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New Strategies of Mobility and Interaction for People with Cerebral Palsy

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1. Introduction

Cerebral palsy (CP) is one of the most severe disabilities in childhood and makes heavy demands on health, educational, and social services as well as on families and children themselves. The most frequently cited definition of CP is a *disorder of posture and movement due to a defect or lesion in the immature brain*, Bax (1964). The prevalence of CP is internationally 1.5-2.8 cases per 1000 births. Only in the United States 500,000 infants are affected by CP, Winter et al. (2002). In Europe these figures are even higher, Johnson (2002).

The "Surveillance of cerebral palsy in Europe: a collaboration of cerebral palsy surveys and registers" presented a consensus that was reached on definition of CP, classification and description, Cans (2000). This classification divides CP into spastic, ataxic and dyskinetic.

It is demonstrated that it is during early stages of development that fundamental abilities and skills are developed, Gesell (1966); Hummel & Cohen (2005). Thus, it is crucial to give CP infants an opportunity to interact with the environment for an integral development. It is recognized that assistive technology can improve the functional capabilities limited by CP, LoPresti et al. (2004). Approximately 50% of children affected by CP need technical aids for assisting their mobility (braces, walkers, or wheelchairs).

The motivation of this work arises from the limitations caused by CP in the fundamental areas of human being: mobility, communication, manipulation, orientation and cognition. The aim of this work is to design assistive devices to promote the fundamental skills of children with CP reducing motor and cognitive limitations.

One the one hand, the capacity of exploring and controlling the environment is essential for any human being. Independent mobility plays a crucial role in this exploration, leading to the child's physical, cognitive and social development, Azevedo (2006). According to the state of art of mobility devices for people with CP, most devices are more focused on mobility than the integral development.

One the other hand, the posture and motor disoders associated to CP limit frequently the access to general assistive devices. The human machine interaction results a critical factor. According to the state of art of person-computer interfaces for people with CP, there are a wide diversity of solutions. However, authors assert that the usability decreases dramatically when users have a severe motor disability.

From such considerations, the following needs are identified: 1) To emphasize the learning of the physical and cognitive skills through mobility experiencies, 2) to characterize the control limitations caused by posture and motor disorders, 3) to facilitate the interaction between the child and the assistive device by filtering those control limitations.

In this context, the main contributions of this work are:

- Design and evaluation of a robotic vehicle, called PALMIBER, for cognitive and physical rehabilitation.
- Software tool for objective evaluation of the driving task and interfaces.
- Design and evaluation of a novel person-machine motion-based interface, called ENLAZA, to increase the accessibility of the vehicle.
- Characterization of the posture and motor disorders of people with CP by using the ENLAZA interface.
- Design and validation of a filtering technique to reduce the effect of the involuntary motion on the control of the interface.
- Functional validation of the ENLAZA interface and filtering technique as pointing device for the computer.
- Functional validation of the ENLAZA interface as input device for driving the vehicle.

A review of asssitive devices for mobility focused on people with CP is presented in section 2. Section 3 presents the design and evaluation of the vehicle PALMIBER, a pre-industrial prototype for the integral rehabilitation. A review of person-computer interfaces for people with CP is presented in section 5. The ENLAZA interface is presented in section 5.1. Section 5.2 describes the characterization of motor disoders of people using the ENLAZA interface. Section 6 presents a novel algorithm to reduce the effect of the involuntary movements on the control of the interface. Finally, section 7 presents the functional validation of the ENLAZA interface as input device for the computer. Section 8 presents the functional evaluation of the ENLAZA interface as input device for driving the PALMIBER vehicle.

People with CP and therapists from ASPACE Cantabria (Spain) have participated in all phases from the conceptualization to the validation to guarantee the usability of the devices. The inclusion criterion has included people with severe motor disorders which have been described. It is expected that results are representative for people with similar profile.

2. Assistive devices for mobility focused on CP

There are basically two groups of assistive devices to help people with mobility problems: the alternative devices and the empowering (or augmentative) devices. These solutions are selected based on the degree of disability of the user. In the case of total incapacity of mobility (including both bipedestation and locomotion), alternative solutions are used. These devices are usually wheelchairs or solutions based on autonomous especial vehicles. Because of that, the wheelchairs are the focus of research of many groups all over the world.

Advanced wheelchair-based devices constituting a doctrine body known as Autonomous Robotic Wheelchairs (ARW), which can be considered a specialized version of the well-known autonomous mobile robot (AMR). In fact, a number of topics are common to both technologies, particularly obstacle detection and avoidance, localization, path planning, and wall following. Nevertheless, an important distinction must be made because an ARW is

specifically designed to transport people. As a result, some issues become very important, such as safety, stability, smooth driving, and higher maneuverability, generally due to nonstructured environments. Many references can be found in the literature about research projects leading to experimental prototypes, such as OMNI, Hoyer et al. (1997), SIAMO, Mazo et al. (2002), VAHM, Bourhis & Agostini (1998), TetraNauta, Civit (1998), BREMEN, Rofer & Lankenau (1998), and SENARIO, Katevas et al. (1997).

Different technical aids focused on CP can be found such as canes, walkers, orthosis. Canes are the most traditional tool to help people walk. Walkers are a device to maintain balance or stability while walking. There are many types of walkers, considering their constitutive materials, accessories, sizes and structural configurations. An orthosis is an external orthopedic appliance that prevents or assists the movement of the spine or limbs. There are some interesting solutions which combine both solutions.

The NF Walker by EO Funktion® has been developed to give children the possibility for movement, both standing and walking. It promotes body awareness and improves respiratory and cardiovascular functions through regular activity, as well as reduces the risk of chronic diseases such as high blood pressure, osteoporosis and gastrointestinal disorders. The SMART Walker® Orthosis has been designed and manufactured by Advanced Orthotic Designs. It encourages a child with CP to learn to stand and ambulate with hands-free support.

There are assistive devices for motor rehabilitation which combine orthoses, user's weight support and a treadmill. The Lokomat®, designed by Hocoma, is a driven gait orthosis that automates locomotion therapy on a treadmill and improves the efficiency of treadmill training. Preliminary studies have demonstrated that Lokomat® has a positive impact on motor rehabilitation of children with CP, Borggraefe et al. (2009).

Most of the implementations described above are conceived as technical aids to help increase the mobility of the disabled. A few of the systems described in the literature address the particular problems of children affected by neuromotor disorders accompanied by mental retardation. One outstanding case worthy of mention is the Communication Aids for Language and Learning (CALL) center that developed a smart wheelchair specifically for children with mobility impairment. In this case, a standard wheelchair was instrumented and adapted in terms of the user's interfaces.

The *Gobot* is a special vehicle that enables mobility for children with CP created by the Hospital of Lucile Packard Stanford (US). It moves easily from a horizontal to a vertical position. Tray, hip, lateral supports and full foam knee supports are also simple to adjust. The *Magellan Pro Robot* is a commercial robot made by the iRobot corporation. Researchers from the Delaware University (US) used it for rehabilitation of children with CP, Galloway et al. (2008); Lynch et al. (2009). The robot was equipped with an on-board computer and odometry. Their results demonstrated that young infants will independently move themselves via a mobile robot. Their data do provide indirect evidence that infants were not simply focused on moving the joystick but were associating joystick activation with their motion.

