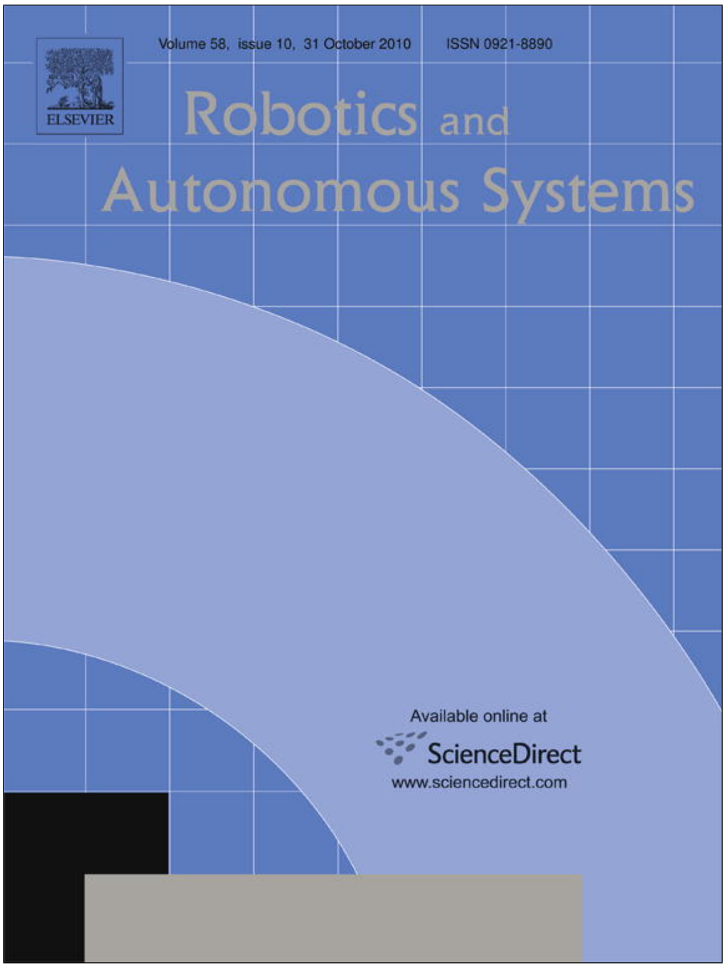

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Smart wheelchair control through a deictic approach

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ABSTRACT

In this paper, the implementation of assistance to the driving of a smart wheelchair through a deictic approach is described. Initially, a state of the art of mobility assistance, interfaces and types of commands for smart wheelchairs is presented. The deictic concept, and more particularly, the approach used for the design of our interface is examined. Then the two functionalities carried out to implement this type of interface, as well as methodology used to control our wheelchair are illustrated. Finally, the usability of this deictic approach for the assistance to the driving of a smart wheelchair is discussed.

1. Introduction

Many people with disabilities experience difficulties when driving their electric wheelchairs with a standard joystick. A clinical study, presented in [1], shows that 9%–10% of people with severe disabilities are in this case. In order to enable these people to retrieve their mobility, research has been carried out since the end of the eighties on the development of smart wheelchairs [2]. Different approaches to the design of mobility assistance using different types of control have been considered.

On the first smart wheelchairs, resulting from mobile robotics, autonomous mode is preferred: the user indicates a localization to be reached or a direction to be followed so that the wheelchair moves automatically. The situations met are dealt with in an autonomous way using perception without calling upon human cognition. Here, the user may have the feeling he is led by the wheelchair and may be reluctant to use this type of assistance. Contrary to this approach, the manual command requires the user to move the wheelchair by himself with his own analysis. However, it imposes a too high physical load on him. We can try to find an intermediate approach more centred towards the co-operation between the user and the machine [3,4]. It is necessary to determine the right compromise between the autonomy suggested by driving assistance and the control of the user. To achieve this, we will focus on a semi-autonomous approach proposing a set of functionalities of mobility assistance that the user activates from an adapted human–machine interaction (HMI) sensor and an intuitive graphic interface ("deictic" control).

In what follows, after a review of the literature on the different functionalities, types of commands and interfaces used on existing smart wheelchair prototypes, the methodology adopted to design our deictic approach of a smart wheelchair control is described. Finally, results from tests on the prototype are presented and discussed.

2. Background

2.1. The functionalities of mobility assistance

The objective of these functionalities of mobility assistance is to replace the person driving a wheelchair in specific situations. Thus, obstacle avoidance has been developed to help the user through a cluttered environment. Its role is to alter the trajectory of the wheelchair to avoid collisions with the environment. It has been designed using different methodologies, for example, the method of potential fields [5], the VFH method (Vector Field Histogram) [6], or methods directly using the distances to obstacles around the wheelchair [7,8].

When the user has difficulties in following his trajectory in a stable manner, wall following or person following can bring valuable assistance. The objective of these functionalities is to track the target while maintaining a safe distance between it and the wheelchair. For example, in the case of wall following, the wheelchair moves forward so as to keep the distances measured with ultrasonic sensors, infrared or laser, constant [8,9]. Person following can be carried out from a vision system to control the orientation of the wheelchair and from ultrasonic measurements to control the forward speed of the wheelchair [10].

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The user can also have difficulties in operating the wheelchair. This can be overcome by automatic passing through a door. It can be carried out as an extension of another functionality (like on the Navchair [6]) where obstacle avoidance allows to bring the wheelchair to the centre of a door when the user moves towards it. This methodology is effective as long as there is no complex manoeuvre to perform. There are other approaches, which require more autonomy, in which the user has to indicate the door by clicking on the two vertical sides of the target on the video image [11]. Then, a trajectory is calculated and followed with a dead-reckoning system to pass through the door.

