitation of P300 potential is affected by these issues).

The other aspect of the visual display is the stimulation process to elicit the P300 visual evoked potential when the user is paying attention to a given option. An option is "stimulated" by displaying a circle on the selection (Figure 3). One sequence of the stimulation process is a stimulation of all the options in a random order as required by the P300 oddball paradigm. In order to reduce the duration of a sequence and the dimension of the pattern recognition problem, we follow here the Farwell and Donchin [12] stimulation paradigm. In this paradigm, the flashing of the stimuli is done by means of rows and columns instead of flashing each option individually. Thus, in our interface there are 9 stimulations (rows plus columns) and two classification problems of 5 and 4 classes (the target option is the intersection of the target row and the target column). The number of sequences and all the scheduling of the stimulation process (time of exposition of each stimulus, inter-stimulus duration and inter-sequence duration) can be modified to equilibrate the user capabilities and preferences with the performance of the system.

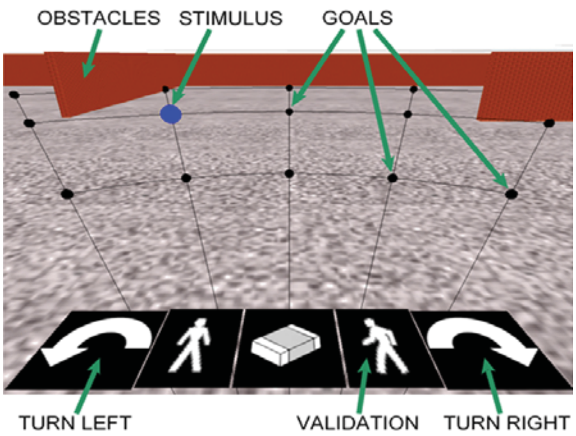

Figure 3: graphical interface designed.

2.2. Navigation system

The other system consists of the navigation system integrated in the wheelchair. The robotic wheelchair was constructed based on a commercial electric wheelchair that complied with basic user mobility and ergonomic requirements. It has two computers: The first computer performs the control of the back wheels, and the second computer performs the navigation computations and managing the communications between the wheelchair and the BCI system.

The second computer is used for medium-level control, performing the navigation computations and managing the communications between the wheelchair and the BCI system. The main sensor is a SICK planar laser placed in the frontal part of the vehicle. This sensor provides information about the obstacles in front of the vehicle. We have incorporated to the robot an autonomous navigation technology that is able to drive the vehicle to a given destination while also avoiding the obstacles, both static and dynamic, detected by the laser sensor [13]. This module has two functionalities. On the one hand, a modeling module integrates the sensor measurements to construct a local model of the environment and track the vehicle location. On the other hand, a local planner computes the local motion based on the hybrid combination of tactical planning and reactive collision avoidance.

Figure 4: Snapshots of different subjects during the experiments.

Once developed each unit and linked between them with a communication system, the global system is fully functional for the user to use. Briefly, the **execution protocol** works as explained next. Initially, the user observes an screen with the graphical interface explained before. In this phase, wheelchair's system is stopped, waiting orders from the user. When the visual stimulation begins, the user concentrates on desired option, and after that on the validation option. Once the order is validated, it is sent to the wheelchair, and the stimulation process stops. In that moment, the wheelchair plans the movement and starts moving in order to reach the destination. Once the wheelchair reaches it, it will send a response to the graphical interface informing that the movement is finished, and then the stimulation process will start again.

3. Methodology and evaluation

In order to execute the experiments, several users were selected to perform the experiments according to inclusion criteria. Specifically, five healthy, 22 years old, male and right-handed students of the University participated in the experiments. None of them had ever utilized an electric wheelchair before. The study was accomplished in three phases in the BCI laboratory of the University of Zaragoza. We summarize next the first two phases, and focus on the third phase since it involves the rehabilitation device.

The first phase was the screening session. The objective of this session was to screen the subjects for the next stage and to come up with a graphical interface that equilibrates the user capabilities and preferences with the performance of the system, in terms of color and brightness of the stimulus and environment textures. The second phase consisted on a training subphase and on a test in a wheelchair simulator, which emulates the underlying mechanisms of the user interface and the wheelchair navigation.

