Designing a navigation aid for a smart wheelchair

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Abstract. Piloting an electric wheelchair is an imperious necessity for the everyday activity and social life of a number of disabled individuals. In the same time, such control, using most of the time a joystick-type interface, is indeed a difficult and exhausting task for people presenting various sensorial, motor and cognitive disorders. One solution to this problem has been, for a long time, to use approaches in autonomous robotics, in order to let a machine take care of the "hard job". In particular, we used a dynamic approach to automatize aspects of spatial navigation control, such as wall following, obstacle avoidance, door passage or goal seeking behaviors. The WAD "Wheelchair Attractor Dynamics" project has been developed on an experimental wheelchair, which successfully accomplishes these tasks, with limited calculation and simple electronics. The next step was to define a navigation interface, trying to optimize man-machine cooperation. A first validation experiment was conducted among a group of cerebral-motor disabled children, demonstrating a relatively fast learning of the interface. The current phase of the project consists in using virtual reality facilities, in order to optimize the smart wheelchair design, the sensori-motor interface and man-machine cooperation.

Key words: Smart Wheelchair, Handicap, Virtual Reality, Dynamical systems, Man-machine cooperation

1. Introduction

The overall framework of this project is to restore autonomy to severely disabled people by helping them use independently a power wheelchair. However, piloting a wheelchair, using for instance a joystick for heading and speed control, is always a hard task for a number of sensorial, motor or cognitive impairments or handicaps. For example, navigation sub-tasks such as obstacle avoidance or driving through aperture require sustained concentration and training. In this context, numerous approaches have been used in the field of mobile robotics. The aim is to enable, facilitate or partially automatize vehicle control. In particular, the dynamical approach uses both conventional dynamical systems and dynamic fields, implemented on robotics devices. It enables, without any human intervention the generation of behaviors, such as target acquisition, obstacle avoidance, representation of space, path planning, exploration, and vision-based navigation, while minimizing calculations. Such architecture generates smooth trajectories, without collisions. Trajectories are based on information about the mobile device instantaneous position and about its distance to environmental obstacles. Such information is gathered in real-time using on-board low-cost captors, implemented on a smart wheelchair. We also designed a custom man-machine interface. Its purpose is to enable a general population to have access to the manipulation of a smart wheelchair. More precisely, the problem is to develop the cooperation between the user and an ensemble of automated functions, such as obstacle avoidance or goal reaching. The sensorimotor interface we have developed enables the user to specify the source and goal of a

displacement through a domestic environment, or to switch between an automatic and a manual mode of control of the smart wheelchair. An evaluation study was conducted among a group of cerebral-motor disabled children. Results emphasize the relatively fast efficient learning of the man-machine interface and the smoothness of trajectories realized in the automatic mode in a familiar environment.

We will here present in greater details our current studies, aiming at the definition of an accessible and reliable navigation aid. This work uses both simulation and virtual reality technical tools. In particular, the goal is to try to define, on a smart wheelchair, the optimal spatial configuration of proximity detectors, whose role is to detect environmental obstacles on the ground and at "table level". Simulations of displacements in virtual spaces are realized, integrating "smart wheelchair" behaviors, such as obstacle avoidance and goal reaching in a domestic environment. Another aspect of these studies is the development of a virtual reality wheelchair simulator. This interactive simulator will enable us to optimize graphical and control interfaces, as well as human-machine cooperation, following a general concept of task allocation between the human controller and the autonomous capabilities of the machine [1,2]. It is also developed as a virtual wheelchair control training system and as an aid to the prescription of a wheelchair suited to a given handicapped individual.

2. Theoretical approach

A number of studies and approaches suggest potential solutions of "smart wheelchairs" [3,10]. These computer-assisted wheelchairs propose a "toolkit" of automatic functions, such as wall following, obstacle avoidance or door passage. Such navigational aids use a global and dynamical model of the environment. The perception of the environment is realized via external captors (sonar, infrared, laser or video). Finally, wheel encoders and motor commands integration give an estimate of the wheelchair's position and orientation.