In order to lighten the workload of the user during a movement, several approaches for navigation assistance have been developed. This functionality allows to automatically bring the wheelchair in the position selected by the user via the interface. For example, in [12], cameras are placed in an indoor environment and continuously locate the wheelchair. The user specifies a location to reach via his interface and the wheelchair goes there automatically. This approach requires a base of knowledge of the environment and many sensors. A second approach consists in identifying specific elements of the environment and planning a trajectory relative to these landmarks. For example, in [13], walls and corners are detected in the environment, then, the user chooses to carry out several actions via his interface, like turning around, following, moving to, etc. This permits to obtain a set of basic assisted movements.

All these mobility assistance systems have been developed on many prototypes and have shown some effectiveness. However, their use brings about several problems, including the ergonomics of the human machine interface.

2.2. Human machine interaction

The choice of human machine communication is essential for a system interacting with humans, and especially when they are in situations of disability. It must be adapted to the user and must provide all information necessary to perform the right action. Its implementation depends primarily on the kind of mobility assistance provided by the system, on the type of interaction sensor corresponding to the physical link between the user and the wheelchair, and on the interface presented to the user, allowing him to obtain the feedback from the state of the wheelchair.

The most commonly used control interface is the joystick [6,9]. All common electric wheelchairs use one. The advantage of this type of command is the intuitive way in which it is used. However, it is difficult to manipulate for people with severe disabilities because it requires dexterity and continuous control. Interfaces using the joystick have been developed for some smart wheelchairs. For example, in [14], the approach is to show a map of the environment to the user in which he indicates where he wants to go. To do so, he moves a cursor with the joystick and when it has been motionless for some time, the room shown is selected. This approach therefore requires knowledge of the environment.

When the user has difficulties using a joystick, on–off controls are generally used, like for example, head or chin contactors, or breath sensors [15]. Thanks to the simple information provided by this type of sensor, the system can be adapted to severe motor deficiencies. However, it requires a more complex communication interface. Thus, most smart wheelchairs using an on–off control are equipped with a screen to communicate with the user. The interfaces based on this type of control use a scanning approach. It consists in providing different navigation options on a screen, one after the other. Then, the user selects the desired action by pressing the control sensor [7,16]. Control by voice recognition can also be considered as an on–off control. For example, in [5], the user provides basic commands such as: forward, stop, turn, rapidly, slowly.

Finally, more sophisticated human–machine interface sensors may also allow to control the wheelchair: control based on physiological signals (EOG) [16], on the analysis of body language or of the user's face with a video camera [17], or more recently, command with a brain computer interface (BCI) [18] and command based on the use of the tongue [19]. It is worth noting that human–machine communication using this type of command does not necessarily present a hardware interface. For example, it's the case in [20], where user control is achieved by observing him with a video camera. Through an image processing system, the orientation of his face and his eyes are extracted to determine the direction that the wheelchair will follow. A control law is determined by following two rules. When we want to turn to a location, we look towards this location, and, the farther we look the faster we go.

2.3. "Deictic" approach

The deictic approach consists in using a vision of the environment as a control interface. This vision must be as close as possible to the perception of the user so that the interface is intuitive and therefore easy to use. To move, the user specifies the location within the environment he wants to go to by pointing at it on the interface. Then the wheelchair will move automatically to that position. As the command is given from time to time, it does not require much effort from the user. This concept has been proposed in various fields, such as mobile robotics, tele-operation or the development of smart wheelchairs.

In the field of mobile robotics, there are several projects that illustrate this approach. For example, in [21], a mobile platform uses the video camera as a control interface. The user points at a location of the video image and the robot goes there automatically. The methodology used is based on a video tracking algorithm. Here, the functionality of navigating to a point is complemented by an obstacle avoidance system that ensures movements without collisions.

The deictic approach has also been proposed in tele-operation. For example in [22], a mobile robot equipped with a vision system and encoders is controlled remotely by computer. Its interface presents the view from the robot to the user. To move, the user has to indicate the location he wants to move the robot to by pointing on the video image. The point shown is converted into a topographic position using a projection model of the video image on the ground. Then, a trajectory is planned and tracked using odometer data. This approach is also used in assisting the prehension of objects by a robotic arm mounted on an electric wheelchair [23].

In the field of smart wheelchairs, a first approach based on a vision system is developed in [13]. The deictic interface contains a menu presenting the different moving options and the video image as a view of the environment. To control the wheelchair, the user selects the type of command on the menu and he points at the location where he wants to go on the video image. Then, the target located in the image is tracked with an image processing system based on the Bayes theorem. Here, the control of the wheelchair has not been implemented. A similar approach has also been developed in [11], where the interface is projected with a video projector on the table of the wheelchair. This projection contains a video image of the environment and buttons to select the operating mode (go to, avoid obstacles, follow this wall, go there in three points). To move, the user selects a functionality by showing it on the table, and then he must point at the video image where he wants to go.

Fig. 1. Vahm-3 prototype (autonomous vehicle for people with motor disabilities).

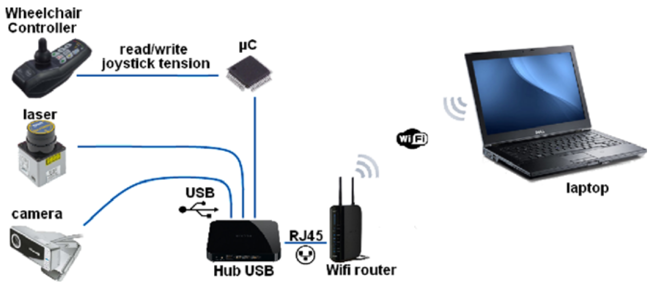

Fig. 2. Hardware architecture of the prototype.

