Visual servoing for autonomous doorway passing in a wheelchair using a single doorpost

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***Abstract*— Constrained spaces like doorways make efficient navigation using a wheelchair difficult and hazardous, especially in the cases where the user suffers from motor impairments. This paper introduces a monocular vision based autonomous framework for the fundamental task of doorway passing in an electric wheelchair. We propose a novel Lyapunov-based visual control process which is used to generate a smooth trajectory about a single doorpost. The scheme relies on line features which represent the doorposts in an image to calculate the wheelchair motion. This framework ensures that the wheelchair is able to pass the doorway regardless of its starting position. Results of experiments on a robotic wheelchair show that the system is able to perform robustly in different corridors with a variety of door representations.**

I. INTRODUCTION

Wheelchair users typically are the elderly and disabled people, who may suffer from motor impairments like Parkinson's disease or cerebral palsy. It is difficult for a user, particularly in the case of severe disability, to utilize an electric wheelchair in constrained environments efficiently and safely [1]. Keeping in mind that independent autonomy is an essential part of the social and mental well being of an individual [2], smart assistive systems have to be developed in order to facilitate the user to navigate effectively without the help of another person. Among the many wheelchair assistive technologies developed recently, one can mention the TAO Project [3], the NavChair [4], European FP7 Radhar project [5] and the recent SYSIASS project [6] as the state of the art in the area of autonomous wheelchair assistive systems.

In this paper, we address the problem of doorway passage in this work as it is one of the fundamental capabilities for indoor wheelchair navigation. This is a non-trivial task which depends on a variety of high level constraints, one of them for example, being the status of the door (i.e. open/closed). The aim of this work is to focus on low level control without the help of a global planning framework while considering the fact that this is a first step in developing the concept of *semi-autonomous assistive systems* [7]. Such systems require control architectures that are human-in-the-loop schemes where the user has considerable presence in the control loop. Therefore, the higher level attributes are left for the user/home automation system to set as they are not the objective of this work. Our previous work [8] has shown a similar robust visual servoing system for corridor following.

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Some of the previous work addressing the autonomous doorway passage issue using an intelligent wheelchair are summarized in [9]. To explain further, the capability to perform autonomous door passage in the case of the TAO wheelchair was achieved using a low speed discontinuous trajectory [3]. Furthermore, in [10] a Bezier curve-based smooth dynamic trajectory planning framework was presented, and finally a SLAM based approach with an integrated frontier point method was utilized in [11] to perform smooth autonomous doorway passing. The two major highlights of the above mentioned systems are that they utilize complex multi-sensor architecture, explicit environment representations and/or visual memory based solutions thus requiring a dedicated learning stage.

Thus, this paper proposes a solution which targets low-cost hardware (two monocular cameras in the present case, one for the doors on the left and one for the doors on the right) and which avoids any explicit representation of the environment. These are important advantages owing to the fact that low cost sensors ensure widespread usage which can lead to easier commercialization. It also facilitates the system to perform in any indoor environment without the use of global a-priori data. A similar vision-based system was proposed by [12] for corridor navigation of a humanoid with capability of turning at junctions.

In this paper, we typically consider that the door is already open (e.g. by means of a home automation system which can be directly set on the wheelchair). If the idea is to design a robust low-level controller that achieves the adequate motion given a detected doorway, the use of monocular cameras add major constraints. Indeed, when passing the door, the *doorpost* at the far end of the desired trajectory will no more be present in the field of view of the camera. Consequently we have to design a solution which uses a single (i.e. the initial) doorpost in the image as the input to the system.

A Lyapunov-based visual servoing scheme is designed which generates a smooth (and safe) trajectory around the detected doorpost. The control system uses the position of the doorpost in the image to perform the navigation. Thus a dedicated door detection and tracking framework is concurrently employed for this purpose. It is shown that the control process is able to autonomously take up a circular trajectory around the doorpost for a smooth passage. Results of experiments on a robotic wheelchair platform show the feasibility and robustness of the proposed system as a low-level control system for a semi-autonomous assistive wheelchair to be designed as a second step.