The last phase consisted of real-time navigation with the wheelchair along pre-established circuits. The objective of this battery of experiments was to create the basis for a technical and coherence evaluation of the brain-actuated wheelchair: to explore the navigation capabilities of the system and to assess the performance of the subjects in real settings. We designed two circuits that the user had to solve by autonomously navigating with the wheelchair. The first circuit was designed to accomplish complex maneuverability tasks and avoidance of obstacles in constrained spaces. The second circuit involved navigation in open spaces.

Regarding the results of the experiments, the reader is directed to [14] for more details about the first two evaluations, and we focus on the evaluation of the brain-actuated device itself. The overall result is that all the users were able to successfully use the device with relative ease showing a great adaptation, and also a high robustness and coherence (Figure 4). Next is detailed a general evaluation of the brain-actuated wheelchair, a particular evaluation the brain-computer interface and a coherence analysis.

1) Overall performance: we follow here the metrics proposed in [11] to evaluate the performance of autonomous wheelchairs:

- Task success: degree of accomplishment of the task.
- Path length: distance traveled to accomplish the task.
- Time: time taken to accomplish the task.
- Collisions: number of collisions.
- BCI accuracy: accuracy of the pattern recognition.
- Number of missions: a mission is defined as a selection of goal + validation.

The results are summarized in tables I and II.

Table I: Overall performance, task 1

	min	max	Mean	Std
Path length (m)	12.8	19.0	15.7	2.0
Time (sec)	448	834	571	123
Practical BCI accuracy	0.88	1	0.95	0.04
# missions	8	14	9.6	1.9

Table II: Overall performance, task 2

	min	max	mean	std
Path length (m)	37.5	41.4	39.3	1.3
Time (sec)	507	918	659	130
Practical BCI accuracy	0.81	1	0.94	0.07
# missions	7	12	9.2	2.9

All the subjects succeeded to autonomously navigate along the two circuits, which is the best indicator of the device utility. No collisions occurred during the experiments. The path length, time taken and number of missions was very similar for all the subjects indicating a similar performance across subjects. The interaction with the device was also satisfactory since the accuracy on average was always above 94%. We understand that all these results are very encouraging since the experiments were carried out in scenarios carefully designed to cover many of the typical real navigation situations of these devices.

2) BCI performance: there have been some metrics proposed to evaluate BCI performances [15]. Based on them, we propose the following measures:

- Theoretical BCI accuracy: BCI correct selections vs total.
- Total errors: number of incorrect selections.
- Useful errors: incorrect selections of the BCI that the user decided to reuse.
- Practical BCI accuracy: correct selections plus useful errors vs total.

The results are summarized in tables III and IV.

Table III: Performance of BCI, task 1

	min	max	mean	std
Theoretical BCI accuracy	0.85	1	0.93	0.05
Practical BCI accuracy	0.88	1	0.95	0.04
# Total errors	0	4	1.6	1.35
# Useful errors	0	1	0.3	0.48

Table IV: Performance of BCI, task 2

	min	max	mean	std
Theoretical BCI accuracy	0.77	1	0.92	0.07
Practical BCI accuracy	0.81	1	0.94	0.07
# Total errors	0	7	1.9	2.13
# Useful errors	0	1	0.4	0.52

The theoretical accuracy on average was almost always greater than 92%, indicating a high accuracy. We have distinguished between theoretical and practical accuracy. This is because in some situations, although the BCI system did not recognize the user's selection, the BCI selection was used by the subject to achieve the mission. These useful errors were almost 20% of the total errors making the practical accuracy greater than the theoretical one. Furthermore, they reduced the number and the time for selections and validations.

3) Coherence Analysis: we outline next the main results of a coherence analysis of the experimentation sessions, related to how coherent the execution of the trials was and how coherent the execution of the tasks among subjects was. We propose the number of selections, missions, distance and BCI failures normalized in time as the basis for this coherence study. To measure the coherence we use Pearson's correlation coefficient: values close to one indicate strong coherence while values far from one indicate weak coherence.

Firstly, the coherence between trials indicates the grade of similarity between the two trials executed for each subject in each task. For all the subjects, this coherence was always greater than 0.98 indicating that the coherence among trials is very high. We understand from this result that all the subjects used the device to solve each navigation task in a coherent way.

Secondly, the coherence between subjects represents the grade of similarity between the trials executed by the subjects against the trials executed by the other subjects. Results of this analysis are shown in tables V and VI.

