A New Approach for Operating Powered Wheelchairs by People with Severe Impairments

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***Abstract* - This paper discusses the introduction of mechanisms to adapt commercial powered wheelchairs in order to facilitate its driving by people with severe impairments. Several models of operation are proposed and the most promising, at the moment, called legacy adapted mode, is detailed. A part of the formal operation model is presented. The model is then used in the STAGE simulator, not only for its evaluation, but also to tune operational parameters that will be specific of each patient and to train the patients without a real wheelchair.**

I. INTRODUCTION

A joystick is the primary interface between a person with disability and a commercial powered wheelchair (CPW). While the needs of many people with disabilities can be satisfied with standard manual or powered wheelchairs, a segment of the disabled community finds extremely difficult or impossible to use a CPW for activities of daily living [1]. This is because they haven't the motor skills to effectively operate the conventional joystick. This is the case, for example, of some patients with quadriplegia. So, devices like smart wheelchairs can provide navigation assistance to the user.

When designing a smart wheelchair, the adaptability to the individual and the fulfillment of safety requirements must be considered [2]. Also, indoor or outdoor environments will pose different requirements.

In this work, a new architecture for an assistive powered wheelchair (APW) is proposed in order to provide an effective and safe control of the APW for people who haven't enough strength to operate the joystick. The goal is to adapt each APW, tuning it to each individual.

This new proposal differs from previous work [3] in two aspects: a new version of the Legacy Adapted Mode (LAM) operation that arose from the need to adapt the LAM to a particular type of patients and the presentation of some experimental results.

This paper is organized as follows: section 2 discusses the motivation, section 3 includes a review of related work, section 4 describes the operation of the APW; section 5 describes the legacy adapted operation mode, section 6 shows how Stage is used for validation and parameter set-up, section 7 presents some simulation results and section 8 concludes the paper and describes the work in progress.

II. MOTIVATION

The functionality of a person's body following spinal cord injury will depend on the level of injury, and whether it was complete or incomplete. Quadriplegia or tetraplegia is when a person has a spinal cord injury above the first thoracic vertebra; this usually affects the cervical spinal nerves resulting in paralysis of all four limbs. This may result in partial or complete paralysis of the arms as well as complete paralysis of the legs [4]. These patients need a wheelchair to obtain mobility and, in the majority of the cases, they aren't able to use a manual wheelchair. The joystick is the primary interface between a person with disability and a CPW and, to be able to use it, the user must have the motor skills to operate a conventional position joystick.

The CMRRC-RP -"Centro de Medicina e Reabilitação da Região Centro- Rovisco Pais"- in Portugal is a centre of rehabilitation for disabled persons, most of them with a spinal cord injury. The clinicians of this centre are not only concerned with the rehabilitation but also with the adaptation of the patients to their new way of life. The centre has a set of training houses in which patients are trained to use adapted facilities and assistive devices. Our team has been working there in smart houses for quadriplegic persons [5], the B-Live Project. One of concerns in this work is the patients' mobility. Patients must be able to drive a powered wheelchair when they leave the centre. Even if they are taught how to drive a CPW using their adapted skills, some of them have, however, enormous difficulties to operate the joystick.

From our work with the clinicians at the CMRRC-RP we identified a problem related with the manipulation of the CPW joystick by patients with insufficient strength in the hands. We have been working with three patients of this population. One of them is a woman that has become a C4 (this is an indication of the disability [4]) in the right arm and a C6 in the left arm. Because she can't extend the left hand and she hasn't flexion of wrist and fingers, she pushes the joystick with the back of the hand. She had already done some training in manoeuvring the wheelchair but she feels tired quickly.

The other patient was a man that is now a C3 and a C4 in the left and right arms respectively. He has great difficulty to operate the joystick not only because of inadequate positioning but also because he doesn't have enough strength to drive it continuously. He has made a few tests but he also felt very tired quickly.

The last and the only one that is currently in the center, is a man that is a C5 and a C6 in the right and left arms respectively. He can drive his powered wheelchair but he feels tired quickly.

These cases, and knowledge of similar ones, led us to learn that these patients have two kinds of problems in operating the joystick: the inadequate position of the hand and the reduced strength in the hand and arm. The inadequate position of the hand can be compensated with adaptations that may vary from case to case. Weakness is more difficult to solve and, even if they are able to operate the joystick quite a while, they feel tired soon.