The paper is divided as follows. Section II gives the geometrical modelling of the robotized wheelchair. The visual servoing scheme is explained in Section III. Final Section (IV) deals with experimental results.

II. MODELLING

We model the wheelchair as a six-wheeled robot which moves on a horizontal/inclined plane where the two wheels located in the middle are differentially actuated. For support, four additional caster wheels with two each in the front and back are required. This configuration allows modelling the wheelchair as a unicycle-like robot thus matching non-holonomous constraints. The two robot DOFs are its translational velocity u and rotational velocity ω. The cartesian frames considered in this study are depicted in Figure 1. The wheelchair uses two monocular cameras located on each side which are rotated at a suitable angle θ away from the body of the robot as the perception medium. This is done for the purpose of keeping the doorpost in view while the wheelchair passes through a door (on either side). In this study, we formulate the solution for the camera located on the right side of the wheelchair. It can be said the solution for the other camera would be symmetric in the opposite sense.

According to Figure 1, we define the robot frame as $\mathcal{F}_r(P_O, x_r, y_r, z_r)$. The origin of the robot frame $\mathcal{F}_r$ is chosen as the mid-point of the line segment joining the two centres of the differential wheels. The camera (right) frame is defined as $\mathcal{F}_c(C, x_c, y_c, z_c)$ where its optical center is given by C located at coordinates $(l, -w, 0)$ and rotated at an angle θ with respect to $\mathcal{F}_r$. Note that $w > 0$ and $\theta < 0$ for the configuration depicted on Figure 1.b.

By denoting ${}^f\mathbf{v} = \left[{}^f u_x, {}^f u_y, {}^f u_z, {}^f \omega_x, {}^f \omega_y, {}^f \omega_z\right]^T$ the velocity of a frame $\mathcal{F}_f$ expressed in $\mathcal{F}_f$, where the first three components represent the translation velocities and the last three components represent the rotational velocities, we have

$$ {}^r\mathbf{v} = [u, 0, 0, 0, 0, \omega]^T . \quad (1)$$

Since the translation ${}^r\mathbf{t_c}$ between the robot frame and camera frames is given by vector $[l, -w, 0]^T$, by applying the well known formula

$$ {}^c\mathbf{v} = \begin{bmatrix} {}^c\mathbf{R}_r & [{}^c\mathbf{t}_r]^c_\times \mathbf{R}_r \\ 0 & {}^c\mathbf{R}_r \end{bmatrix} \quad {}^r\mathbf{v} \quad (2)$$

where ${}^c\mathbf{R}_r$ is the rotation matrix between the camera and the robot, we obtain

$$ {}^c\mathbf{v} = [{}^c u_x, 0, {}^c u_z, 0, {}^c \omega_y, 0] \quad (3)$$

where

$$ \begin{cases} {}^c u_x = u \sin\theta - \omega(l \cos\theta + w \sin\theta) \\ {}^c u_z = u \cos\theta + \omega(l \sin\theta - w \cos\theta)) \\ {}^c \omega_y = -\omega \end{cases} \quad (4)$$

III. LYAPUNOV-BASED VISUAL SERVOING

The aim of a visual servoing scheme is to control the relevant DOFs by minimizing the errors between a set of measured features in the image and a set of desired features [13]. Thus control laws have to be formulated relating the image features to the system dynamics. In the present case, we choose the rotational velocity ω as the DOF to be controlled while applying a constant forward velocity $u = v$.

As stated in Section I, we propose to use a single doorpost. A novel Lyapunov-based control scheme is designed which exploits the position of the line representing the initial doorpost of the door in the image (i.e. the doorpost closer to the robot) as visual feature.

A. Door recognition and tracking

There are several methods for detecting and representing doors in an indoor navigation construct [14] [15]. But, in the present case, the representations have to be simple enough so that effective features can be extracted.