Compared to these classical methods, being often time and computing resource consuming, the dynamic approach we follow is an efficient one. The central hypothesis of this approach, applied to autonomous mobile robotics, is that navigation-related motor behavior and internal representations have to be continuously generated in time. They have moreover to be resistant to the "natural" perturbations and noise to which any real system is submitted [11, 14]. This approach leads to a concept in which behavior and effective representations are stable solutions (attractors) in a set of dynamical systems. Sensorial information is translated into (mathematical) continuous variable constraints.
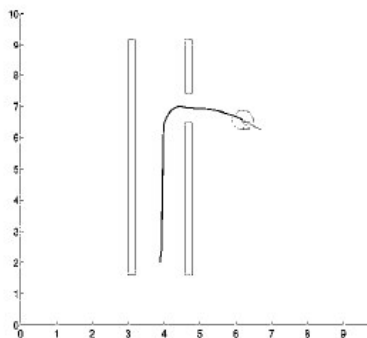

Figure 1. This example depicts the trajectory generated by the dynamic system from a starting point to an end point defined by the operator. Although this approach is an entirely local one, only based on current sensory information, and not on a global map of the environment, the obstacle-avoidance and the target-acquisition behaviors help the mobile vehicle follow the wall of the corridor, find the door, enter, and move towards the target.

Important side-advantages of this dynamical approach are the reduced size of the computational code, the smoothness of the emergent trajectories of the mobile device, a relative immunity of the system to the degraded precision of the low-cost captors we use, and the crucial real-time and continuous availability of diagnosis tools necessary to evaluate and tune on-line control variables. The same dynamical system concept allows for obstacle avoidance and (user-defined) goal seeking behavior (figure 1). The user is not required to segment the trajectory into collision-free sub-trajectories.

3. The "Wheelchair Attractor Dynamics" (WAD) Project

The command architecture of the WAD project is implemented on top of a CRUISER commercial wheelchair from INVACARE Corporation (figure 2). The wheelchair is equipped with a standard DX control system (joystick and power module). A DX Key module was connected to this system, providing an interface between the power module and an on-board computer. Two control modes are available.

In manual mode, the operator uses the joystick to control the speed and direction of displacement of the wheelchair. In automatic mode, infrared proximity sensors deliver information related to environmental constraints and incremental encoders about the instantaneous position and orientation of the goal with respect to the current wheelchair position and orientation. These data are processed by the on-board computer running the dynamic system. The program sends speed and direction commands to the power module via the DX Key interface. In this mode, the wheelchair is thus able to reach its destination without any human intervention.
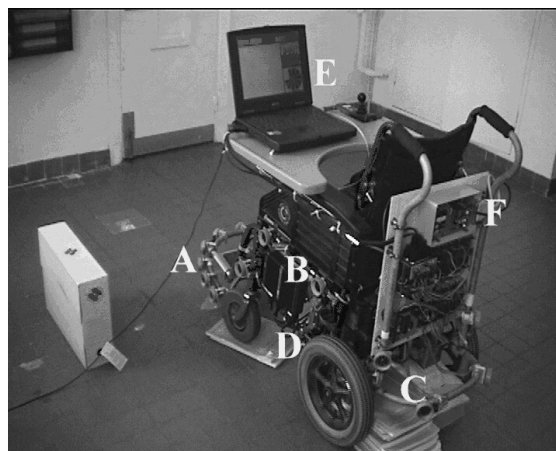

Figure 2. The WAD smart wheelchair. A : front proximity infrared sensor. B : lateral infrared sensor. C: rear infrared sensor... D: incremental encoder on the wheel. E: on-board notebook processing information from the sensors and delivering motor commands through the dynamical model. F: The DX Key module provides an interface between the computer and the wheelchair DX control system.