According to the clinicians, the ideal solution for the problem of these people would be to navigate the wheelchair without the need of continuous driving force. This suggestion was the motivation for our research work reported here.

III. A REVIEW OF RELATED WORK

A. Smart wheelchairs

In the 90´s, smart wheelchair development has grown up in a significant way. The goal of most of the research was to design semi-autonomous wheelchairs rather than fully autonomous ones, thus designing wheelchairs for disabled people letting them to have some control over the wheelchair navigation. Thus, smart wheelchairs are able to carry on their own tasks, like guaranteeing safety, but they have to rely on the human operator desire and experience when performing some other tasks.

One of the features of the smart wheelchair is the form factor and it can be used to classify the smart wheelchairs [6]. Several researchers have used technologies originally developed for mobile robots to create smart wheelchairs. Early prototypes were actually mobile robots to which seats were added like VAHM [7] (1998) and Mister ED [8] (1990).

The majority of smart wheelchair projects are based on modified, commercially available powered wheelchairs [6]. This has been the cases of COACH [9] (1993), NavChair [10] (1999), Rolland [11] (1998), OMNI [12] (1998), Maid [13] (2001), RobChair [14] (1997), SENARIO [15] (1997), Wheelesley [16] (1995) SHARIOTO [17] (2003), SENA [18] (2006). Most of these projects lasted during several years, so the indicated date is just used to give an idea of the time scale.

Recently, a smaller number of smart wheelchairs have been designed as "add-on" units that can be attached to and removed from the underlying powered wheelchair. The SWCS, the Smart Wheelchair Component System [19] (2004), the Hephatestus Smart Wheelchair [20] (2002), the SIAMO [21] (2001) are some examples of systems that have been developed as stand-alone units that can be added to existing wheelchairs.

The variety of approaches to implement control software for smart wheelchairs depends on the functions supported, on the sensors used, and on the HMI (Human Machine Interface) used. The functions define the level of autonomy of the wheelchair. Different levels of autonomy have been achieved in order to adapt to the various disability levels of the user. So, the choice of the processing unit depends on the complexity of the algorithms or functions necessary to control the navigation of the user, guaranteeing always his/her safety.

There are smart wheelchairs completely autonomous and others semi-autonomous [6]. In autonomous navigation mode the user gives one location to go and the wheelchair has the complete autonomy to navigate to the desired location. All the navigation decisions are made by the intelligent wheelchair.

For a wheelchair to be fully autonomous it must have a lot of capacities to perform maneuvres like avoiding and contouring obstacles, wall following, door passages, at least. Smart wheelchairs are needed to help users in their mobility; the main point is to provide autonomy to the user rather than the self-autonomy of the wheelchair. So, the majority of the research groups have developed *assistive* smart wheelchairs, that means, semi-autonomous wheelchairs where the user has an important role in the decisions of path planning and in the most of the navigation responsibilities. So, there is a *shared* control between the user and the "intelligent" controller of the wheelchair.

B. Wheelchair steering joystick

The user must provide some indication of the desired speed and direction for functional driving of a CPW. As already mentioned, conventional position joystick-controlled powered wheelchairs are inappropriate for some categories of disabled people, especially, the disabled people with the high-level of spinal cord injury. Tremors, spasms, weakness and inadequate range of motion are some consequences of their disease that makes it difficult or even impossible to drive a CPW with the joystick.

This means that, for helping these people, their wheelchairs must be adapted in some way that allows them to drive the CPW in safety. This adaptation must be done considering the disability of the user. There are two alternatives for making this adaptation: the joystick remains the same and its output signal is pre-conditioned before entering the controller [22],[23] or the joystick is changed to a more appropriate one [24],[25].

Pre-conditioning can be as simple as a low-pass filter or as complex as a neural network or a fuzzy-logic [22] based system. In [23] a control system that time averages hand tremors and is unresponsive to rapid and erratic movements is presented. The signal from the joystick is amplified, rectified and then time averaged to reduce the effect of tremor on control.

In [24] a force feedback joystick is proposed. The force feedback law is a linear function of the distance between the wheelchair and the obstacles. The user is completely master of the wheelchair and the control logic makes the force feedback joystick less or more difficult to go in some direction.