Consequently, we use a door detection and tracking framework specifically developed for indoor navigation tasks [16]. This framework employs a set of information including the vanishing point to estimate a simple 3-D geometrical structure of the corridor. This structure, then defines a search space in which rectangular shapes representing doors are searched for, by employing a constraint that the doorposts are nearly verticals in the image.

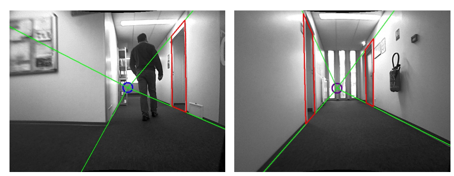

Fig. 2. Door detection framework

For tracking, a dedicated 2-D edge tracker inspired from the *Moving Edges* (ME) algorithm [17] [18] is applied on the doorposts. The implementation of this framework on a generic corridor is shown in Figure 2.

B. Visual Feature - Definition and Extraction

Considering Figure 3, if the foot of the doorpost is represented by the point D then $D = (x_d, h, z_d)^T$ in the plane (x_c, z_c) in the frame $\mathcal{F}_c$. In polar coordinates point D is represented by

$$ r = \sqrt{x_d^2 + z_d^2}, \quad (5a)$$
$$ \phi_d = \arctan(x_d/z_d), \quad (5b)$$

If the point D projects in the image at point $P = (x_P, y_P)$, then due to a calibrated camera, the perspective projection equations reduce to

$$ x_P = \frac{x_d}{z_d} $$

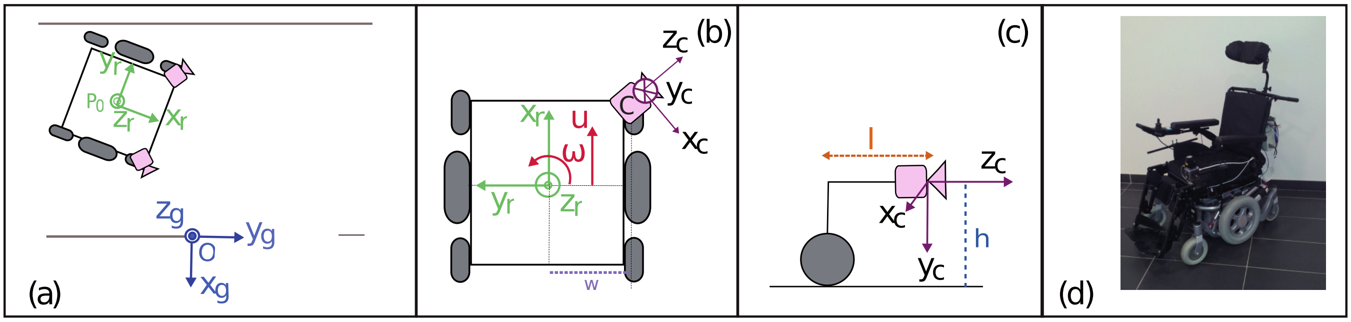

Fig. 1. Definition of the robot and camera frames of reference (a),(b) and (c) along with the robotic platform (d)

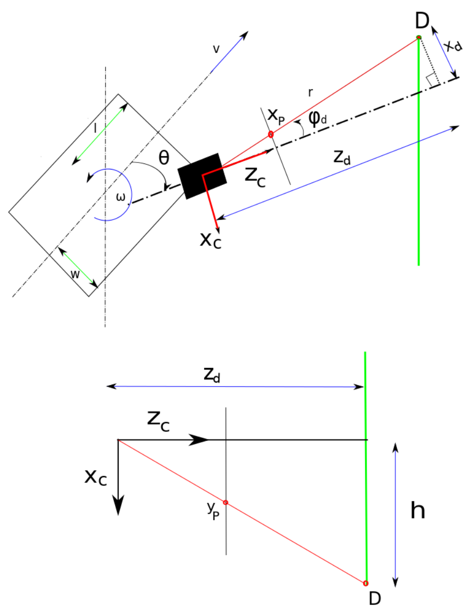

Fig. 3. Geometrical constraints while considering doorway passing(top view on the top, side view on the bottom)