Our goal is to make mobility assistance easy to use while having a light system which is easily adaptable to an electric wheelchair. The principle of a deictic approach, consisting in showing the task that the wheelchair will accomplish on a view of the environment, appears well suited to our approach. What follows is a presentation of the method used to design our deictic approach allowing the implementation of two autonomous navigation functionalities: passing through a narrow passage and wall following.

3. Methodology

3.1. Modality of achievement

To implement our mobility assistance, we use the smart wheelchair prototype Vahm-3 (Fig. 1). It is based on the model Storm3^{TM} of Invacare equipped with sensors and a computer. The wheelchair architecture is illustrated in Fig. 2.

In order to obtain a system which is easy to use, light and adaptable, we have to consider several constraints. Firstly, we will focus on the development of a deictic interface to retrieve the orders of the user. It must enable the user to show the location where the wheelchair will go automatically. To achieve this, a video camera placed in front of the wheelchair is used. The video image of the environment is presented to the user on a screen (Height 480 p and Width 640 p), on which he can point at different areas by means of the joystick. Thus the same sensor is used to drive the wheelchair manually or to activate autonomous functionalities. The transition from one mode to another is implemented by means of a push button with which the joystick is equipped. It is also used to validate the choices on the deictic interface.

On the other hand, in order to design a system that is easily transferable to any type of wheelchair, we will not use odometers. Thus our perception is only an exteroceptive one. It relies on a Hokuyo URG-04LX scanning laser range finder mounted on the front of the wheelchair. This sensor has a field of view of 240°, an angular resolution of 0.36°, with a scanning refresh rate of 10 Hz, and a distance range from 20 mm to 4 m. The measures are taken in the horizontal plane around the wheelchair. The height of the laser sensor is set at 40 cm, it gives a perception of an indoor environment which is sufficient to achieve the navigation tasks. However the user being the supervisor of the movement, if an obstacle is not detected by the laser, he can easily leave the autonomous navigation mode. The functionalities of mobility assistance are based on an analysis of data from this sensor to control the wheelchair in a reactive mode, i.e. without the use of a global model of the environment. They continuously provide a target location computed to carry out the movement designated by the user. We thus design a closed loop control of the wheelchair. Its role is to bring the wheelchair to a determined location.

3.2. Human machine interface

The principle of a deictic approach is that the user chooses his mode of movement (wall following or passing through narrow passages) and then, shows where he wants to go on a view of the environment. To assist the user in his choices, all that the wheelchair can automatically perform is highlighted in the video image (for example, by highlighting the contour of a door, or by showing a wall...). To complete his order, the user specifies an element highlighted on the video image and the wheelchair performs the corresponding automatic movement.

3.2.1. Human machine interaction

The control sensor is the joystick. It is used both to drive the wheelchair and to navigate on the graphic interface. When turned on, the wheelchair is initially in manual mode. To switch to automatic mode, the user presses the button on the joystick and selects the functionality to activate by using the cursor. He validates his choice by pressing a button again. Then, all the locations, on which the functionality can be used, are highlighted on the video image so as to present all opportunities to the user. Finally, to start moving, he has to point at the area he wants to move to with the cursor and confirm by pressing the button. Once the wheelchair is moving, the joystick automatically returns to mode "driving of the wheelchair" which allows the user to take back control (if necessary) with a simple action on it (either by moving the joystick or by pressing a button). The manual mode has priority on the automatic functionalities. In addition, to enable the user to check the status of the wheelchair, the name of the active functionality is displayed at the bottom of the video image.

3.2.2. Conversion of the user command into useful information for the system

To perform an automatic movement, it's necessary to extract the right functionality, and the location in the environment where it has to be applied. These two pieces of information are retrieved from the user's command given on the interface. For the first piece of information, all possible choices of mobility assistance are displayed in a menu next to the video image, as shown in Fig. 3. The user has to choose the functionality before pointing at the video image.

The second piece of information to extract is the location in the environment of the target selected by the user. As the functionality

Fig. 3. User interface: choice of functionality (left) and view of environment (right).

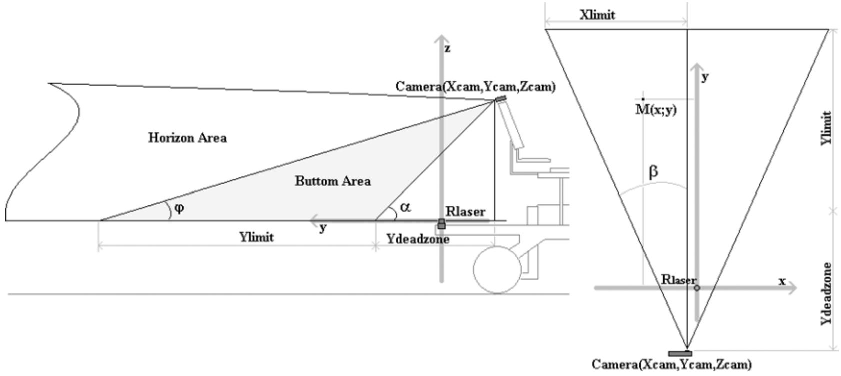

Fig. 4. Diagram showing the parameters used for the video image/environment conversion, on the *YZ* axis (left), and on the *XY* axis (right).

uses laser data to obtain the perception of the environment, the target location must be expressed in a coordinate system related to the laser. Therefore, we have to establish a conversion of points from the video image to points of the environment expressed in this coordinate system (R_{laser} is the coordinate system of the laser and $R_{\text{image\_vidéo}}$ is that of the video image). For this, we develop an approach similar to [24] that we have extended and adapted to our problem. It uses the location of the laser sensor and the intrinsic and extrinsic parameters of the video camera (the camera position in relation to the laser: Xcam, Ycam and Zcam, the distances corresponding to the laser measurement limits: Ylimit, the distance corresponding to the camera width limits: Xlimit; and the angles related to the camera tilt and focal: α, β and ϕ). It is carried out as follows (Fig. 4).