An isometric joystick (IJ) requires essentially no range of motion to operate and may provide a proportional control alternative for some individuals [25].

In what concerns our work, the motivation, as said before, is that the conventional position joystick-controlled powered wheelchairs are inappropriate for disabled people with a high-level of spinal cord injury. Our work follows a similar approach of [23], i.e., the output signal from the joystick is modified before entering the motors drivers. The disabilities we are dealing with are different from [23] and thus different solutions must be derived. Also, in [23] the target is an analogic circuit and the selection of a joystick, while we are using the legacy joystick of the CPW and we will be using a microprocessor based module to implement a finite state machine (FSM) operational model.

IV. OPERATION OF THE APW

A. Overview of the APW architecture

The APW can operate in two operational modes: 1)- a legacy mode in which the joystick commands the wheelchair as it comes from the factory; 2)- an adapted mode, for whose implementation, two modules are added to the wheelchair legacy modules: the Command Interpreter System (CIS) and the AM_ON module (Fig.1).

The AM-ON module is a switch whose position can be selected by the user. It allows choosing between the legacy and the adapted mode of operation. The AM-ON interface can be a button installed near the joystick.

In the adapted mode the CIS module is in service and it becomes responsible for the support to the navigation of the wheelchair.

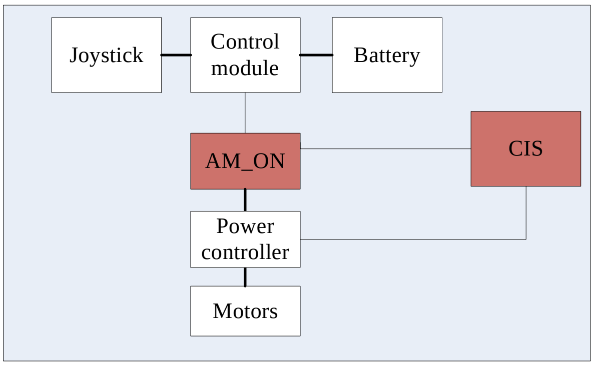

Fig.1. Architecture of the APW

B. APW modes of operation

The adapted mode provides three different modes of operation and the choice among them depends on the initial skills of the patient, the improvement of those skills after training and the manoeuvres to execute which can be less or more demanding.

The three modes are: legacy adapted mode (LAM); semi-autonomous transfer mode (SaTM); and autonomous transfer mode (ATM).

In [3] we proposed a LAM appropriate for users who have strength to give some impulses of pushing and pulling the joystick and some precision in issuing the desired direction. So they are able to make some manoeuvres like, for example, going along a corridor and they are also able to make the necessary corrections to the trajectory and to avoid obstacles. ATM is targeted for those who aren't able to drive the wheelchair in specific situations, where there is the need to make fine grained movements with the wheelchair like passing a narrow door. SaTM is targeted for users that are able to give stimuli (e.g. touches) to the joystick but are not able to give successive touches in the joystick or keep them steadily, like for example, when it is necessary to make the correction to the trajectory of the wheelchair in a narrow space.

The selection among different operation modes is made by the wheelchair users.

In all modes of operation, if, for any reason, the wheelchair collides with some obstacle, it will stop immediately due to the action of bumpers and, automatically, it returns to legacy mode.

In the current state of the work, LAM is the most developed mode and therefore the one described in more detail.

C. A novel adaptation of LAM for patients still with more severe impairments

As referred, in the work reported in [3], LAM was used by patients who could define a direction with different degrees of precision. However, during our work at the CMRRC-RP we found a significant number of patients with more severe impairments.

These patients are not able to indicate directions.

In fact, in the universe of these people, there are some able to spin to the front, others to spin to the left and to spin to the right. That means, there are some able to move the hand to the front, others to the left or right. Normally, they are able to do the movement to the back but not in a continuous way.

If, for example, someone is just able to spin to the left, the only movements that he/she is able to do are to give some impulses in the joystick to the left and to the back. So, he/she should be able to navigate the wheelchair by giving some impulses in the joystick just in those two directions, that is left and back.

So, we considered a new version of LAM in which the same movement in the joystick commands the wheelchair in two different ways: go forward or change direction. The distinction between the two movements is done by manually switching between them. This means that the patient will define the future wheelchair movement direction with the wheelchair stopped that is, just rotating without linear movement. This is done by successive interaction with the joystick using their abilities, for example spinning left as in the case described above.