and

$$y_P = \frac{h}{z_d}.$$

To perform a successful doorway passing, the wheelchair needs to avoid the closest doorpost with a predefined margin m. To do so we formally define the visual feature as the angle ϕ_d. We do so due to the fact that it can be easily estimated from the measure of the position of the doorpost. Indeed, from x_P coordinate, we immediately obtain, using (5b),

$$\phi_d = \arctan(x_P).$$

Similarly from the y_P coordinate of P, we can compute the distance r. Since $z_d = r\cos(\phi_d)$ (see Figure 3), we finally obtain

$$r = \frac{h}{y_P \quad \cos(\phi_d)}. \tag{6}$$

Now, to assign a desired value ϕ_d^* which must be achieved by ϕ_d for task completion, we have to first assess the trajectory the wheelchair must follow for passing through the doorway.

C. Desired trajectory

We specify the desired trajectory that the camera should follow for a successful doorway passage as presented in Figure 4. This trajectory has been chosen since the wheelchair must be able to turn around the doorpost with a tolerance of m no matter what its starting position and orientation are. Consequently, the wheelchair must ideally take a tangential path towards an imaginary circle centered at the doorpost defined by a margin m. When the camera distance to the doorpost r is equal to m, it must take up a smooth circular trajectory about the doorpost as shown.

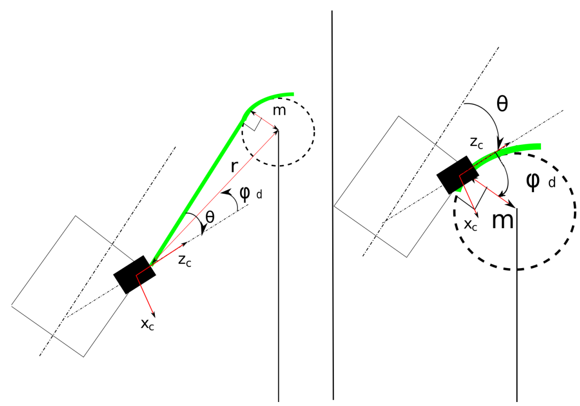

Fig. 4. The desired camera trajectory shown in green

The trajectory can thus be decomposed into two parts with the first one containing the tangential motion towards the circle (when $r > m$) and the second containing the circular motion around the doorpost (when $r \leq m$).

The characteristic of the tangential motion toward the circle is that ideally the value of ϕ_d should be equal to $\theta + \arcsin(\frac{m}{r})$. Thus if the desired value of $\phi_d = \phi_d^*$, then

$$\phi_d^* = \arcsin(\frac{m}{r}) + \theta \quad \text{if} \quad r > m. \tag{7}$$

As r gets close to m, the wheelchair must switch to the circular motion around the doorpost. For such case it is obvious from Figure 4 that the desired value of the visual feature ϕ_d^* must be equal to $\theta + \frac{\pi}{2}$. Therefore, we can state that

$$\phi_d^* = \theta + \frac{\pi}{2} \quad \text{if} \quad r \leq m. \tag{8}$$

D. Control law formulation

To achieve an asymptotically stable condition for $(\phi_d - \phi_d^*)$, we select as a classical Lyapunov candidate function

$$V = \frac{1}{2}(\phi_d - \phi_d^*)^2. \tag{9}$$

Of course we have $V = 0$ when $\phi_d = \phi_d^*$. We now have to compute $\dot{V}$ to deduce a stable control scheme. We have,

$$\dot{V} = (\phi_d - \phi_d^*)(\dot{\phi_d} - \dot{\phi_d^*}). \tag{10}$$

We deduce $\dot{\phi_d}$ from equations (4), (5b) and from the well known kinematics equation $\dot{\mathbf{x}} = -\mathbf{u} - [\omega]_\times \mathbf{x}$ as

$$\dot{\phi_d} = \omega + \frac{1}{r}\left[Su + (lC + wS)\omega\right], \tag{11}$$

where $S = \sin(\phi_d - \theta)$ and $C = \cos(\phi_d - \theta)$.