To obtain a view of the environment which is as close as possible to human view, the camera is slightly tilted toward the ground while looking at the skyline. To perform the conversion, we must consider two areas of the video image. The first is the lower part of the video image ("bottom area") in which there is a direct correspondence with the plane of the laser measurement. The second is the area representing the skyline ("horizon area") in which the correspondence is outside the field of laser measurement. Fig. 5 illustrates this division of the video image (we note W and H respectively the width and the height of video image and th% the threshold separating the two area).

Our objective is to determine the point $M(x, y) \in R_{\text{laser}}$ from the corresponding point $I(i, j) \in R_{\text{image\_vidéo}}$. For this, we consider the area of the video image where $I(i, j)$ is located and trigonometric

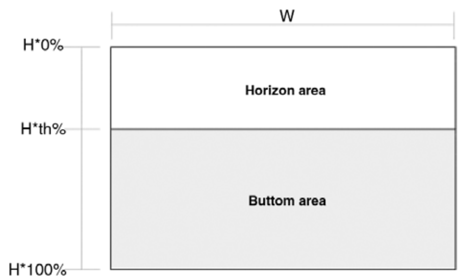

Fig. 5. The two areas of the video image $I(i, j)$.

rules. For the bottom area of the video image, we determine the x and y coordinates of point M by the following functions:

$$y = \frac{Z_{\text{cam}}}{\tan\left(\varphi + \frac{(j\text{-th\%}\times H)\times(\alpha-\varphi)}{\text{th\%}\times H}\right)} \tag{1}$$

$$x = y \times \tan\left(\frac{\beta \times (2i - W)}{W}\right). \tag{2}$$

For the horizon area, the points of the video image are too far from the sensor to have a real correspondence with the field of measurement of the laser. We chose to limit the correspondence to the limit of perception of the laser sensor. For this, we consider that all points, measured beyond the maximum distance of perception, are blocked at this limit. Thus the calculation of x does not change (we use (2)), and y is determined by the following function:

$$y = \frac{Z_{\mathrm{cam}}}{\tan(\varphi)}. \tag{3}$$

3.2.3. Display feedback on the interface

To display the locations which can be selected on the interface, it is necessary to have a display feedback on the video image. For this, each functionality must provide all the locations of the environment where it can be used. It is therefore necessary to perform the inverse conversion (obtain the points of the video image from the points of the environment). As the points to convert come from an analysis of the laser data, they correspond to the "bottom area" of the video image. To establish this second conversion, the functions defined earlier in this area are reversed and we obtain:

$$i = \frac{W}{2} \times \left(1 + \frac{\tan^{-1}\left(\frac{x}{y}\right)}{\beta}\right) \tag{4}$$

$$j = \mathrm{th}\% \times H \times \left(1 + \frac{\left(\tan^{-1}\left(\frac{Z_{\mathrm{cam}}}{y}\right) - \varphi\right)}{\alpha - \varphi}\right). \tag{5}$$

3.3. The functionalities

Our interface is designed to activate different autonomous functionalities. Initially, we have established two of them: an automatic passing through narrow passages and wall following. In order to carry out these functionalities, they have to continuously provide a point of the environment that the wheelchair will track to accomplish its task. We call this point "target point". The closed loop control of the wheelchair (& Section 2.3) allows to drive it towards this position.

3.3.1. Passing through narrow passages

The first functionality achieved has to allow to automatically cross a narrow passage. It involves several steps. Firstly, the detection of narrow passages with the laser sensor allows to identify each possible passage. Then, the passage selected by the user has to be tracked in the environment. Finally, the target point is continuously calculated to bring the wheelchair to its destination.

The detection of narrow passages

To detect narrow passages in the environment from laser sensor data the following methodology is used. The principle is to merge the measurement points from the laser sensor in sets representing groups of obstacles. A set is separated from another if there is a possible passage of the wheelchair between them. To generate these sets, we scan the measurement points in the order in which they are provided by the laser sensor. For each point, the distance between it and the previous one is calculated. If this distance is greater than what is necessary for the wheelchair to pass, then, a new set is created. Else, this point is added to the current set. Thus, several sets representing groups of obstacles of the environment are obtained.

Then, we must identify the narrow passages. For this, as each set is composed of a group of points, we determine the combination of points from two sets allowing to minimize the distance between them. If this distance is between 850 and 2000 mm, then these two points will be considered as boundary points of a narrow passage. Every narrow passage characterized by two points is saved. Fig. 6 shows an overview of selected passages. Each of them is identified by a cross and a circle.

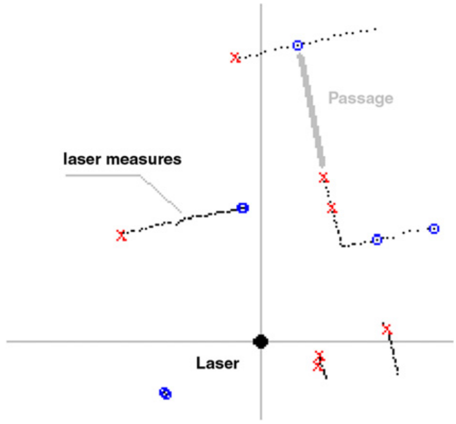

Fig. 6. Map of the environment from laser data on which narrow passages are detected. Each narrow passage is between a cross and a circle.