After the direction is defined, then the movement is performed, in front or back, using the two joystick movements that the patient is able to perform (for example, spinning left to go in front or pushing the joystick back to go back).

It should be noticed that these patients are used to take some time in their displacements and that this solution was considered to be the most adequate by the medical doctors with whom we are working.

V. THE LEGACY ADAPTED OPERATION MODE

Concerning the legacy adapted mode of operation (LAM), we propose an interface in which the user gives a non continuous touch to the joystick in order to indicate the start and stop of the wheelchair and the displacement direction. So we define a set of variables and constants:

$m_{a:}$ a boolean variable indicating if the LAM is ON or OFF. This is done by the user and the system command can also switch to off if a safety critical situation occurs.

$c_{d:}$ a boolean variable indicating if the change direction is ON or OFF.

The stroke is defined by two variables:

t_{stroke}: a touch during a specified duration $t_{stroke}=t_r-t_a$ where $t_r > t_a$ and t_a is the instant in which the joystick is actuated in any direction and t_r is the instant in which the joystick is released.

α_{stroke}: the angle of the joystick stroke measured from 0º, being 90º the wheelchair movement direction at the instant of the stroke. In this case we can just define two very coarse values for $\alpha_{stroke,}$ for example 180º and 270º for patients that spin left.

During the navigation, the distance from obstacles is computed from sensor fusion:

d_{obs}: minimum distance from an obstacle among the distances obtained from different obstacle detection sensors positioned in the movement direction.

In what concerns constants or parameters, defined before run-time operation, we have:

T_{start}: the minimum duration of a joystick stroke to be interpreted as a command to start the wheelchair movement (protects the system from noise spikes or from spasms or other involuntary strokes in the joystick).

T_{stop}: the minimum duration of a stroke to be interpreted as a "panic" stop command.

D_{obsb}: the boundary distance bellow which an obstacle in the movement direction starts being taken into account.

D_{saf}: the minimum safety distance to an obstacle, i.e., the distance bellow which the wheelchair must be stopped for safety reasons (even if bumpers are also used for impact protection).

Δ: the delta precision adapts the system to the user precision when he/she operates the joystick. It is defined as the number of orientation angles that the wheelchair can rotate. A small delta indicates more orientations but implies a larger number of impulses in the joystick to attain a specific orientation.

The hierarchical FSM is shown in Figs. 2 and 3. The state transition conditions C are indicated in Table 1.

1. When the wheelchair is powered ON, it starts in legacy mode, where it operates as usual, reacting to a usual driving from the joystick.
2. To switch to LAM mode, the transition condition C_1 must be true.
3. When the user gives a touch in the joystick and wants to go ahead, condition C2 and C12 both true, the system will start in the acceleration state while condition C6 is true.

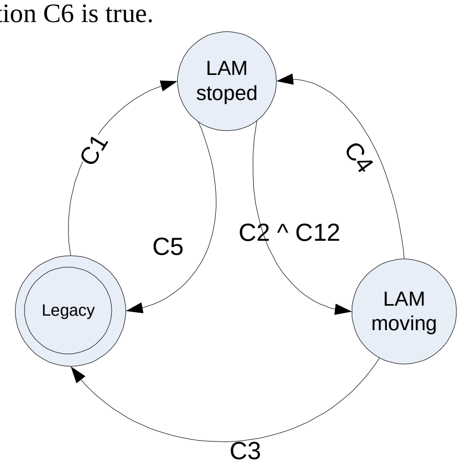

Fig. 2. LAM operation finite state machine

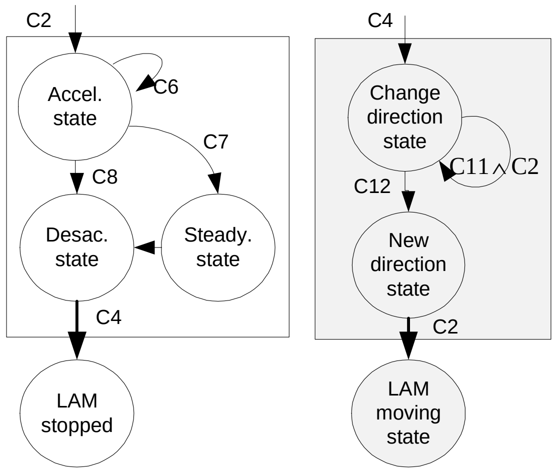

Fig. 3: Left)- LAM moving and state; Right)- LAM stop state

The increase of the velocity in these circumstances depends of a stair shaped function depicted in Fig.4. The temporal constant T_{acc} defined off-line, represents the time the wheelchair will stay in a velocity (or in a power level) before it changes to the next one. These different values for the speed belong to a set of reference speed values V :