However, two factors require the adjunction of a man-machine interface. First, at any moment, the operator must be able to switch between the automatic and manual control modes. Second, the operator must specify (in automatic mode) the source and destination of the displacement to the dynamic control system.

4. Man-Machine Interface

We implemented a man-machine interface, which had to respond to different constraints. It must first fit a spectrum of user profiles.

4.1. User profiles classification.
The classification was defined along two main axes, motor and cognitive. Along the motor axis, two categories are distinguished: The subject has action capacities and is able to manipulate objects with relative temporal and spatial precision (motor profile 1). The subject has (almost) no capacity to manipulate objects (motor profile 2). Along the cognitive axis, we distinguish between subjects having acquired reading ability (cognitive profile 1) and those who cannot read (cognitive profile 2). This classification thus leads to 4 user profiles.

4.2. Control interfaces.
Motor profile 1 subjects use a joystick; motor profile 2 subjects will use an "all-or-nothing" interface (foot, hand, chin, switch…).

4.3. Tasks sequence and graphic interfaces.
In the automatic mode, in order to let the wheelchair reach a target location from a given starting position, four sequential tasks are to be accomplished. Each of these required an adapted graphic interface, implemented on the PC notebook LCD panel. The first task consists in defining the starting position. For the subject this consists in defining the room where the wheelchair is situated (of course this requires minimal cognitive spatial ability and a map of the environment (figure 3). Each room is a selectable item.
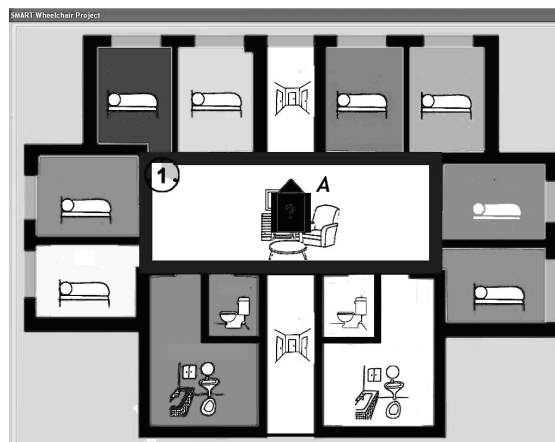

Figure 3. Selection of the initial location of the wheelchair. The operator (onboard the wheelchair) must select the room where he/she is. The black central icon (A) representing the wheelchair moves from room to room, either at a selectable pace, or via the joystick.

The next task is the validation of the starting location (figure 4, left). The user has a choice between two items: going back to the selection of the starting position (left icon) or validation (right icon). The third task consists in selecting the target location (goal of the displacement). The rooms on the map are all selectable items. An arrow connects the source to the destination locations (see figure 4, right).
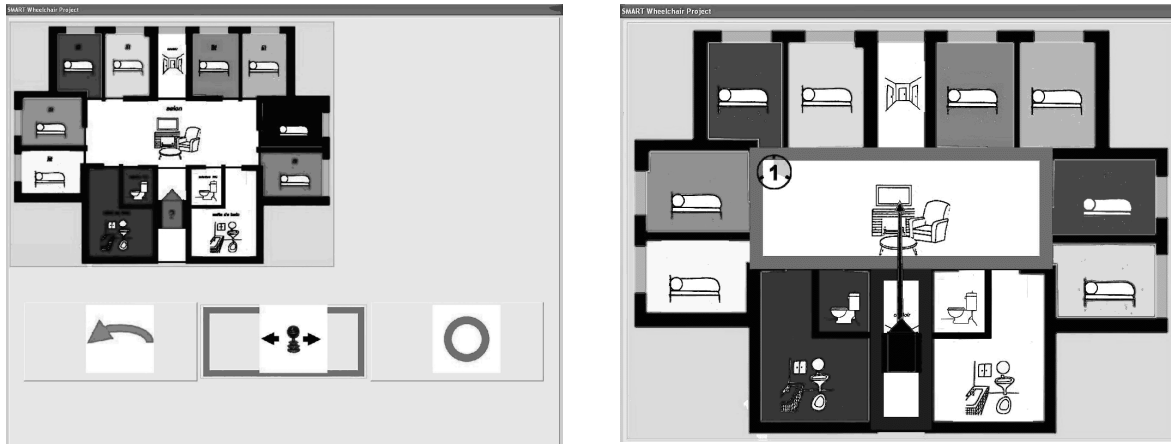
Figure 4. Left: Validation of the starting location. The left arrow icon represents "back" and the right circle represents "validation. The central icon enables the user to rest. Right: Selection of the destination location.