Then, from (7) and (8) we obtain

$$\dot{\phi_d^*} = -\frac{d(\arcsin(\frac{m}{r}))}{dt} = \frac{\dot{r}m}{r\sqrt{r^2 - m^2}} \quad \text{when} \quad r > m \tag{12}$$

and

$$\dot{\phi_d^*} = 0 \quad \text{when} \quad r \leq m. \tag{13}$$

Again, from equations (4), (5a) we obtain $\dot{r}$ as

$$\dot{r} = -Cu + (lS + wS)\omega \tag{14}$$

Now, by substituting (14) in (12), and using equations (11) and (12) for $\dot{\phi_d}$ and $\dot{\phi_d^*}$, we finally obtain an expression for $\dot{V}$ of the form

$$\dot{V} = (\phi_d - \phi_d^*)\left(uA(r, \phi_d) + \omega(1 + B(r, \phi_d))\right) \tag{15}$$

where, when $r > m$

$$\begin{cases} A(r, \phi_d) = \left(\dfrac{S}{r} + m\dfrac{C}{r\sqrt{r^2 - m^2}}\right) \\ B(r, \phi_d) = \dfrac{lC - wS)}{r} - m\dfrac{wC + lS}{r\sqrt{r^2 - m^2}}. \end{cases}. \tag{16}$$

and when $r \leq m$ in which case we recall that $\dot{\phi_d^*} = 0$,

$$\begin{cases} A(r, \phi_d) = \left(\dfrac{S}{r}\right) \\ B(r, \phi_d) = \dfrac{lC - wS}{r}. \end{cases}. \tag{17}$$

Thus in both cases, we choose ω such that

$$\omega = \frac{-k(\phi_d - \phi_d^*) - A(r, \phi_d)u}{1 + B(r, \phi_d)}, \tag{18}$$

where k is a positive gain factor, so that $\dot{V} < 0$. This ensures that the system is globally asymptotically stable and the visual feature ϕ_d will converge asymptotically to the desired value ϕ^*.

Furthermore, when $r > m$, it can also be shown that $\omega = 0$ when $\phi_d = \phi_d^*$ thus providing a straight tangential motion towards the circle. Finally, as soon as $\phi_d = \phi_d^* = \theta + \frac{\pi}{2}$ (when $r \leq m$) from (17) we have $A = \frac{1}{r}$ and $B = -\frac{w}{r}$ from which we deduce $\omega = \frac{-u}{r-w}$ which naturally corresponds to a circular motion.

IV. Experiments and Results

The robotized wheelchair used in this study is an off-the-shelf Penny and Giles system adapted to use ROS middleware. It is equipped with two Raspberry PI camera modules with 100° field of view. The cameras are aligned at an angle of $\theta = 45°$ with respect to the frame $\mathcal{F}_r$. The video stream from the camera runs at 15 frames per second and correspond to 808 x 480 pixels. The cameras were coarsely calibrated with $h = 0.5$m, $l = 0.0$m, $w = -0.4$m. It has to be noted that we focus our experimentation process on the right camera that was installed at the center right of the wheelchair body thus making $l = 0$. This is done in order to ensure the wheelchair is able to view the doorpost until the convergence of the control law. Visual feature extraction and control law computation were performed using the ViSP software [19].

The aim of the following experiments was to validate the convergence of the control law and to assess the effectiveness of the control system as a first step in developing it into a *semi-autonomous system*. Thus, autonomous door passage experiments were conducted where the wheelchair started at an unknown position from a specific door. The wheelchair was given a constant forward velocity ($v = 0.2\text{ms}^{-1}$) and the visual servoing was applied to control the angular velocity ω while the wheelchair managed to pass the specific doorway.