$$V = \{0, v_1, v_2, ... v_i, v_{N\max}\},$$

where N_{max} is the maximum number of reference speed imposed to or available at the commercial wheelchair.

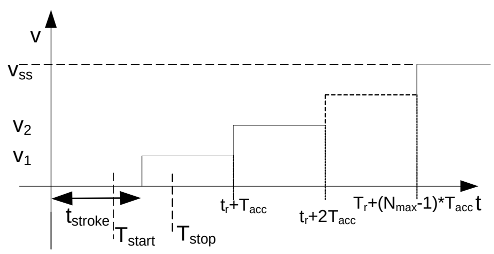

Fig.4. Example of a gradual increase in speed considering k=5

4. If, during the wheelchair movement, condition C7 is true and if it will stay beyond the D_{obsb} of any obstacle (which is determined by the sensors) then the speed may attain the steady state value v_{ss}, which is chosen by the user.

5. If the user wants to stop the wheelchair, condition C_9 or C_{10}, then the decrease of the speed depends also on a stair shaped function depicted in Fig. 5 where T_{dacc} is a temporal constant defined off-line. It represents the time the wheelchair will stay in a speed before it changes to the next one.

6. In these preliminary experiments, if during the displacement the condition C8 becomes true, the wheelchair speed will change depending of the d_{obs} value. It should be noticed that the wheelchair is moving, and then the d_{obs} is decreasing with time. For example, if the wheelchair moves with the highest velocity, $v_{ss}=v_5$ a gradual decrease in velocity such as shown in Fig. 6 can be imposed, according to the number of intervals k=5.

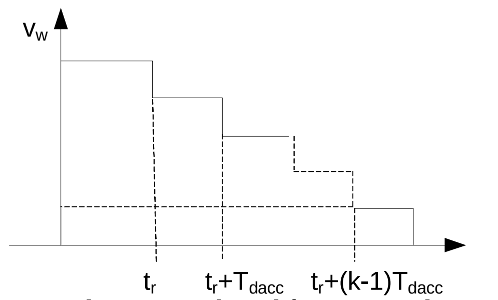

Fig. 5. Velocity stair shaped function used to stop the wheelchair

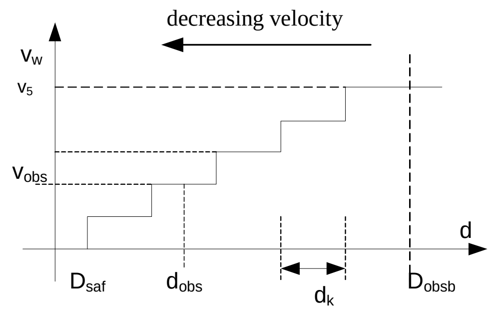

Fig. 6. Example of a gradual decrease speed considering k=5

7. When the wheelchair reaches zero speed (it stops), condition C4 is true. Once in the stopped state, the LAM system waits for another command given by the user: go ahead or change direction.

8. If in the stopped state, condition C11 is true and the user gives a touch in the joystick, condition C2, then the wheelchair rotates according to the predefined delta precision.

9. If in the stopped mode and if conditions C12 and C2 are true then the wheelchair enters in the LAM moving state.

10. If, for some undesirable reason, the wheelchair enters in the danger distance from an obstacle and the condition transition that triggers C_3 becomes true then the wheelchair will stop and changes to the legacy state must occur.