Although these devices are focused specifically for children with CP, they are based on standard or commercial devices. The following work addresses the development of an assistive platform designed specifically for alternative mobility of children affected by CP. Both mechanical structure and driving modes have been designed according to the user's needs. Moreover, the vehicle PALMIBER fulfills the technical requirements related to safety,

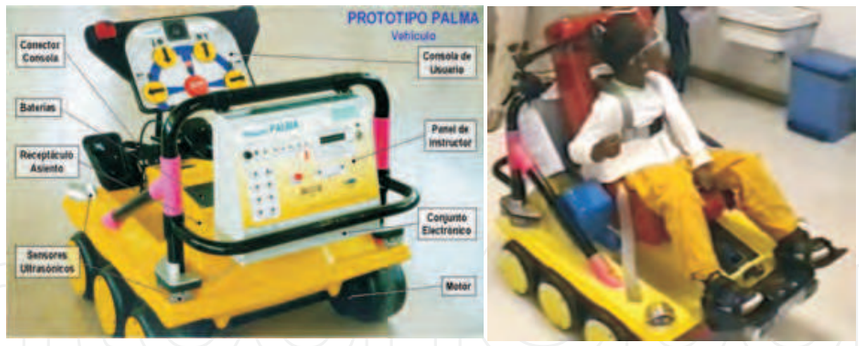


Fig. 1. Prototype PALMA project

Fig. 2. Prototypes of PALMIBER project

stability and robustness. This rehabilitation tool is conceived as an attractive tool for integral development of children with severe neurological problems.

3. The PALMIBER vehicle

The origin of the PALMIBER vehicle (Fig. 2) was the PALMA project, Fig. 1. The PALMA project was developed with the main aim of proposing an attractive tool for integral development of children with severe neurological problems, Azevedo (2006); Ceres et al. (2005). PALMIBER vehicle aims to create a commercial product based on the concept validated by PALMA project.

3.1 Driving modes

Regarding system driving autonomy, the basic requirement is the adaptability to user dexterity and to user progress and mental development. As a consequence, our approach is basically different to the one presented for the previous ARWs. We are interested in improving children's motor control, driving skills, and their ability to eventually reach a desired destination. The educators in the PALMA team identified six steps in the cognitive development of the children. They are summarized in table 1.

3.2 Electronic architecture and peripheral devices

- A dsPIC controls the different modules of the PALMIBER: the user and educator interfaces, odometry module, obstacle detection system and power and motor management.

Driving mode	Description
Autonomous (Level 0)	The vehicle detects and avoids obstacles without user intervention. In this navigation mode, the vehilce navigates while avoiding obstacles without any predefined target.
Cause-effect relation (Level 1)	The child press any key and the vehicle start to move. The vehicle stop when it finds a obstacle.
Training of the direction (Level 2)	The vehicle stops after detecting an obstacle (a crashing noise and alarm light warn of the eventual crash). The child must press the correct button proposed by the vehicle otherwise the vehicle does not move. If no response is obtained from the child, he is invited to do so by a verbal message.
Decision of the direction (Level 3)	The user decides and presses the driving buttons, but the vehicle automatically stops if any obstacle is detected. Verbal commands are generated. At this level, the children start deciding on a navigation target.
Fully user guided (Level 4)	The vehicle is fully driven by the user; no sensors are active in this operation mode.

Table 1. Driving modes of the vehicle

- User and educator interfaces. The whole system includes a user board as the I/O interface between the child and the system and an educator board to select the mode and the parameters of driving and the general control of the vehicle.

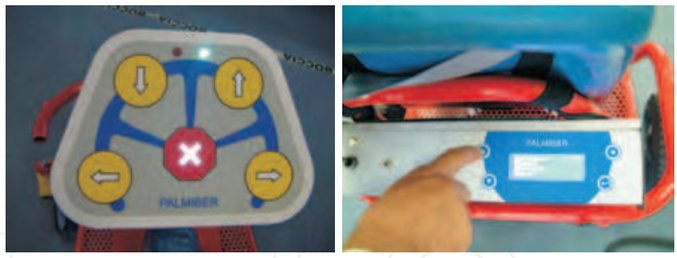
  The user board is placed opposite to the child by means of an articulated arm so that it can be placed and oriented accordingly. In its basic configuration, it comprises four buttons to command forward, backward, left, and right displacements and has an additional stop button. Every button includes a lighting pilot. Specific user interfaces have been allowed by our system. In particular, we provided single or dual button interfaces in combination with scanning approaches where the children were unable to cope with the standard interface.

  The educator board is comprised of a display and buttons used to configure the driving mode. The system is programmed so that five driving levels are available, from lower to higher child intervention (higher to lower vehicle autonomy).

  Besides of driving modes, the system allows for different driving speeds, driving time, minimum time between consecutive button pressings, ressing time, and scanning intervals.
- Obstacle system detection

  For the obstacle detection system, various technologies were evaluated, i.e., vision cameras, laser sensors, and IR sensors. Eventually, ultrasonic sensors were selected because of their relative simplicity (in terms of system configuration and signal processing capability) and for the intrinsic possibility of obtaining range information to obstacles and the possibility of configuring independent detection lobes without additional angular scanning.

  The detection principle is based on computing the time of flight between transmitted ultrasonic waves and received echoes, using specific algorithms for detecting the start



a) b)

Fig. 3. User and educator interfaces

of the echo signal. Concretely, a fast model-based algorithm for ultrasonic range measurements has been designed and evaluated an error estimation lower than 0.5 centimeter, Raya et al. (2008). The algorithm is based on the mathematical model of the ultrasonic envelope signal.

An architecture based on a digital signal processor (dsPIC) has been implemented to excite the ultrasonic transducer with a burst of 40 kHz composed of a pulse train. A set of seven ultrasonic sensors is placed around the vehicle. Each ultrasonic transducer works as both an emitter and a receiver. To reduce the effect of the dead zone (time period in which sensors cannot accurately detect the target) the number of exciting pulses is alternated between 5 and 15. Using 5 pulses, the system can detect obstacles close to the vehicle ($< 20cm$). Using 15 pulses, the system is capable to detect small obstacles such as chair legs.

3.3 Software tool for capturing and analysing the driving task

A distinctive feature of the PALMIBER system is the software tool to analyze the driving task. The vehicle capture the events during driving such as:

- Direction button pressed
- Direction proposed by the vehicle (voice message or lights)
- Time elapsed between above events (user's reaction time)
- Obstacle detection
- Driving path

All this information can be downloaded from the vehicle to the computer. The combination of these elemental events can be used to create an global evaluation function. For instance, if the user is suggested to reach a target destination, parameters such as path, time, manoeuvrability, reaction time can be captured. After several sessions, the learning progress can be evaluated. Fig. 4 depicts some screens of the software tool.