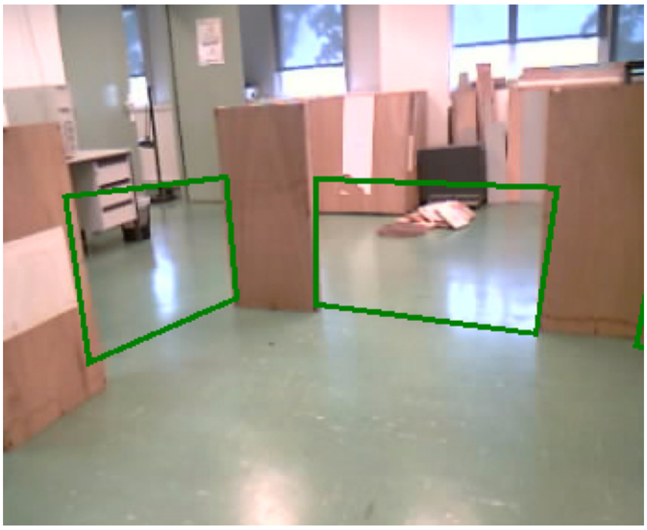

Fig. 7. Display of the narrow passages on the video image (green quadrilateral).

Then, all the narrow passages have to be presented to the user by highlighting them on the video image. To do this, a template is assigned to each passage which is limited in width by the two border points, and in height by the ground and a fixed value (500 mm). Next, we determine the four points of the template projected on the plane of the laser sensor to convert them into points of the video image with functions (4) and (5). Lastly, we connect these four points in the video image to form a quadrilateral adapted to the shape of the narrow passage. Fig. 7 shows an example of the display.

Choice and tracking of a narrow passage

To choose a passage, the user points at it on the interface and presses the button to confirm. Therefore, the point indicated is converted into the environment, and the passage retained is the one which corresponds to this point. Then, each time the measurements are updated, to track the passage into the environment we look for the passage which is the nearest to the one previously used. Then the passage is followed until crossing.

Generation of the trajectory

When a passage is selected, the wheelchair has to perform a series of manoeuvres in order to bring itself in front of the passage. As we do not have any map of the environment or proprioceptive measurements allowing the localization of the wheelchair, we cannot use standard methods of trajectory generation. Furthermore, we can't carry out a direct navigation to the centre of the narrow

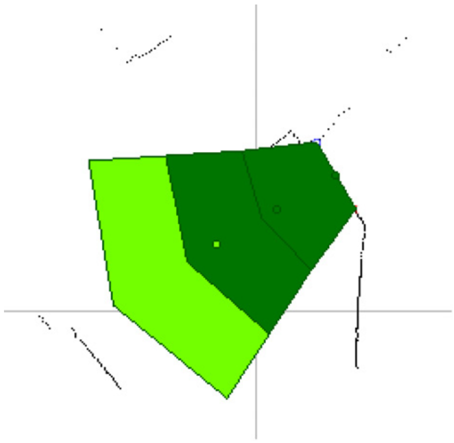

Fig. 8. Overview of areas and target points during an automatic passing through a narrow passage.

passage because the wheelchair would arrive in front of it with a wrong orientation.

The approach achieved is based on a navigation directly linked to the location of the narrow passage [25]. The wheelchair has to move towards the goal, step by step, by tracking a succession of target points to reach the centre of the passage in correct position and orientation. To do this, a set of contiguous areas is constructed relatively to the location of the narrow passage and a target point, located on the axis of the passage in the adjacent area, is assigned to each of them. Then, the area selected is the one containing the wheelchair, and the target point is the one which corresponds to it. During a movement, the wheelchair will move from area to area, thus changing target points. And it is the succession of these target points which brings the wheelchair to the passage centre. We can see in Fig. 8 an overview of these areas (the clearer area shows the active area and the clearer point is the corresponding target point).

3.3.2. *Wall following*

The second functionality must allow the user to automatically follow a wall on the left or right. The methodology consists in extracting several significant distances in the environment that are used to determine a target point. It will be calculated to maintain the wheelchair a safe distance from the wall chosen by the user. The procedure involves several steps. Firstly, we get the user command via the interface. Then, we extract the significant distances from the laser measurements, which allows us to determine the situation of the wheelchair in its environment. Finally, we work out the target point based on these distances to obtain a smooth trajectory.

The user's choice

To choose the wall to follow, two rectangles, on the left and right side of the video image, are displayed. The user specifies one of them by using the joystick, in mode "interface pointer", and validates with the button.

Analysis of the environment

Most methodologies of wall following use telemetric data from ultrasonic or infrared sensors set on the sides of the mobile base. Our perception is based on the measurements of laser sensors located in front of the wheelchair so we have developed our own methodology. The goal being to keep the wheelchair at a given distance from the wall, it's necessary to extract the distances from the environment to evaluate the situation in which the wheelchair is located relatively to the wall. For that, we consider three significant distances (we are in the case of right wall following, the other one running symmetrically). The first is the distance d_{Dr} to the wall that the user wants to follow. It corresponds to the distance measured to the right side of the wheelchair. The objective is to keep it constant and equal to a safe distance. The second is the distance d_{Av} to obstacles in front of the wheelchair. It allows to adjust the forward speed of the wheelchair. The third is the distance d_{Ga} measured on the left side of the wheelchair providing information on the width of the passage taken. It allows to adjust the safety distance in case of lack of space. To obtain these three distances, we establish three areas as shown in Fig. 9. For each of them, we determine the point of measure which is the closest to the wheelchair and the distance between this point and the wheelchair is considered as the significant distance of this area. Thus, d_{Ga} is the distance measured in the area to the left side, the distance d_{Av} is measured from the front area, and the distance d_{Dr} from the right side area.