Table V: Coherence between subjects, task 1

	S1	S2	S3	S4	S5
S1	1	0.962	0.984	0.953	0.981
S2	-	1	0.941	0.951	0.976
S3	-	-	1	0.977	0.975
S4	-	-	-	1	0.984
S5	-	-	-	-	1

Table VI: Coherence between subjects, task 2

	S1	S2	S3	S4	S5
S1	1	0.960	0.916	0.953	0.998
S2	-	1	0.963	0.987	0.970
S3	-	-	1	0.989	0.925
S4	-	-	-	1	0.959
S5	-	-	-	-	1

The coherence values are always greater than 0.92 so coherence between subjects is very high. This result suggests that all the subjects used the device to solve the navigation tasks coherently and in an analogous way.

4. Design of the teleoperation system

The ability to brain-teleoperate robots in a remote scenario opens a new dimension of possibilities for patients with severe neuromuscular disabilities: these rehabilitation devices provide the patients – unable to leave their clinical environments – with a physical entity embodied in a real environment (anywhere in the world) ready to perceive, explore, manipulate and interact; only controlled with the brain activity, which could be their only degree of freedom.

Here we report the first EEG-based human brain-actuated teleoperation system. This brain-actuated teleoperation system relies on a user station (patient clinical environment) and a robot station (placed anywhere in the world), both remotely located but connected via internet (Figure 5). The underlying idea of the system is that in the user station, the brain-computer system decodes the user intentions, which are transferred to the robotic system via internet. The user can alternate between a robot navigation mode (to control the robot motion) and camera control (to control the camera orientation). Furthermore, the camera sends live video of the robot station environment, which is used by the user as visual feedback for decision making and control process.

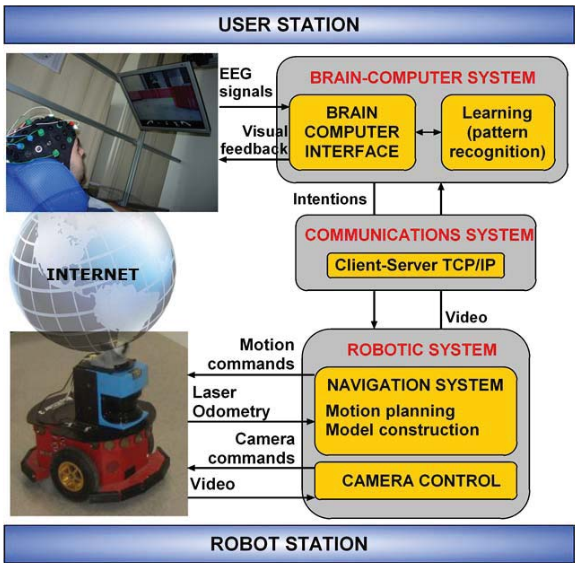

Figure 5: This figure displays the design of the brain-actuated robot, the two stations, the main systems and the information flow among them.

The brain-actuated teleoperation system is composed by two main modules: (i) the brain-computer system that decodes the user intentions, and (ii) the robotic system that executes the user's decisions. Furthermore there is a communications system among them via internet.

4.1. Brain-computer system

The neurophysiological protocol followed in our study is based on the P300 visually-evoked potential as in the wheelchair system (see section 2). Furthermore, it incorporates a graphical interface with two functionalities: (i) it visually displays a predefined set of options that the user can select to control the robotic system, and (ii) it develops the stimulation process to elicit the P300 visual-evoked potential and therefore, enables the pattern recognition system to decode the user's intents.

Regarding the first functionality, the basis of the visual display is the live video received by the camera placed on the robot. This video is augmented by overlapped information related to the two teleoperation modes: the robot navigation mode and the camera control mode.

The robot navigation mode allows the user to control the robot motion (Figure 6). Overlapped to the video, the environment obstacles are displayed by semitransparent walls. Furthermore, there is a grid of destinations over the floor that the operator can select. The obstacles hide the unreachable destinations of the grid. The icons in the bottom part represent the following actions, from left to right: (i) turn the robot 45º left; (ii) refresh the live video to perform a selection based on a more recent visual information of the environment; (iii) change to the camera exploration mode; (iv) validate the previous selection; and (v) turn the robot 45º right.