3.4 Clinical validation of the vehicle

The clinical validation of the vehicle was performed in the framework of the PALMA project, Ceres et al. (2005). In the experiments, a set of potential users was selected. The tests were carried out at Centro de Reabilitacão de Paralisia Cerebral Calouste Gulbenkian (CRPCCG) in Lisbon, Portugal. The criteria for selection included:

- Age range of 3 to 7 years, according to the recommendations for use of similar toy vehicles

Fig. 4. Software tool for analyzing the driving task

- degree of mental retardation and difficulty in communication as well as mobility
- no previous experience of independent mobility

A total of 28 clinical trials were conducted on the various subjects. All clinical trials were recorded on video tape for subsequent through analysis. Each trial had a total duration of 15 minutes; 10 minutes were dedicated to free navigation around the classroom. This initial period was to allow the children to grow accustomed to the new navigation level so they would feel confident in driving the vehicle. Three minutes were dedicated to goal-oriented navigation (with increased difficulty according to the dexterity and navigation level). Targets were varied from passing through doors to delivering objects to friends in the classroom. Two additional free navigation minutes were allowed afterwards.

The analysis of results comprised both qualitative and quatitative parameters. Qualitative parameters (degree of stress and excitation, for example) were used to evaluate the attitude of children when using the rehabilitation tool. Quantitative parameters (number of uprising steps in the driving mode) give a direct measure of how the children increase their autonomy level in driving the vehicle.

The results showed that the learning process enabled the children to progress to more complex driving modes, even when the progress rate was different from user to user. The proposed method has a high impact on the cognitive development of the users, which together with its open and flexible structure makes PALMA an innovative and attractive rehabilitation tool.

3.5 Evaluation of the driving interfaces

The evaluation of the interaction between the child and the vehicle was performed in the framework of the PALMIBER project. The user board and a simple switch button were evaluated across the different driving modes. The tests were carried out at ASPACE Cantabria (Spain). Six children with CP were chosen. The inclusion criteria was:

- Age ranged between 18 months and 12 years old.
- Severe or moderate (only U1) motor disorder. Four limbs affected.
- No visual impairments

Table 3 collects the number and duration of the sessions. Table 2 shows the motor disorder profile of the users. Table 4 summarizes the proposed tasks according to each driving mode.

User	Motor disorder description
U1	Spastic and athetoid tetraplegia with extensor hypertonia. Bimanual grasp and moderate intellectual disability.
U2	Athetoid tetraplegia with flexor hypertonia. Mild intellectual disability.
U3	Spastic tetraplegia. Possible assisted manipulation requiring trunk fixation. Several attempts to reach objects. Severe intellectual disability.
U4	Spastic tetraplegia with global hypotonia. Grasping skills although requiring to be motivated. Severe intellectual disability.
U5	Mixed tetraplegia. Central spasticity and dystonia-athetosis in upper limbs. Severe intellectual disability.
U6	Spastic tetraplegia with global hypotonia. Lack of cervical and trunk control. Reaching and grasping with left hand. Severe intellectual disability.

Table 2. Motor disorder profile of the users

User	N^o sessions	Duration
U1	4	10-15 minutes/session
U2	4	10-15 minutes/session
U3	4	15-20 minutes/session
U4	9	15-20 minutes/session
U5	9	15-20 minutes/session
U6	12	10-15 minutes/session

Table 3. Number and duration of the sessions

Driving mode	Task description
Autonomous	First contact with the vehicle.
Cause-Effect	Driving across the room motivating the child to press any button
Training of the direction	Driving across the room motivating the child to press the suggested key (by voice and lights).
Decision of the direction	Driving the vehicle to pass between two obstacles

Table 4. Proposed tasks according to each driving mode.

- User U1. As expected, U1 presented the best results of interaction with the user board. This is coherent because his motor disorder has been characterized as moderate.

  He started at level 1 but he reached rapidly the level 2. His average reaction time was 3.5 seconds and success (press the suggested key) percentage was 100%. In the level 3, the user was capable to correct the trajectory to reach the two obstacles. Nevertheless, the corrections were influenced by the delay between action planning and execution. As conclusion the user board is an usable interface for U1.
- User U2. U2 started at level 1 (Cause-effect). The user held his hand on the user board. It facilitated the task because the reaching movement was not necessary. As result, the

reaction time was about 3 seconds with 92% of success. In level 2, the user had to press left and right buttons alternatively. In this case, the user could not hold his hand on the board because the task required to perform reaching movements. The average of the reaction time was 9 and 16 seconds for left and right respectively. As a consequence of motor disorders, the user could not reach more advanced driving modes.

- User U3. U3 started at level 0 and continued at level 1 (Cause-effect). U3 used a simple switch because according to the therapists, the direction board was not usable for him. The average reaction time was 9.6 seconds using the switch. The cognitive disability impeded to advance on driving modes.
- User U4. U4 started at level 0 and continued at level 1 (Cause-effect). At the beginning, U4 used the direction board and the success percentage was very low (65%). For this reason, the user start to use the simple switch. The reaction time and success percentage were 93% and 17.5 seconds using this interface. As result, the switch results more usable for this user. The cognitive disability impeded to advance on driving modes.
- User U5. The results for U5 were very similar to U4. U5 started at level 0 and continued at level 1 (Cause-effect). The success percentage was 63.5% with the direction board. The reaction time and success percentage using the simple switch was 13.6 seconds and 96% respectively. The cognitive disability impeded to advance on driving modes.
- User U6. The results for U6 were very similar to U4 and U5. U6 started at level 0 and continued at level 1 (Cause-effect). The success percentage was 52.67% with the direction board. The reaction time and success percentage using the simple switch was 9.2 seconds and 95% respectively. The cognitive disability impeded to advance on driving modes.

The findings shows that people with mild voluntary control of their upper limbs (U1) could drive the vehicle, whereas people with severe motor disorders present meaningful limitations. The simple switch is an alternative solution. In fact, this device is commonly used to access to other assistive devices such as computer. However, new technologies can be useful to create novel interfaces more adapted to user's needs.

A review of person-computer interfaces focused on people with cerebral palsy is presented in the following section. Our goal is to identify the shortcomnigs of the current person-computer interfaces and propose a novel solution to reduce them.

4. Human-computer interfaces focused on CP

Davies et al. (2010), published a systematic review on the development, use and effectiveness of devices and technologies that enable or enhance self-directed computer access by individuals with CP. The study showed that twenty-four studies had fewer than 10 participants with CP, with a wide age range of 5 to 77 years. International standards exist to evaluate effectiveness of non-keyboard devices, but only one group undertook this testing. Authors concluded that access solutions for individuals with CP are in the early stages of development.

The access solutions for individuals with CP can be divided into: 1) pointing devices, 2) keyboard modifications, 3) screen interface options, 4) Speech-recognition software and 5) Algorithms and filtering mechanisms.

Touch screens, Durfee & Billingsley (1999), switches with scanning approaches, Man & Wong (2007) and joysticks, Rao et al. (2000), are examples of pointing devices. The eye and face

tracking systems have been widely researched in the last years, Betke et al. (2002); Mauri et al. (2006). Eye and gaze-based interfaces have the potential to be a very natural form of pointing, as people tend to look at the object they wish to interact with. Moreover, they do not require the user to wear any thing in contact with the body. In these approaches the system can track either the movement of the head, or the pupil's movement relative to the head. In the last case, the user's head must remain fixed in relation to the camera position. This is an critical aspect if the user has involuntary movements.