Table 1: Transition conditions

C1	m_a=ON
C2	$T_{start}<t_{stroke}<T_{stop}$
C3	$d_{obs}<D_{saf}$
C4	$v_w=0$
C5	m_a=OFF
C6	$t<t_{stroke}+kT_{acc}$
C7	$t>t_{stroke}+kT_{acc}$
C8	$D_{saf}<d_{obs}<D_{obsb}$
C9	$(T_{start}<t_{stroke}<T_{stop})$^$(180^o<\alpha_{stroke}<360^o)$
C10	$T_{stroke}>T_{stop}$
C11	c_d=ON
C12	c_d=OFF

VI. USING STAGE FOR VALIDATION AND PARAMETER SET UP

To validate this solution, the Stage simulation software is being used [26]. Stage is a collection of software tools to support research in autonomous robotics and intelligent sensor systems. It provides configurable and composable device models like sensor and actuator models, including sonar or infrared rangers, scanning laser range finder, bumper and a versatile mobile robot base with odometry [12].

Currently, we have adapted Stage to read information from a joystick and we have introduced the architectural plant of the training house of the CMRRC-RP (Fig.7). We have also programmed the LAM operational mode. With a group of menus, we can input the off-line parameters like, T_{start}, T_{stop}, the v_{ss} and Δ (Fig.8).

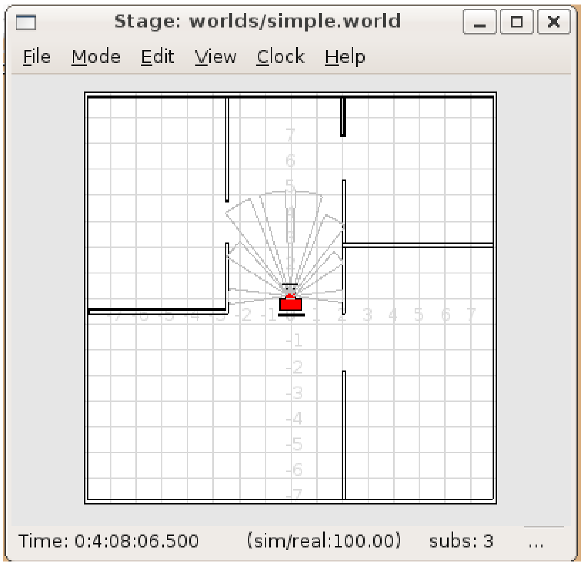

Fig.7. Architectural plant on Stage

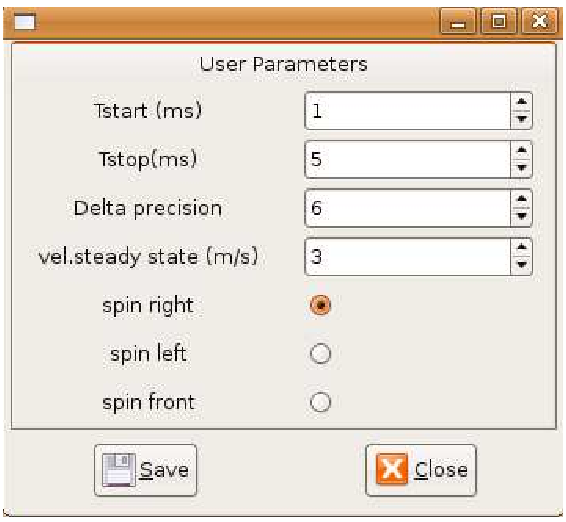

Fig.8. Architectural plant on Stage

A very important aspect in this mode of operation is that the same movement in the joystick commands the wheelchair in two different ways: go forward or change direction. The distinction between the two movements at Stage is made by an option that can be selected. In real implementation this is performed by two large buttons that can be pushed by the patients. The use of Stage will be required in two different phases of our work. Firstly, we are relying on it to make our initial study concerning the evaluation of the navigation algorithms we are thinking to use and to test and evaluate the operational modes we are proposing.

Once the experimental platform is deployed, we will be able to perform tests with patients using real wheelchairs. However parameter set-up in real environments can be cumbersome to perform. Thus we are considering the use of Stage to represent the operation of the wheelchair and to be used by patients to set-up operational parameters that enable a better navigation considering their disabilities.

VII. SOME RESULTS

At present, the platform was tested by only one patient in the centre. This patient is a C5 and a C6 in the right and left arms, respectively, and he is only able to spin to the front. In his opinion, the LAM mode of operation proposed is very interesting because he has not to push the joystick continuously to drive the powered wheelchair, thus feeling much more comfortable. He was highly motivated when he was doing the tests.