The fourth and last task is the validation of the destination location, similar to the second task (figure 4, left). As concerns the cognitive profile 2, an exclusively iconic interface is presented. For the cognitive profile 1, both lexical and iconic items are presented on the graphic interface.

4.4. Navigation interfaces

For motor profile 1 subjects (who are able to manipulate objects with relative dexterity), a manual interface (joystick) is used for the above tasks. The subjects have to navigate through the items. In order to select a given item, the navigation program does not require the user to take the distance between items into account and tolerates a (programmable) wide range of variation in angular direction. In the subsequent evaluation, we used a minimum tolerance value of 10 degrees. Validating an item corresponds to the fact that the subject does not activate the joystick for a programmable duration.

Motor profile 2 subjects cannot manipulate objects. A scrolling navigation system has been implemented. It consists in presenting the subject with a succession of items which are selectable during a given programmable duration. The selection of a given item is made by a given motor response, which depends on the subject capabilities. The time during which an item can be selected is visualized by a timer on the screen, so that the subject can plan his/her motor response.

5. Evaluation of the system in a group of cerebral-motor disabled children

5.1. The Saint-Thys Center

An evaluation of the usability of the system in real-life conditions was recently carried out in a day-care center in Marseilles, among children presenting cerebral-motor developmental disorders. This center was kind enough to welcome our experimental protocol, being the reference center for motor-cerebral handicap in the south-eastern part of France (Provence-Alpes-Côte d'Azur Region). The main mission of the Saint-Thys Center is to favor the social integration, both in cultural and professional terms, of children and teenagers. One goal along this way is to help them acquire the best possible autonomy. Tools are sensori-motor training, and adapted scholarship. The type of system we are trying to define appeared as an interesting potential aid for these subjects. In return, this evaluation was, for us, a decisive contextual

feedback for further improvement. This multiple case-study was carried out in collaboration with ergotherapists.

5.2. Methods

Four children, aged between 11 and 14 years, participated in the study. They suffer from tetraparesy. Such pathology is characterized by continuous and anarchic (uncontrolled) movements of the four limbs [15]. This impairment obviously renders impossible the continuous manual control of a motorized wheelchair. However, despite such disorganized movements, these subjects are able to achieve a few voluntary actions, with a variable level of precision that is dependant upon the severity of their disorder. They thus appeared as potential users of the smart wheelchair, provided that they could make use of our man-machine interface.

2 children presented a capacity to manipulate objects (motor profile 1), while the two other had none (motor profile 2). All of them were already using computers. Each child uses a motor interface to the computer that is adapted to his/her handicap and to his/her motor repertoire. The two children presenting the motor profile 1 used, respectively, a chin joystick and a hand joystick. The two children with motor profile 2 used a hand contactor and a foot contactor (all-or-nothing switch). None of these subjects has acquired reading. They thus all correspond to the cognitive profile 2.
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5.3. Evaluation protocol

This study took place over a period of three weeks and two phases: a learning phase and an evaluation phase. The learning phase consisting in training each child in the use of the navigation interface (designation of the starting and target locations of a displacement with the wheelchair in automatic mode). Training was, of course, individualized, and lasted for (about) twice half an hour. The usage of the sequential tasks of the navigation planning was acquired by all four children. However, from a motor standpoint, we had to customize parameters of the functional interface, such as the timing of the scrolling cursor, the joystick transfer and gain functions, the validation delay, etc….).