As regards the keyboard-based solutions, some studies have demonstrated that modifications improve speed and accuracy, Lin et al. (2008); McCormack (1990). Screen interface refers to scan through screen icons or change dinamically the icon position. Children with significant physical impairments (who are unable to point) use visual scanning and switches to select symbols. Symbol-prediction software is a method of access that involves highlighting a specific symbol within an array on the basis of an expected or predicted response, Stewart & Wilcock (2000). The prediction software reduces the response time required for participants but there is a trade-off between speed and accuracy.

Some devices are voice-based human computer interfaces in which a set of commands can be executed by the voice of the user. Speech-recognition software is difficult to customize for users with CP who have dysarthric speech. A combination of feedback information through auditory repeat and visual feedback may help users to reduce variability in dysarthric utterances and enable increased recognition by speech-recognition software, Havstam et al. (2003); Parker et al. (2006).

Algorithms and filtering mechanisms are focused on improving the accuracy of computer recognition of keyboard input or tracking of cursor movement. In connection with techniques to facilitate the cursor control, there are two different approaches: 1) target-aware and 2) target-agnostic. Target-aware techniques require the mouse cursor to know about, and respond to, the locations and dimensions of on-screen targets. Examples are gravity wells, Hwang et al. (2003), force fields, Ahlström & Leitner (2006) and bubble cursors, Grossman & Balakrishnan (2005). In contrast, few techniques are target-agnostic, meaning that the mouse cursor can remain ignorant of all on-screen targets, and targets themselves are not directly manipulated. Conventional pointer acceleration, Casiez et al. (2008), is by far the most common target-agnostic technique, one found in all modern commercial systems. Wobbrock et al. (2009), have designed an algorithm that adjusts the mouse gain based on the deviation of angles. However, the results showed general conclusions for all participants in which cerebral palsy was included among other disabilities such as parkinson or Friedreich's ataxia. Some mathematical analyses showed that additional modelling and filters within the computer software could theoretically improve icon selection when using a mouse as the input, but this was not tested in real time with participants, Olds et al. (2008).

Although there are many developments for disabled people in general, there are few evidences from motor disabled community using these alternative interfaces, Bates & Istance (2003). Moreover, most of the authors of access solutions affirm that the usability decreases dramatically when user suffers a severe motor disability. Our goal is to create an access solution that takes into account the particular limitations caused by the motor disorders. The first step will be to characterize the limitations of the user. The second step, will be to design filtering strategies to reduce the limitations.

5. Inertial human-computer interface for people with CP

5.1 The ENLAZA device

The novel interface proposed, called ENLAZA, is addressed to people with pathological movements, which involve voluntary and involuntary movements, such as tremor or spasms. The interface is based on inertial technology which will be useful to extract kinematic patterns of the voluntary and involuntary movements. Although all areas of the motor function are limited, limbs are usually more affected than the head motion in infants with CP, Wichers et al. (2009). Hence, the inertial interface ENLAZA is a head mounted device.

The interface consists of a headset with a commercial helmet and an inertial measurement unit (IMU), Fig. 5. The IMU (developed by the collaboration between the authors and Technaid S.L.) integrates a three-axis gyroscope, accelerometer and magnetometer. A rate gyroscope measures angular velocity by measuring capacitance and it is based on the Coriolis force principle during angular rate. The accelerometer measures the gravity and the acceleration caused by motions (by Hookes law). The magnetometer measures the earth magnetic field. The 3D IMU is based on MEMS technology and is available in a package measuring 27x35x13mm and its weight is 27 grams which is less than other sensors used in the field Rocon et al. (2005), Roetenberg et al. (2005). The 3D IMU is capable of sensing +/- 2.0 gauss, $+/-500^o/s$ angular rate and +/- 3g acceleration about three axes independently. It has an angular resolution of 0.05^o, a static accuracy less than one degree and a dynamic accuracy about 2^o RMS.

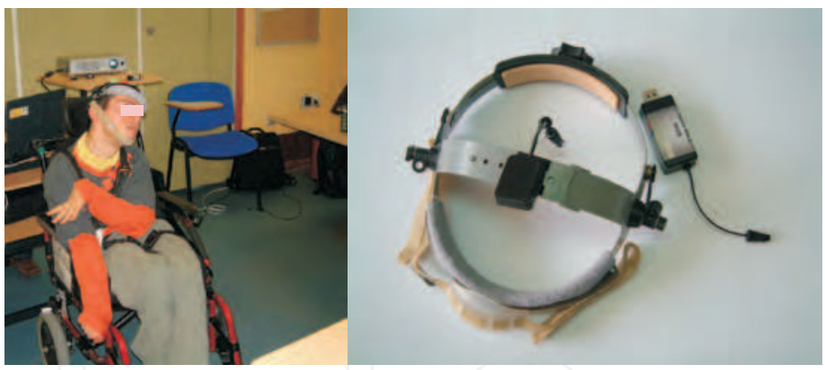


Fig. 5. Inertial interface ENLAZA

The interface ENLAZA translates the head rotations into cursor displacements. The Euler angles give the information about the rotation around the three axes (α, β and γ, rotations frontal, sagital and tranversal respectively). The calibration process gives the information to estimate the vertical and horizontal angular ranges (θ_v and θ_h). It consists of looking at three points on computer's screen (left-up, right-up and center). The Euler angles can be calculated following the next equation:

$$\begin{aligned} R_{GS} &= R_s \cdot (R_G)^{-1} \\ \alpha &= \arctan(-R_{GS}(2,3)/R_{GS}(3,3)) \\ \beta &= \arcsin(R_{GS}(1,3)) \\ \gamma &= \arctan(-R_{GS}(1,2)/R_{GS}(1,1)) \end{aligned} \tag{1}$$

where R_G is the orientation matrix corresponding to center position and R_s is the orientation matrix at each frame. The pointer position can be calculated with the following equations:

$$\begin{aligned} x &= \gamma \cdot W/\theta_h \\ y &= \beta \cdot H/\theta_v \end{aligned} \tag{2}$$

where W and H are the screen width and height respectively.

The inertial interface was technically validated by five healthy users, Raya et al. (2010). The metric used was the Throughput defined by the ISO 9241-9 "Requirements for non-keyboard input device". The result was 2 bits/s which was found in agreement with other similar devices presented in the literature, Music et al. (2009).

An important distinction must be made respect to interfaces in the literature because the basis principle of the ENLAZA interface is to know the motor limitations of the user and adapt its performance to them. The device intends to be versatile and adaptable to different ranges of motion, postures and velocities. This aspect is considered to be essential because of the heterogeneous alterations caused by CP.

5.2 Characterization of cervical motor disorders using the inertial interface

The aim of the work presented in this section is to characterize the cervical motor disorders of people with CP using the inertial interface. The information extracted from these experiments will be used to design the filtering techniques to reduce the effect of the involuntary movements on the control of the ENLAZA interface.

Four people with severe CP were recruited (Table 5). Their mean age was 29 years (range: 26-35), Raya et al. (2011). They cannot control mouse pointer or keyboard. 3 healthy users participated to extract the normalized patterns for comparison. Tests with CP people were carried out in ASPACE Cantabria (Santander, Spain). ASPACE Cantabria has expertise in using some alternative devices as eye-tracking interfaces. Tests with healthy users were carried out in Bioengineering Lab CSIC (Madrid, Spain).