So, before each simulation, we have defined different pathways inside the apartment like for example, going from the dinner room to the kitchen or to the bedroom. Also, we have defined some metrics that we will use like:

- The time it takes to complete the pathways
- The time it takes to complete the pathways but with obstacles;
- The number of joystick interventions needed to change direction;
- The degree of fatigue;
- The time of reaction of each user.

As these were the first tests that took place, we have only considered all the possible pathways without obstacles.

First of all, the patient was asked to train some movements such as moving forward, backward, turn the chair and pass doors. Then, he tested turning the wheelchair with different delta precision, like two, four and six. First he tried to make the simulation tests with a delta equal to two because, as he said, there is no need to touch the joystick so much times. But then, he felt that he needs more training with the experimental platform to position the wheelchair in the right place. So, he chose a delta precision equal to six, because there is an augmentation of the direction angles and consequently he could move the wheelchair with a greater precision in certain movements, like passing a door. The choice of this parameter is a compromise between the number of needed impulses given on the joystick and the direction angles.

We have defined six possible pathways:

1. dinner room <-> room
2. dinner room <-> bath room
3. dinner room <-> kitchen
4. room <-> bath room
5. room <-> kitchen
6. kitchen <-> bath room

He performed twelve simulation tests, two for each pathway and for each one we have used two of the metrics defined in the beginning of this section: the time it takes to complete the pathway and the number of joystick interventions needed to change direction. The metric degree of fatigue was not measured but it was observed by us when the patient begun to show signs of tiredness. The other two metrics will be target of our future study and experiments. Table 2 presents the simulation results.

Table 2: Simulation results

Simulation number	Pathway	Time (sec)	Number of intervention
7	1	48	7
10	1	13	3
5	2	48	15
6	2	1’05	10
4	3	58	12
11	3	1’10	18
2	4	58	14
8	4	1’43	15
3	5	1,29	20
9	5	1’08	18
1	6	59	10
12	6	1’30	13

These tests were made according to the wishes of the patient, which means that the order of these tests was not pre-defined but it was him that chose what he wanted to do each time.

The tests took about two hours to be performed and, during this time, he was always navigating the wheelchair with success. Although the experimental platform allows to navigate the wheelchair in the legacy mode, this patient did not even attempt to do that because he is not able.

During the execution of these simulations, we have noticed that he has well learned the mode operation and also that he showed signs of tiredness. One of the symptoms that he was tired was that sometimes, when he pushed the joystick to the front to put the wheelchair in movement and when he dropped the joystick to making the arm movement to the back, he touched unintentionally in the joystick, thus triggering false stops.

So these results are not fully conclusive because the fatigue was making him a little nervous and he was also concerned because he begun to fail.

At the end of these two hours we have concluded, together with the clinician and the patient himself, that he needs to do some more training tests but not for so long time. The idea is to adapt the duration of each training session so that the learning process is not affected by the fatigue. With the learning process we want that he learns when he must exactly stop the wheelchair. When he does not stop the wheelchair in the right position he has, in some situations, to perform many more impulses in the joystick to reposition the wheelchair in the right pose.

VIII. CONCLUSIONS AND FUTURE WORK

In this paper we presented a solution to adapt CPW to enable quadriplegic users, with reduced strength and handling skills, to move autonomously in indoor environments.

The solution implies a reasonably simple adaptation of the wheelchair hardware and the definition of new modes of operation which rely on stimulli introduced by patients in the joystick. In the paper special emphasis has been put on the so-called LAM, Legacy Adapted Mode. For this mode, a formal definition of the wheelchair operation has been derived, leading to a hierarchical finite state machine (HFSM) that can be used to program the embedded system required for the wheelchair (HFSMs can be directly used with programmable logic, e.g. FPGAs – Field Programmable Gate Arrays).

The novel LAM adaptation was implemented on the Stage and it has been used to train the patients without the need of using a real wheelchair. The developed simulation platform has also been used to develop a set of studies concerning the adequacy of the operation modes.

The platform was tested by only one patient in rehabilitation center. So the reported simulations results presented are preliminary, still inconclusive but promising results.

Future work will include further validation of this new mode of operation, avoiding the fatigue problems identified in these preliminary tests.

Another issue is to guarantee that the control system is effective when it is subject to an erratic input signal and other variations of movement that a human being with such kind of disabilities exhibits.

Moreover, an obstacle detection and avoidance system is under development to allow safe navigation.

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