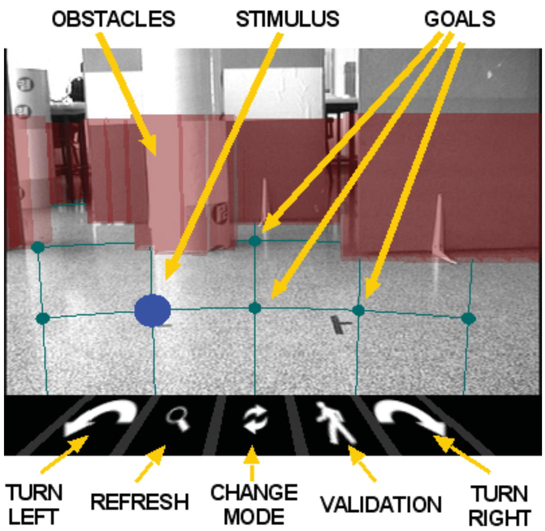

Figure 6: Visual display in the robot navigation mode.

The camera control mode allows the user to control the orientation of the camera to perform a visual exploration of the environment (Figure 7). Overlapped to the video there is a grid of locations, uniformly placed in a 2D plane in front of the camera, that the user can select to orientate the camera in that direction. The icons in the bottom of the screen represent the following actions, from left to right: (i) align the robot with the horizontal camera orientation and change to the robot navigation mode; (ii) refresh the live video; (iii) change to the robot navigation mode; (iv) validate the previous selection; and (v) set the camera to its initial orientation.

Regarding the second functionality, the stimulation process must elicit the P300 visual-evoked potential when the user is concentrated on a given option. The options of the visual display are "stimulated" by flashing a circle on a grid intersection or icon in the visual display. The Farwell&Donchin paradigm is followed [12] as in the wheelchair system; thus, the flashing of the stimulus is done by means of rows and columns instead of flashing each option individually, obtaining 9 stimulations (4 rows plus 5 columns) per sequence. We keep constant the topology of the augmented reality items in both teleoperation modes to maintain a uniform stimulation pattern. All the elements of the display can be customized in terms of color, texture, shape, size and location; and all the scheduling of the stimulation process (time of exposition of each stimulus, inter-stimulus duration and inter-sequence duration) can be modified to equilibrate the user capabilities and preferences with the performance of the system.

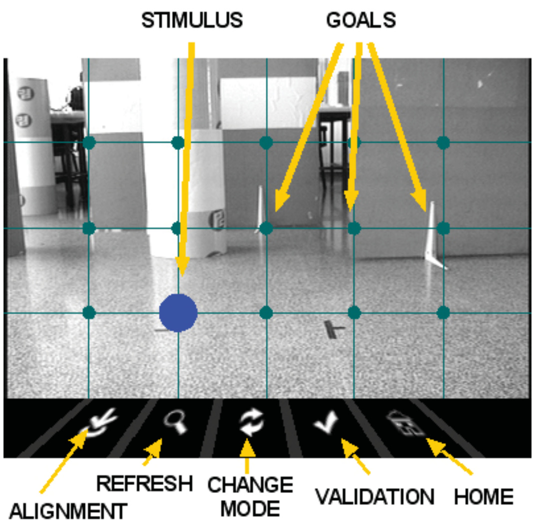

Figure 7: Visual display in the camera exploration mode.

The overall system works as follows. The user concentrates in a given option of the visual display (described above). Initially, the robot is stopped, waiting for the user decisions, and the visual display starts in the navigation mode. Then, a stimulation process starts and an option is selected. A new stimulation process starts and, if the option selected is the validation one, the previous option is transferred to the robotic system; otherwise the process starts again. When the robotic system receives an option, the stimulation process stops and the robot executes the relevant action. Meanwhile the graphical interface receives the video information of the robot camera. Once the execution of the action finishes, the video transfer stops and the process starts again.

4.2. Robotic system

The robot is a commercial *Pioneer P3-DX* equipped with two computers. The low-level computer controls the back wheels that work in differential-drive mode and the high-level one manages with the rest of the computational tasks.

The main sensor is a *SICK* planar laser placed on the frontal part of the vehicle. It works at 5 Hz, with a field of view of 180º and 0.5º resolution (361 points). This sensor provides information about the obstacles located in front of the vehicle. The robot is also equipped with wheel encoders (odometry), with a wireless network interface card that allows connecting the vehicle to a local network during operation, and with a pan/tilt/zoom camera *Canon VC-C4* placed on the laser, which allows performing a visual exploration of the environment.