Subject	Motor Function Characteristics		
	Cervical tone	General tone	Associated movements
CP1	Extensor hypertonia	Extensor hypertonia	Athetosis
CP2	Dystonia	Distonia	Ballistics
CP3	Hypotonia	Hypotonía	No
CP4	Hypotonia	Dystonía	Dystonia

Table 5. Motor characteristics of participants with CP

The trial required participants to look at an on-screen target and dwell on it for selection. Then, the target changed its position following a sequential order. Participants were instructed to locate the cursor over the target as quickly as possible using head motion. There were 5 sessions during a week using an inertial pointing device. The kinematic data were recorded during the trial. The experiment consisted of reaching the target 15 times. This trial was repeated during 5 days one time per day. Therefore the target-reaching task was carried out 75 times in total. The target-reaching task is attractive because it provides a statistical description

of the involuntary movements made during voluntary activity. The metrics to quantify the motor disorder were analyzed in three domains: 1) Time, 2) frequency and 3) space.

The analysis according to these three domains concluded the following statements:

- Kinematic analysis showed characteristic patterns for hypertonia and hypotonia disorders.
- Hypertonia (high muscle tone) causes involuntary movements at higher peak frequency (1.3Hz) than voluntary movements (0.3Hz).
- Hypotonia (low muscle tone) is characterized by abnormal postural activity. The frequency of hypotonic movements (0.3Hz-0.6Hz) is considerably similar to the frequency of voluntary motion.
- Voluntary and involuntary motion are combined at the same bandwitdh.
- The spatial-domain analysis showed that the unbalanced sagittal rotation was clearly wider respect to frontal and transverse, especially for hypotonic cases. It might be explained because the pull of gravity makes difficult to hold his head up.
- While hypertonia affects more to fine motor skills, hypotonia affects more to gross motor skills.
- Time-domain analysis revealed characteristic intention components with markedly increasing difficulties to control the pointer accurately around the target region.
- There was an association between motion frequency and capacity to maintain the trade-off between speed and accuracy.

Fig. 6 depicts the differences between voluntary and involuntary motor control in time domain. Fig. 7 compares the spectrogram of a healthy user with the spectrogram of a person with CP (CP1). Finally, Fig. 8 illustrates the range of motion for a healthy user and a person with cervical hypotonus (CP3) in which the head drops forward because of the gravity effect is evidenced.

6. Filtering algorithms to reduce the effect of the motor disorders

6.1 Joystick mode

Using the joystick mode can be a simple way to filter the involuntary movements. In this mode, pointer increases its position step by step according to the head pose. Fig. 9 illustrates this control mode. For instance, user looks at the grey area to stop the pointer. User looks at the red region to move the pointer towards the right direction.

Click task is easier using this mode because it is not necessary that user hold his/her head in an acurate position, only in a certain range.

6.2 Adaptive filters

The aim of the filtering techniques is to improve the target adquisition for users with CP. The conclusions described in the section 5.2 will be considered to design the adaptive filter. On one hand, filters based on separating frequency bands are not adequate because voluntary and involuntary movements are within the same bandwitdh. This fact eliminates simple low-pass filters.

Fitts' Law, Fitts (1954), models the voluntary motor behaviour in a reaching task. The reaching task consists of an initial movement that rapidly covers distance and a slower homing in

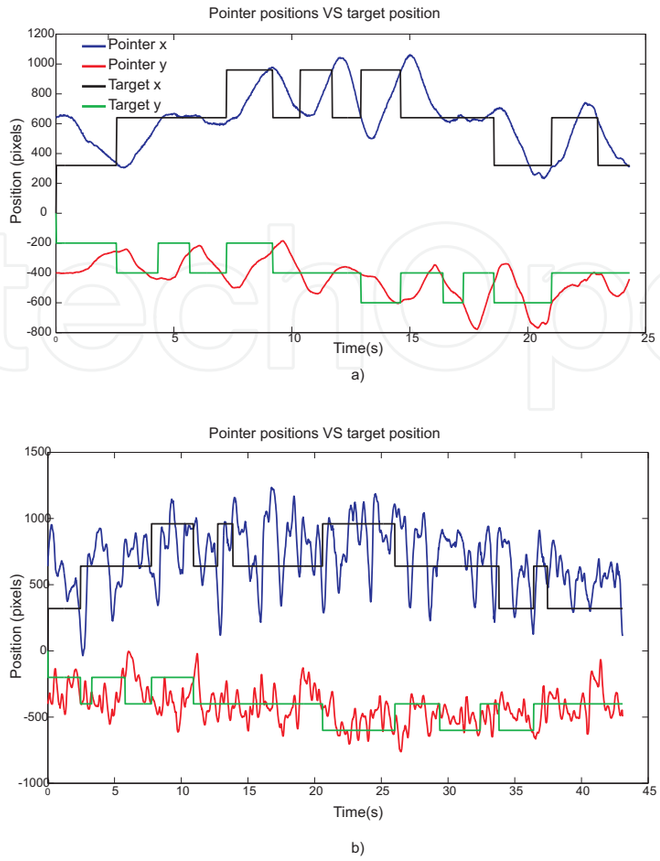


Fig. 6. a) Pointer versus target positions (healthy subject), b) Pointer versus target positions (user with cervical hypertonia (CP1))

phase. The results showed that people with CP performed satisfactorily the initial movement with increasing submovements around the target region.

The proposed hypothesis states that long trajectories correspond to the initial movement (high probability of voluntary component) and rapid changes (generally performed around the target region) are undesirable. As consequence, the filter should have a dynamic gain adaptation related to the deviation of the cursor trajectory.

Adaptive filters are time-varying since their transfer function is continually adjusted driven by an reference signal that depends on the application. The general block diagram of adaptive filtering implementation consists of the prediction and update steps as depicted by figure 10.

The parameter k is the iteration number, $x(k)$ denotes the input signal, $y(k)$ is the output signal and $d(k)$ defines the desired signal. The error signal $e(k)$ is the difference between $d(k)$ and $y(k)$. The filter coefficients $W(k)$ are updated as stated by the error signal.

The equation parameters can be adjusted to track the movements of the mouse pointer. In some cases, the algorithms to track mouse positions assume a constant speed movement model. This assumption is reasonable since that sample period is very small compared with the movement speeds, Brookner (1998), i.e., the sample period adopted was $20ms$ and the

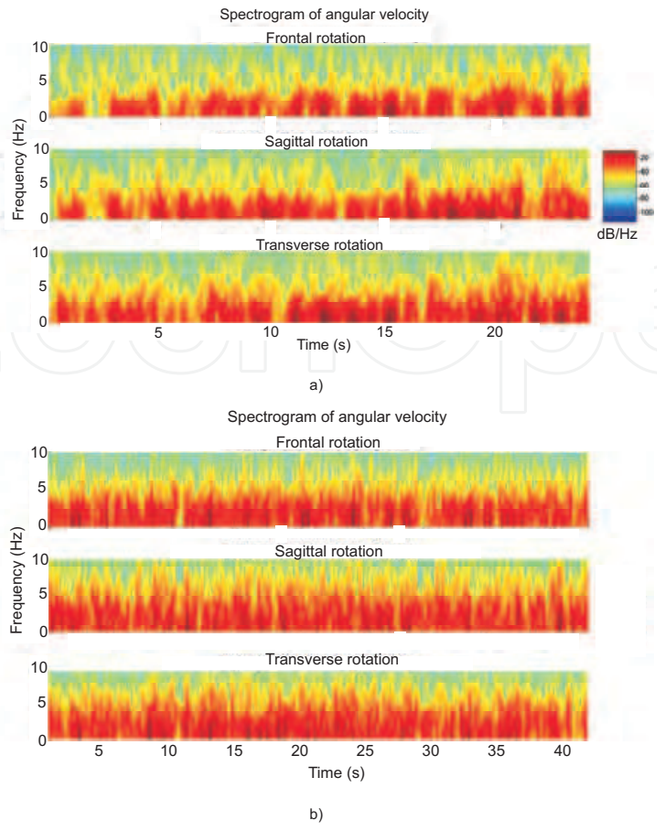


Fig. 7. a) Spectrogram of a healthy subject, b) Spectrogram of a person with cervical hypertonia (CP1)

voluntary movement estimated occurs in a bandwidth lower than 2Hz (75% of the power spectral density, Raya et al. (2011)).