The evaluation phase itself consisted in a first evaluation of the navigation interface (without an actual displacement), followed by two trials in which two displacements (from one room into another) were actually realized in the automatic mode of control of the power wheelchair (figure 5). The path of travel was the same for all four subjects. It consisted in following a hallway, avoid a flower pot and a piece of furniture, go through a door and stop in the center of the destination room. During the second trial, the smart wheelchair had to avoid a moving person.
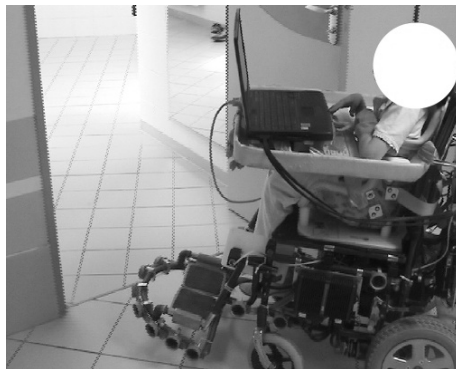

Figure 5. An image of the travel of one child using the smart wheelchair in automatic mode.
The wheelchair is passing safely though the aperture.

5.4. Main results

We already knew, from simulation and experiments with the smart wheelchair alone, that the device was able to reach a target (once the starting and end locations were set). In all the sessions with the four children, the wheelchair was again able to achieve its task. Moreover, each child was able to select correctly the starting and target locations. This suggests the usability of the smart wheelchair. On a more subjective level, what struck us was the joy expressed by the children when they discovered they were able to move on their own, which constitutes a promising perspective for the future of this project.

More precisely, over the two validation tasks the subjects had to execute in each trial (source and target designation), they had, on average to correct once their selection. The average number of motor commands that were necessary to program the wheelchair displacement was 11 (one motor command corresponding to the selection of an item). A difference between the two motor profiles appears. In the motor profile 1 (relative ability to manipulate objects), 15 actions are executed (on average). In the motor profile 2, 6 actions only are necessary (see table 1). This difference is related to the characteristics of the navigation interface corresponding to each profile. In profile 1, the subject uses a joystick to "navigate" through a set of rooms, potential destination locations. This may require a great number of actions, especially if the destination is far from the starting point. The minimum number of actions may thus vary from 4 to 10. In profile 2, the subject has to make his/her selection form a scrolling automatic navigation interface. The set of successive tasks can thus be achieved in four motor commands. However, due to the scrolling method, this might require more time. In particular, we noted an increased execution for subject S3, using a foot contactor (table 1). In this case, the scrolling cursor goes through all selectable items. If the subject does not make a selection, the whole process has to start over again, thus doubling execution time. Finally, we noted, for motor profile 1, an increase of motor commands during the trials. This suggests that subjects were tired from the use of a joystick command, given their relative clumsiness. This result argues for the necessity of extended work on the navigation interface. In particular, a trade-off might be sought between the "motor cost" of the joystick command and the "time cost" of the scrolling interface, in relation with the characteristics of a given subject.

Subjects		Number of actions	Execution time (s)
Motor profile 1	S1 (hand joystick)	11 (sd=7)	47 (sd=19)
	S2 (chin joystick)	20 sd=12)	43 (sd=27)
Motor profile 2	S3 (foot contactor)	5 (sd=1)	83 (sd=43)
	S4 (hand contactor)	7 (sd=4)	45 (sd=4)

Table 1. Average number of actions and execution time for the 4 subjects in the navigation task.