Determination of the target point

We must then determine the target point, characterized by its polar coordinates ρ and θ to follow depending on d_{Dr}, d_{Av} and d_{Ga}. The goal is to find the target point allowing adjustment of the trajectory so as to keep the wheelchair at a safe distance d_{Securite}. Initially, we set it to 800 mm. This distance corresponds to half the width of the wheelchair with a safety margin. Then, if the width of the taken passage is reduced, this distance is decreased. So, if d_{Ga} is lower than the safety distance (meaning that the taken passage gets narrower) then the safety distance is gradually decreased to a minimum value set at 400 mm (slightly more than the half-width of the wheelchair). After that, if the passage widens again, the safety distance is increased gradually to 800 mm. It allows to center the wheelchair in a narrow passage of a corridor, or bring the wheelchair close to the wall when it crosses a person in a hallway.

To determine the angle θ so as to keep the following distance d_{Dr} equal to the security distance d_{Securite} the difference between these two distances is used as an image of the orientation error of the wheelchair. We consider this error varies from $-d_{\mathrm{Securite}}$ to d_{Securite} (underneath, the wheelchair would collide with the wall, and above, it would be too far to follow it). Then, we determine the proportional link between the angle θ and the error, in order to obtain a variation of the angle of the target point which will be understood by the closed loop control, i.e. from -90° to 90° (we define $\mathrm{A}_{\max} = 90^\circ$). θ is calculated by means of the equation:

$$\theta = \frac{A_{\max}}{d_{\mathrm{securite}}} \times (d_{\mathrm{Dr}} - d_{\mathrm{securite}}). \tag{6}$$

Finally, ρ is determined in order to gradually reduce the forward speed of the wheelchair when it approaches an obstacle. For this, $\rho = d_{\mathrm{Av}}$ is established when an obstacle is located relatively close to the wheelchair and $\rho = d_{\mathrm{Avmax}}$ is used otherwise. The maximum distance d_{Avmax} is set at 300 mm, corresponding to the distance required to stop the wheelchair when it moves at its maximum speed. Therefore:

$$\rho = \min(d_{\mathrm{Av}}, d_{\mathrm{Avmax}}). \tag{7}$$

3.4. *Closed loop control of the wheelchair in position*

Two control modes can be selected, a manual mode in which the user moves the wheelchair with the joystick and an automatic mode in which each functionality provides a target point where the wheelchair is driven to perform the requested task. In order to solve the problem of impermeability of the technologies used on existing wheelchairs (communication bus, electronic devices establishing the commands depending on the voltages of the joystick), it has been decided to establish our control loop by simulating the joystick of the wheelchair: the voltages which would be sent by the real joystick are generated for each of its positions. Thus, the manual control will be achieved by sending the

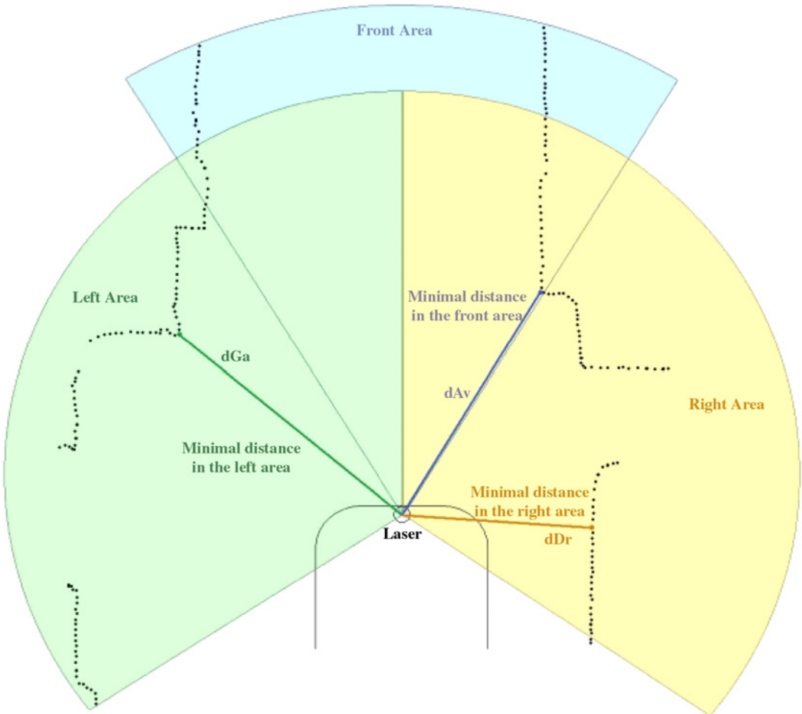

Fig. 9. Determination of the significant distances of wall following.

voltages of the real joystick, and automatic control by sending an angle and amplitude (ρu, θu) of the simulated joystick, calculated by the computer and converted into "voltages from the joystick".

To achieve this, a fuzzy logic block is established allowing the generation of joystick voltages from the angle and amplitude of a simulated joystick. This block is based on analyzing the behaviours obtained for each position of the joystick. The advantage of this system is that it is adaptable to any type of electric wheelchair.

Having chosen not to use proprioceptive sensors, the closed loop control of the wheelchair works only with exteroceptive data. Its role is to bring the wheelchair to a target point during the operation of autonomous functionalities. The feedback is achieved by the analysis of laser data, which are defined for each autonomous functionality (see Section 3.3) and it generates the target point.