The g-h filter (sometimes called α-β filter) is a simple recursive adaptive filter. It is used extensively as a tracking filter. The g-h algorithm consists of a set of update equations:

$$\dot{x}^*_{k,k} = \dot{x}^*_{k,k-1} + h_k \left(\frac{y_k - x^*_{k,k-1}}{T} \right) \tag{3}$$

$$x^*_{k,k} = x^*_{k,k-1} + g_k \left(y_k - x^*_{k,k-1} \right) \tag{4}$$

and prediction equations, Brookner (1998):

$$\dot{x}^*_{k+1,k} = \dot{x}^*_{k,k} \tag{5}$$

$$x^*_{k+1,k} = x^*_{k,k} + T\dot{x}^*_{k+1,k} \tag{6}$$

The tracking update equations or estimation equations (equations 3 and 4) provide the mouse pointer speed and position. The predicted position is an estimation of x_{k+1} based on past states and prediction, equations 5 and 6, and takes into account current measurement using updated states. T is the sample period and the parameters g_k and h_k are used to weight the measurements.

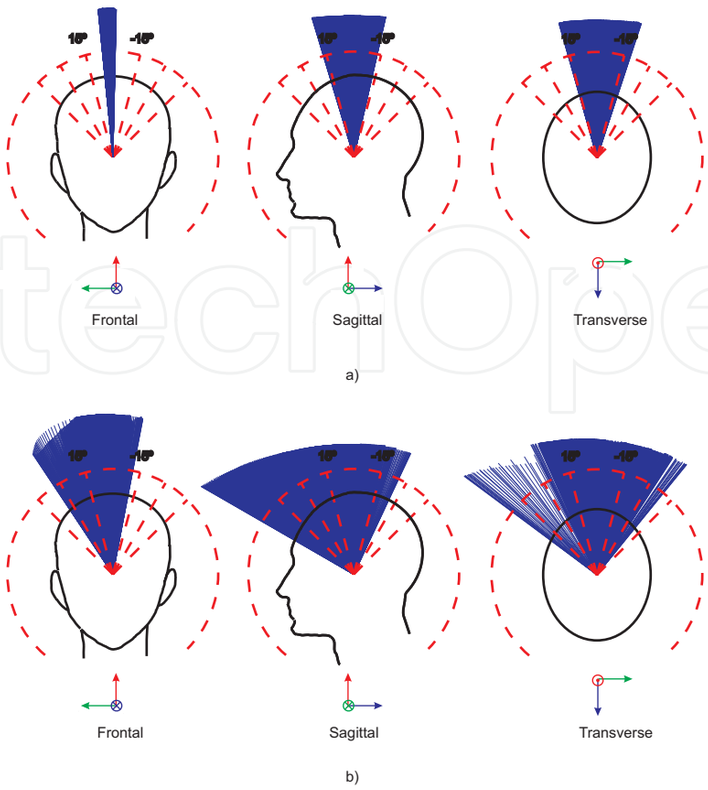


Fig. 8. a) ROM of a healthy subject, b) ROM of a person with cervical hypotonus (CP3)

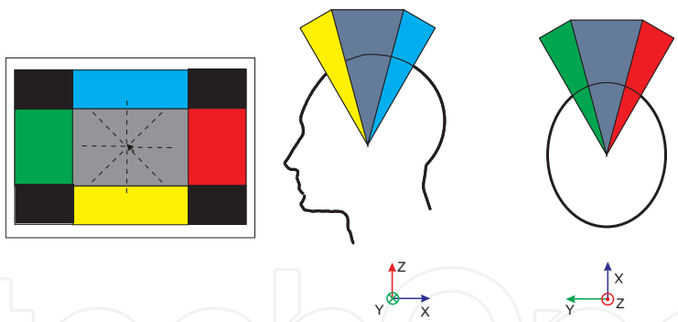


Fig. 9. Control space of joystick mode

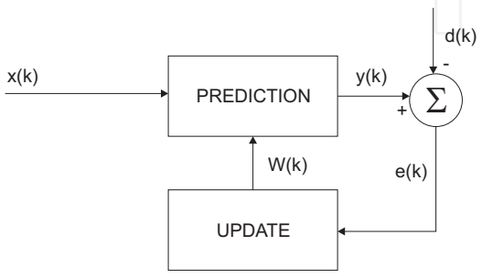


Fig. 10. Block diagram of adaptive filtering implementation

Benedict Bordner filter, Benedict & Bordner (1962), and Kalman filter are adaptive filters commonly used in tracking applications. These algorithms were successfully applied by some authors for tremor suppression, Gallego et al. (2010); Pons et al. (2007); Riviere & Thakor (1998.). The purpose of this investigation is to determine the feasibility of using these adaptive filters for reducing the motor disability effects caused by CP. In addition, we propose a *robust Kalman filter* that improves the performance of the classic kalman because it has been designed to detect outliers.

The performance of these algorithms was compared based on a kinematic descriptor called *segmentation*, McCrea & Eng (2005). The *segmentation* is a useful metric to estimate the corrections or submovements performed during the target-reaching task. Firstly, the function "remaining distance to the target versus time" is calculated. Secondly, the maxima of this function are calculated corresponding to movements performed in opposite direction relative to the target. Figure 11 illustrates an example of segmentation.

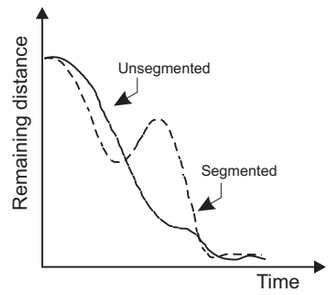


Fig. 11. Segmentation: Kinematic descriptor of the improvement introduced by the adaptive filter

6.3 Benedict-Bordner filter (BBF)

The Benedict-Bordner estimator is designed to minimize the transient error. Therefore, it responds faster to changes in movement speed and is slightly under damped, Bar-Shalom & Li (1998). The relation between filter parameters is defined by equation 7:

$$h = \frac{g^2}{2-g} \tag{7}$$

g-h gains are manually selected and static.

6.4 Kalman filter (KF)

The application of a Kalman filter requires that the dynamics of the target is represented as state space model, Kalman (1960). A simple kinematics approach based on the assumption of constant velocity process is suggested by some authors, , and is shown to track voluntary movements correctly. Figure 12 illustrates the block diagram of the Kalman filter.