6. Ongoing studies and perspectives

This first implementation and "real-life" experiment enabled us to foresee the usability of the smart wheelchair, associated with its navigation interface. However, some implementation choices, concerning the command interface and the navigation interface, were made intuitively. It is now necessary to adopt a more comprehensive approach, without having to carry out too many real experiments. This is precisely here that virtual reality experiments are of major interest, from two main points of view. First, we use virtual reality as an evolved computer-aided design tool, in order to improve the automatic navigation behavior of the smart wheelchair. Secondly, interactive simulations can be carried out with human subjects, in order to study and improve control interfaces and man-machine cooperation.

6.1. Sensors integration on a "real" wheelchair

The integration of our navigation aid on a given commercial wheelchair requires the design of an optimal configuration of the sensors locations. This is a crucial goal in the design process of a safe smart wheelchair, capable of "perceiving" its environment with minimum sensorial capabilities. For instance, proximity sensors have to detect not only wall and doors, but also obstacles (or targets) at human level, such as tables.

It is obvious that the dimensionality of the problem space is high. In order to orient decisions concerning sensors locations, simulations integrating the smart wheelchair automatic behavior (dynamic system), the sensors behavior and complex virtual 3D environments are carried out. We use Virtools® in this context.

We implemented "obstacle avoidance" and "goal seeking" behaviors on a virtual smart wheelchair (figure 6). Simulation sessions enable us to evaluate the performance of various sensors configurations. A great number of factors can be crossed (obstacle type, obstacle size, obstacle elevation, obstacle orientation, etc…). These simulations will allow us to eliminate a great number of non-efficient or not-optimal sensor configurations, before implementing them on a real wheelchair
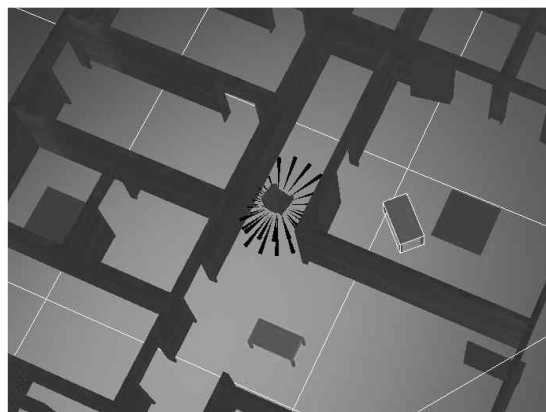

Figure 6. 3D dynamic simulation of the dynamic system, implemented on a virtual wheelchair, with simulated (but behaviorally realistic) proximity sensors. The black cones represent the visibility range of the sensors. Using a dynamic system, the virtual wheelchair is able to avoid obstacles (provided the proximity sensors are efficient) and reach a designated target location.

6.2. The "Virtual Smart Wheelchair" project

As we saw in the previous description of the development of the smart wheelchair and the navigation interface, as well as in the first evaluation study, much remains to be done. In particular, a systematic approach is required.

We already described how a virtual reality tool can be used, in order to specify the multi-dimensional problem of sensor integration on a real wheelchair. In this first application of VR (conceived as an advanced design aid), the human is not directly involved, expect if you consider that a visual inspection of the robot behavior in a virtual environment refers to an intuitive human expertise, which requires a human observer in the design and evaluation process.

We are now trying to develop a design, training and evaluation VR simulator, in which the human subject will be a central agent. These experiments are now being setup in the Mediterranean Virtual Reality Center, in which a "cave-like" [16] system was recently installed, designed to achieve optimal immersion and presence of the subject [17].

This interactive simulator will enable us to optimize graphical and control interfaces, as well as human-machine cooperation. It is also developed as a virtual wheelchair control training system and as an aid to the prescription of a wheelchair suited to a given handicapped individual. More precisely, we are now setting up experiments, implementing the dynamic model on a virtual wheelchair, using Virtools SDK (studies using the actual experimental smart wheelchair will be conducted in a second stage). The objective of the investigation is to optimize human-machine cooperation. In the previously reported clinical trial, the displacement of the wheelchair was fully automatic (the subject was passive during the travel from the source to the destination). It might however be desirable to consider situations in which the driver is active.

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