We have incorporated to the robot the same autonomous navigation technology of the wheelchair. This technology is able to drive the vehicle to a given destination while also avoiding the obstacles, both static and dynamic, detected by the laser sensor [13]. This module has two functionalities. On the one hand, a modelling module integrates the sensor measurements to construct a local model of the environment and track the vehicle location. On the other hand, a local planner computes the local motion based on the hybrid combination of tactical planning and reactive collision avoidance.

5. Methodology and evaluation

In order to execute the teleoperation experiments and to assess the performance and adaptability of the brain-teleoperated robot by able-bodied users in real settings, several users were selected according to inclusion criteria in order to maintain a homogeneous sample as possible. Specifically, five healthy, 22 years old, male and right-handed students of the University of Zaragoza participated in the experiments All of these users were not the same from the ones of the wheelchair's experiments, and none of them had ever utilized any similar device. The study was accomplished in two phases: screening and training evaluation, and teleoperation evaluation.

Figure 8: Snapshots of different moments during the experiments.

The objective of the first session was to screen and to train the subjects for the next stage, and to come up with the graphical interface that better equilibrated the user capabilities and preferences with the performance of the system.

The objective of the second session was to test the teleoperation between remote places (two cities) and to record the data for a posterior evaluation. The experiments were accomplished the week of June, 23th 2008, between the BCI laboratory at the University of Zaragoza (Spain) and the University of Vilanova i la Geltrú (Spain), at a distance of 260km. We designed two tasks in two different circuits that combined jointly navigation and visual exploration to evaluate the boundaries of the system and to assess its performance: task 1 addresses navigation in constrained spaces with an active search of two visual targets, task 2 addresses navigation in open spaces with an active search of one visual target.

Concretely, next is detailed a general evaluation of the teleoperated robot, a particular evaluation of the brain-computer system and a coherence analysis.

Regarding the results of the experiments, we outline here the results obtained in the experimental sessions (Figure 8). The reader is directed to [16] for more details on the evaluation.

1) Overall performance: following [11] the subsequent metrics are proposed for the study:

- Collisions: number of collisions.
- Path length (m): distance travelled by the robot.
- Time (sec): time taken to accomplish the task.
- Missions: number of missions to complete the task, i.e. selection of goal + validation.
- BCI accuracy: recognition rate of the BCI system.

The results are summarized in tables VII and VIII.

Table VII: Overall performance, task 1

	min	max	mean	Std
Path length (m)	10.99	13.53	11.84	0.90
Time (sec)	685	1249	918	163
# missions	12	19	13.9	2.3
Practical BCI acc	0.83	1.00	0.92	0.07

Table VIII: Overall performance, task 2

	min	max	mean	Std
Path length (m)	19.68	21.83	20.68	0.63
Time (sec)	706	1126	910	154
# missions	10	15	11.7	1.6
Practical BCI acc	0.78	1.00	0.89	0.07

All the subjects solved two times each task demonstrating that they were able to combine the navigation and camera control capabilities of the device. There were no collisions. The path length and the number of missions were similar for all the subjects in the two tasks, which indicate a similar performance. The variability of the total time across subjects is significative since the number of stimulation sequences of the BCI changed among them. This is because the number of sequences had to be customized for each subject to achieve a minimum of BCI accuracy (more sequences involves more accuracy, but also more stimulation duration). The BCI accuracy was very high, on average about 90%.

In conclusion, the results suggest a high performance of the brain-teleoperated robot. Notice that both tasks were designed to test the combination of both teleoperation modes in different working conditions (navigation in constrained and open spaces; and visual search of one or two targets that do not fit in the initial camera field of view).

2) BCI performance: Based on [15], the next metrics were proposed to assess the BCI performance:

- Real BCI accuracy: BCI correct selections vs total.
- Practical BCI accuracy: correct selections plus useful errors vs total.
- Total errors: number of incorrect selections.
- Useful errors: incorrect selections that the user decided to reuse to accomplish the task.

The results are summarized in tables IX and X.