The main difference respect to g-h filters is that a Kalman filter uses covariance noise models for states and observations. Using these, a time-dependent estimate of state covariance is updated automatically, and from this the Kalman gain matrix terms are calculated.

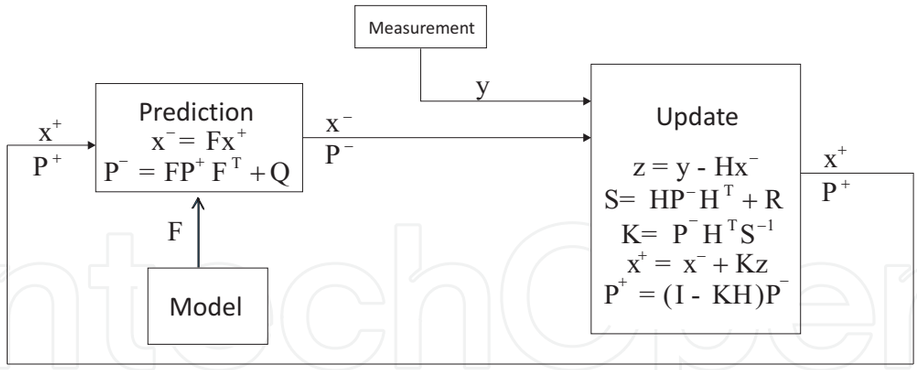


Fig. 12. Block diagram of the Kalman filter

6.5 Robust Kalman filter (RKF)

The Kalman filter is commonly used for real-time tracking, but it is not robust to outliers. The submovements around the target region caused by motor disorders can be considered as outliers respect to the constant velocity model (voluntary model). In our application, it is difficult to define a complete model of the pathological patterns because they are not repetitive. We propose to establish a model of voluntary model and consider the observations that lie outside the pattern of normal distribution as outliers. Using RKF, to the normal distribution containing the variances for the observations a second normal distribution is added which has larger variances than the first.

The robustification is based on the methodology of the M-estimators by following Huber's function, Huber (1981). The difference between the measurement and the estimation is weighted according to this Huber's function. For scalar observations, the Huber's function ψ_H of the form, Cipra & Romera (1991):

$$\varphi(Kz) = Kz \cdot min(1, b/|Kz|)$$

where $|Kz|$ is the euclidean norm. Figure 13 illustrates the Huber's function. Figure 14 depicts

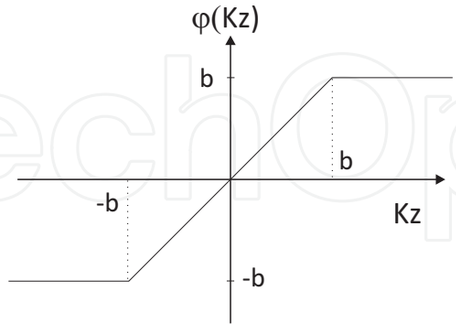


Fig. 13. Huber's function

the block diagram of the robust Kalman filter. The result is a very easy implementation and simple derivation of classic Kalman algorithm that includes the detection and elimination of undesirable data by an iterative downweighting of the outlying observations within the method of least squares.

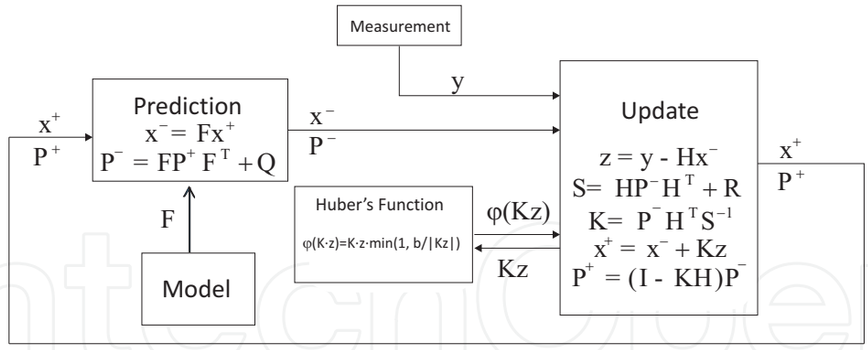


Fig. 14. Block diagram of the robust Kalman filter

6.6 Evaluation of the adaptive filters

The filtering algorithms BBF, KF and RKF were applied offline to the previously captured data. The kinematic data were registered during the experiments described in the section 5.2. The task consisted of reaching 15 targets which changed sequentially their location once reached (locate the pointer over the target). The task was repeated during five days. As result, a total of 75 reaching tasks were registered and post-processed.

The segmentation of the movement will give interesting information about the number of submovement. It is expected that the reduction in the number of submovements will improve the fine control being a critical aspect in the target adquisition for people with CP. Segmentation is estimated calculating the number of local maximums separated by 200ms of the function "Remaining distance versus time". The average of submovements was $M = 1.41(STD = 0.18)$ for healthy subjects. As expected, results showed higher number of submovement for participants with CP where the mean was about 8 submovements for CP1, CP2 and CP3 and slightly higher for CP4. Table 6 summarizes the number of submovements without and with filtering application. All filters considerably reduce the number of submovements reaching about a 65% of reduction.

User	Filtering algorithms %(Mean(std))			
	Without filter	BBF	KF	RKF
CP1	7.92(1.26)	4.83(0.96)	3.93(0.70)	3.5(0.77)
CP2	8.06(3.38)	3.97(1.71)	3.10(0.98)	2.83(0.85)
CP3	7.82(1.54)	4.08(1.22)	3.04(0.77)	2.77(0.76)
CP4	14.35(8.07)	7.02(4.09)	4.73(2.42)	4.64(2.39)

Table 6. Segmentation during the target-reaching task

The effect of the filtering techniques can be graphically shown. Figures 15b, 15c, 15d depict the target-reaching path without and with filtering for BBF, KF and RKF filters. Table 6 demonstrates that RKF filter had the best performance followed by KF and BBF filters.

BBF responds faster to changes in movement being able to filter movements of high frequency. However, in our application voluntary and involuntary movements can appear combined within the same bandwitdh. The detection and elimination of outliers (submovements) result useful for our application. The gain filter is modulated in real-time being lower during straight paths in which the prediction error is smaller. By means of outliers suppression and the dynamic filter gain, the initial movement that rapidly covers distance is smoothly filtered

whereas the movements around the target are strongly filtered. As consequence, the fine control is facilitated.