The errors are defined by the difference in orientation and distance between the target point and the wheelchair axis, that's why the set-point is initialized at zero. The PID controller, which generates the position of the simulated joystick, is adjusted with the Takahashi method. This allows to compute the parameters of the PID directly in a closed loop, without having to identify the model of the wheelchair [25]. The control loop is illustrated in Fig. 9. The sketch of the feedback control system is given in Fig. 10, it only requires the laser and an onboard computer therefore it could be placed on any standard powered wheelchair.

4. Results

Tests have first been conducted in laboratory by performing these two automatic functionalities in different movements and situations in order to estimate their robustness and effectiveness. To do this, the trajectories of the wheelchair in autonomous mode are observed.

For passing through a narrow passage, the trajectory of the wheelchair is calculated by recording its perception of the focused passage at each iteration. Fig. 11 shows some results obtained during our first tests with the trajectory performed on the right and the video image at the start of experimentation on the left [25]. On these results, the variations of speed can be seen thanks to the deviation between the successive rectangles representing the wheelchair. This allows to analyse the behaviour of the wheelchair during its movement. For example, in the second test, the wheelchair turns slightly to move away from the door, then, moves forward by gradually increasing its forward speed until it arrives in front of it. Then the wheelchair turns to the door by gradually reducing its forward speed while increasing its angular speed until it is aligned with the passage. When the wheelchair approaches alignment, the angular speed is reduced and it gradually accelerates its forward speed until it crosses the door. In this case like in the other, we notice that the trajectories obtained are very similar to those a human being would have achieved manually.

In almost all situations this functionality is effective. However, a limit due to the perception of the wheelchair is observed. When it is very close to a wall and the user wants to pass through a door in its alignment, the wheelchair has to move away from the wall and when the deviation is too large, the door can be lost by the laser vision. In this case the wheelchair stops immediately.

Then, to evaluate wall following, the operation is described by analysing the behaviour of the wheelchair at every step of a standard movement. This is shown in Fig. 12, in which the trajectory of the laser sensor at the front of the wheelchair has been represented. In ①, it moves forward along the wall and when the right distance becomes large (moving past the angle); it turns right in order to keep this distance equal to the safety distance. In ②, the wheelchair approaches the wall at the front and begins to turn slowly (because the wall is first seen through the right distance which becomes less than $d_{Securite}$), then when the wall is seen at the front, the wheelchair slows its forward speed and turns more steeply. Finally, when there is no obstacle in front, the wheelchair accelerates again and, thus, the bend is passed smoothly. In ③, when the wheelchair detects the door on the right side, it perceives the next wall on which it settles, and does not modify its trajectory. In ④ the wheelchair avoids the object to its right side by turning slightly to the left and after that it gradually comes back towards the wall. Finally, in ⑤, when the wheelchair detects the left wall,

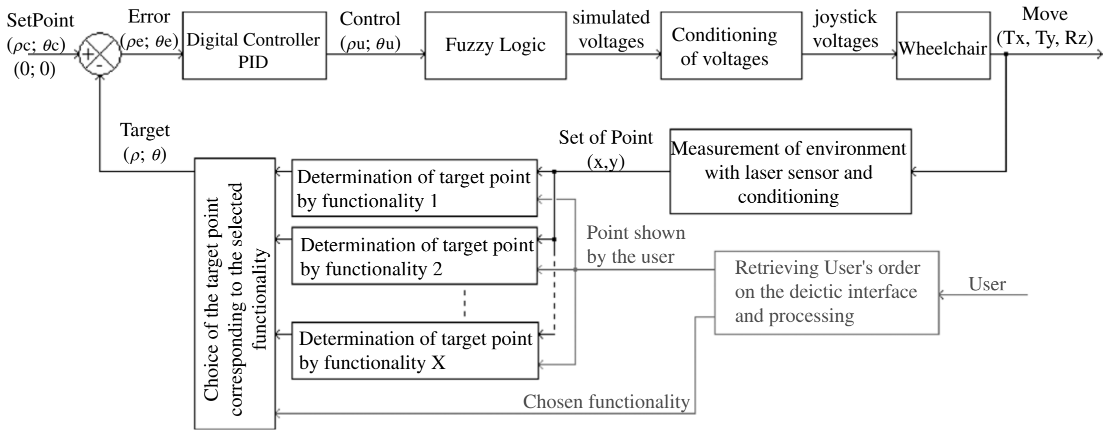

Fig. 10. Position control system of the VAHM-3.

Fig. 11. The view at the start (left) associated to the trajectory (right) performed during an automatic passing through a narrow passage.

it reduces the safety distance in order to be placed in the middle of the corridor. In this example, the trajectory is smooth and offers the expected comfort.

We then tested this functionality in the laboratory in various situations: following a wall on the left, on the right, in a corridor, with or without obstacles, with narrowing, widening. In most configurations the automatic wall following functionality meets our expectations by generating safe and smooth trajectories. These trials allow to identify two difficult situations. The first one is when the wheelchair has to turn over 90° around a wall. As the laser sensor is in front of the wheelchair, the wall comes out of its field of perception before the rotation movement is completed. Thus, this manoeuvre cannot be guaranteed by the functionality. The second one is when the wheelchair follows a wall that leads to a dead end. The safety distance and the speed will be reduced to stop the wheelchair at the end of the dead end. The user then has to exit manually, or, to anticipate this situation by switching to manual mode.