Table IX: BCI system performance, task 1

	min	max	mean	std
Real BCI accuracy	0.81	1.00	0.90	0.08
Practical BCI accuracy	0.83	1.00	0.92	0.07
# Total errors	0	6	2.90	2.56
# Useful errors	0	2	0.60	0.84

Table X: BCI system performance, task 2

	min	max	mean	std
Real BCI accuracy	0.73	1.00	0.86	0.09
Practical BCI accuracy	0.78	1.00	0.89	0.07
# Total errors	0	11	4.90	3.70
# Useful errors	0	5	1.20	1.81

The convention [17] used to assess that a person is able to use a BCI is when his accuracy is above 80%. In our experiments, the real accuracy was 90% and 86% (on average). We have distinguished between the real and the practical accuracy, since in some situations, although the BCI system failed, the selection was reused by the subject to achieve the task. These useful errors turn the practical accuracy (92% and 89%) greater than the real one. The BCI system set two incorrect missions to the robotic system in all the executions (representing in total a 0.78%), which is twice the theoretical probability of this situation (0.3%).

3) Coherence Analysis: We outline next the main results of a coherence analysis of the experimental sessions. The first one is related to how coherent was the execution of the trials of each one of the tasks, and the second one is related to how coherent was the execution of the tasks among subjects. We propose as metrics the number of selections, the number of missions, and the distance traveled (all of them normalized in time). The coherence is described by Pearson's correlation coefficient, whose values close to one indicate strong coherence while values far from one indicate weak coherence.

On the one hand, the coherence between trials indicates the similitude grade among the two trials executed for each subject in each task. For all subjects, we computed the correlation of the previous metrics across trials. The result was that the coherence across subjects in the tasks is always greater than 0.98, indicating a strong coherence among trials. Thus, these results suggest that all the subjects used coherently the device to solve each task.

On the other hand, the coherence between subjects indicates the similitude grade between the executions of the tasks. For all subjects, we computed the correlation of the previous metrics. Results of this analysis are shown in tables XI and XII. The coherence values are very high (always greater than 0.87). These results suggest that all the subjects used the device to solve the tasks coherently and in an analogous way.

Table XI: Coherence between subjects, task 1

	S1	S2	S3	S4	S5
S1	1	0.962	0.984	0.953	0.981
S2	-	1	0.941	0.951	0.976
S3	-	-	1	0.977	0.975
S4	-	-	-	1	0.984
S5	-	-	-	-	1

Table XII: Coherence between subjects, task 2

	S1	S2	S3	S4	S5
S1	1	0.96	0.98	0.96	0.93
S2	-	1	0.97	0.97	0.95
S3	-	-	1	0.92	0.99
S4	-	-	-	1	0.87
S5	-	-	-	-	1

6. Conclusions

This paper describes two EEG-based human brain-actuated robotic devices for rehabilitation. On the one hand, we describe a new brain-actuated wheelchair concept that relies on a synchronous P300 brain-computer interface integrated with an autonomous navigation system. This combination gives great accuracy in the interaction and flexibility to the user, since the wheelchair can autonomously navigate in unknown and evolving scenarios using the onboard sensors. On the other hand, we describe a brain-actuated robotic system to carry out teleoperation tasks between remote places via internet. In operation the user can combine two teleoperation modes (robot navigation and camera control) to solve visual exploration tasks where the robot must also navigate in the environment.

The wheelchair was used and validated by five healthy subjects in three consecutive steps: screening, virtual environment driving and wheelchair driving sessions. The teleoperation system was validated with five healthy subjects, which performed pre-established navigation and visual exploration tasks for one week between two cities 260km far away. During the real experiments, both systems showed high performance since all the subjects accomplished two different tasks with relative easiness. Notice that the experiments were carried out in settings designed to cover typical navigation situations, such as open spaces and complex maneuverability; combined with exploration tasks in the case of the teleoperation system. The overall result is that all the subjects successfully used the devices with relative ease showing a great adaptation and coherence. This study shows the feasibility of these technologies in humans and using non invasive techniques.

As future work, we are working on the improvement of the wheelchair system to reduce the recognition time by developing a P300 continuous control of the system. Although the BCI accuracy is high, we are also working on the integration of BCI-based online error detection system to improve it. In the teleoperation system we are now working in the incorporation of high level tasks to improve the navigation (e.g. with tasks like people tracking and following), and the exploration (e.g. tracking and aligning the camera with the location of specific sounds or voices); and in the integration of this system in small, low-cost robots.

An interesting future work would be to perform experiments of both rehabilitation devices with patients with neuromuscular disabilities to evaluate the real usefulness of them.

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