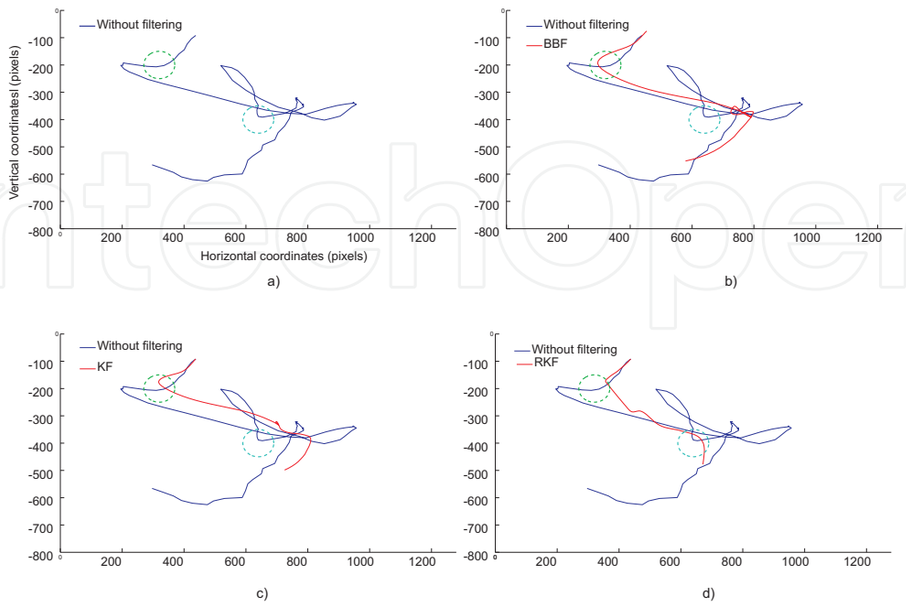


Fig. 15. Pointer path a) without filtering b) with BBF c) with KF d) with RKF

7. Functional evaluation of the ENLAZA interface as input device for computer

Once the filtering algorithm has been designed and validated technically, the ENLAZA interface and the filtering technique must be validated by people with CP. Three of the four people who participated in the experimentation described in section 5.2 participated. One of them, user CP2, could not participate because he was not in the centre ASPACE Cantabria when these trials took place. The table 5 summarized the motor profile of these users.

The task consisted in reaching 15 targets which changed their position once reached. One important difference respect to the experimentation described in section 5.2 was introduced: it is necessary to click on the target for the selection (not only crossing as in section 5.2). In this way, the reaching and the selection is evaluated, that means, the normal operation when using the computer. The condition for selection was to remain the pointer on a region of 60 pixels during 3.5 seconds. A pointing magnifier tool was used to facilitate the selection. The pointing magnifier has been developed by the AIM Research Group (University of Washington), Jansen et al. (2011). It was used by CP3 and CP4. CP1 had better results without it.

The metric used was the reaching time. The following three methods were compared:

- Target-reaching task without filter
- Target-reaching task with robust Kalman filter
- Target-reaching task using joystick mode

Table 7 summarizes the reaching time for each user and method. The main difference is observed in CP1. The adaptive filter RKF reduces about 10 times the reaching time.

Fig. 16. Experiments with the ENLAZA interface at ASPACE Cantabria

As described in section 5.2 the fundamental frequency of CP1 is higher than voluntary movement. The filter reduces the effect of the movements of high frequency, so that, the fine control is improved. The reduction was 2 times for CP3 and CP4 (hypotonus cases). According to the results of section 5.2, the correlation with the voluntary motor control was higher for hypotonus cases. Therefore, the effect of filter is smaller. The joystick mode also facilitates the control. However, although the click task is facilitated, the reaching task can be considerably slower. RKF presents a better trade-off between reaching and selection. Fig. 16 depicts the a picture of the experiments at ASPACE Cantabria. In conclusion, the inertial

User	Methods (%(Mean(std)))		
	Without filter	Joystick mode	RKF
CP1	109(10.98)	15.67(11.70)	8.67(4.78)
CP3	44.16 (34.77)	19.23 (6.74)	18.08(14.82)
CP4	43.26 (37.30)	39.97 (21.26)	17.43 (12.20)

Table 7. Reaching time (seconds) for each user and method

interface ENLAZA is usable as input device for the computer. People with severe limitations to access to conventional interfaces such as mouse and keyboard could access to the computer with an average reaching time between 8 and 18 seconds. Robust Kalman filter facilitates the target adquisition reducing the effect of the involuntary movements on the control.

8. Functional evaluation of the ENLAZA interface as input device for driving the PALMIBER vehicle

As described in section 3.5 some children with adequate cognitive development could not advance on driving modes because of their physical disability. It was the case of U2. The aim of the work presented in this section is to evaluate how the ENLAZA interface can help to drive the vehicle PALMIBER.

The control mode was based on controlling the movement of the vehicle with the head's rotations. The first step consisted of a calibration process to set the reference. Later, the γ angle controlled the turns of the vehicle and the β angle controlled the forward and backward movements.

U2 participated in these experiments. U1 could not participate. U3-U6 did not participate because of their cognitive disability impeded the adquisition of spatial concepts.

Fig. 17. Driving task analysis with the software tool

Fig. 18. Experiments of the ENLAZA as input device for driving the PALMIBER vehicle at ASPACE Cantabria

Nevertheless, U2 is a characteristic case because he knows the spatial concepts but his physical disability limit the capacity to drive the vehicle.

U2 started at the level 1 (Cause-effect). The reaction time was about 3 seconds being very similar to the result with the user board. Following, the driving mode 2 (left-right) was proposed. The average time was 4.2 seconds for both directions. This is a meaningful result compared to the reaction time using the user board (9 and 16 seconds, left and right directions respectively).

Finally, U2 was proposed to perform a functional task consisted in reaching a target destination (level 3). Fig. 17 illustrates an example of the path executed to reach the point. Although, some deviations respect to the ideal path exist, the user reached the goal in a relatively short time. The result is meaningful because U2 could not select the directions with the keys of the user board. Additionally, the control of the directions using the head is more intuitive than pressing button with arrow symbols. This user cannot control a conventional joystick, for instance to control his wheelchair. Therefore, it is expected that the inertial interface can control other types of assistive devices. Fig. 18 depicts a picture of the experiments at ASPACE Cantabria.

9. Conclusions and future work

The aim of this work was to study, design and validate new strategies for mobility and interaction of people with CP. A review of the mobility devices for CP showed that there are a few devices specifically focused on the integral development of the child. A robotic vehicle to promote the integral development of children with CP has been presented. The vehicle design is versatile and open to adapt to the wide variability of motor and cognitive alterations caused by CP.

Generally, human-machine interaction is a critical aspect in people with CP. Recently, many research groups are studying new channels of interaction. There are different advanced solutions for people who cannot use conventional interfaces. However, most of the authors affirm that the usability decreases dramatically when user has a severe motor disability. We proposed a new interface based on inertial technology. The inertial interface allows to characterize the pathological motion of the user. This characterization is an useful information to know the skills and limitations of users in order to create strategies to help them.

A new filtering algorithm (robust Kalman filter) has been designed and validated to reduce the effect of the involuntary movements on the control of the device. Using this approach, the submovements around the target region are reduced and the fine motor control is facilitated. The inertial interface was validated as input device for the computer by users with CP.

Finally, the inertial interface was validated as input device for driving the vehicle. Using this device, the delay between the action planning and its execution is reduced. As result, the user can control the direction of the vehicle and correct the path in the desired instant. Additionally, the relation between movement direction and the symbol on the board requires abstraction which can result difficult for these users. The head's rotation is an more intuitive method of control.

The future work will be focused on:

- increasing the number of subjects
- testing the interfaces with people with other disabilities (e.g. stroke, spinal cord injury)
- testing the filtering algorithm with other interfaces (e.g. eye or face tracking)
- testing the interface with real software applications
- evaluating the learning progress of children on the use of the vehicle in long term

10. Acknowledgment

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