The objective of the system described in this paper is that the user should be able to simply switch from one functionality to another, or, from manual mode to automatic mode (and vice versa) when the wheelchair moves. For example, when the user arrives in front of a door in manual mode, he can use the automatic passing functionality, then, continue by manually moving, and finally, activate the wall following system. To consider several types of switches, we perform a trajectory which involves these different situations (Fig. 13). It begins by passing through a narrow passage, then the user switches to manual control through a simple action on the joystick. Then, to switch from manual mode to the functionality of passing through the narrow passage, the user stops the wheelchair by pressing the button and then the joystick does not control the wheelchair but allows to move the cursor on the screen. Once this second door has been crossed, the user wants to use the wall following functionality. For this, he must stop the wheelchair in order to choose the functionality and points at his target.

On this course, the driving comfort is enhanced by the technical assistance as it avoids fine manoeuvres in delicate passages (doors), or in situations requiring attention in long corridors.

Although the activation of one automatic functionality is performed by means of several actions (choice of functionality, validation, choice of the point on the video image, validation), it is easy

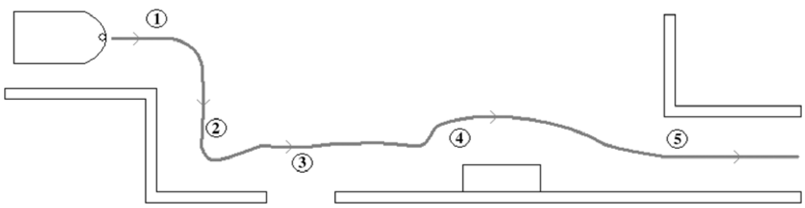

Fig. 12. Example of trajectory performed by wall following.

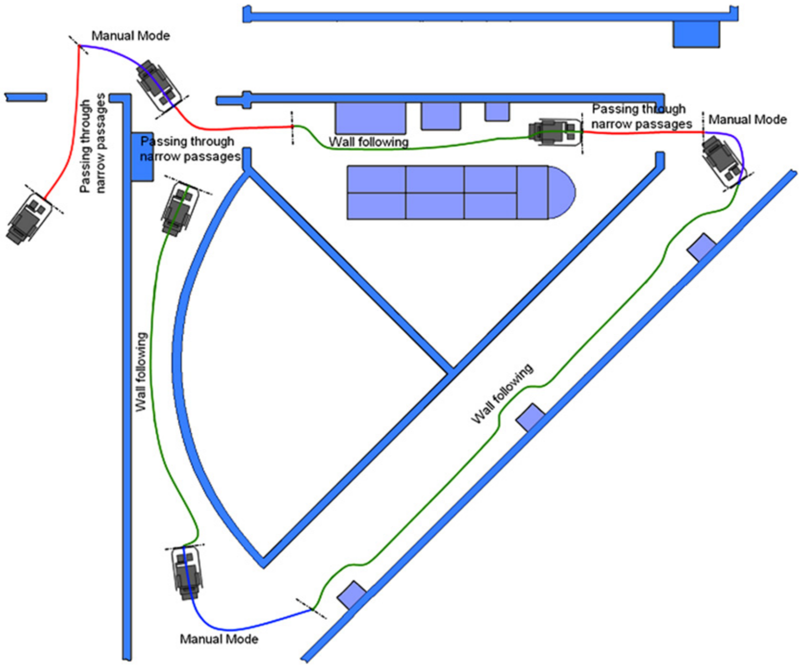

Fig. 13. Wheelchair ride using all automatic functionalities.

to achieve because everything is done at the level of the joystick. Moreover, the fact that the manual control has priority, and that, in any movement, an action on the joystick is followed by an effect, prevents the user from feeling trapped with the automatic mode and allows him to react quickly in emergency situations.

5. Discussion

Tests have been conducted, with and in the presence of people with disabilities and occupational therapists The system was presented to potential users in order to get a first idea about its adequacy with real users' needs. These tests were conducted in several stages, first its functionalities were presented and there were demonstrations, after that, one volunteer tried the prototype (following walls and crossing doors around the room) and finally, there was a discussion with therapists and users about their opinions Generally, the type of interface, the control, and the functionalities offered were appreciated. Moreover, the deictic approach was seen as intuitive and easy to use. The choice of the functionalities seemed natural, especially wall following which appears to make long movements through the corridors of the centre easier. Several requests have been formulated like the introduction of backward trajectories, or giving a wider view of the environment on the interface. We intend to extend the laser perception around the wheelchair. It will allow to enlarge the abilities of functionalities (wall following or passing through a narrow passage) and to use them in backward movement. For this we could place other laser sensors on the sides of the wheelchair. Another way to improve our system would be to simplify the sequence of user orders by activating the autonomous displacement functionality only from the location shown on the video image. For this, as each functionality highlights all the locations where it can be executed, we can be sure that the functionality to activate is that corresponding to the highlighted item. Thus, we can imagine a scan of the highlighted items on the video image on which the user indicates his choice by pressing the button on the active element. Only one action would be required to choose an automatic movement. Thus, the automatic command could be activated from every type of on–off human machine sensor.

6. Conclusion

The design of an approach by deictic control and its implementation for two functionalities of autonomous displacements, show that this method is promising for assistance to the steering of electrical wheelchairs. The additional system is composed of a camera, a laser sensor and a computer, and it can be adapted to any electrical wheelchair without any in-depth modification. Control by pointing the goal to reach on the view of the environment is simple and intuitive, which makes it available to any user. Our methodology to convert an image point into a point of the laser perception space and following by laser perception allows the achievement of autonomous displacements in two modes: "wall following" or "passing through narrow passages", that have been tested in several configurations. Results are satisfactory and the comfort of use is amplified by the fact that in all circumstances, the manual mode has priority. Thus the user never feels the prisoner of an autonomous displacement mode.

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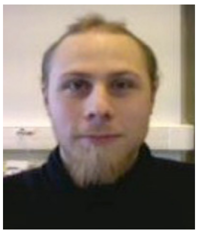

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