A suitable value of the margin m is chosen based on the width of the wheelchair and the doorpost (see Figure 4). In the present case we set m as 0.2 m. The positive gain factor k was empirically tuned and set as 1.5. The results of the two cases presented here have been realised in the corridors of Inria building 12C in Rennes. Case I where the wheelchair started roughly $r \sim 1.9$ meters away from the doorpost and Case II where the wheelchair started roughly $r \sim 1.5$ meters. The servoing process is stopped as soon as the wheelchair is positioned in front of the doorway in Case I while it is stopped after the wheelchair loses the doorpost from its field of view in Case II.

The reconstructed trajectories of the wheelchair for Cases I and II with respect to the doorpost are given in Figure 5. These trajectories have been obtained from the odometry sensors that are used here for validation purposes. From the trajectories we can clearly observe the tangential motion of the wheelchair towards the imaginary circle centred at the doorpost and defined by m. Also, the circular motion of the wheelchair about the doorpost is clearly visible, especially in Case II.

In Figures 6 and 7 we can observe the evolution of the visual feature ϕ_d, the distance from the camera to the

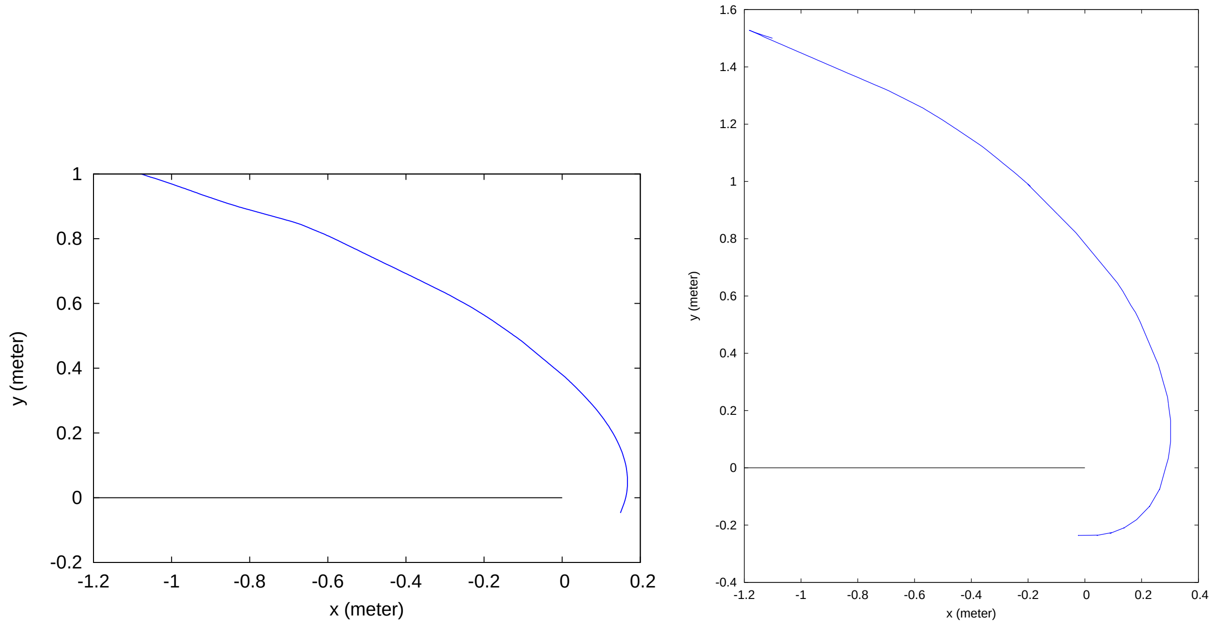

Fig. 5. The trajectory of the wheelchair with respect to the doorpost - Cases I and II

doorpost r and the servoing error $(\phi_d - \phi_d^*)$ for cases I and II respectively.

We can see from the figures that the visual feature ϕ_d converges to its desired value of $\phi_d^* = \theta - \pi/2 \sim -0.8$ rads in both cases. Moreover, as expected, the servoing error $(\phi_d - \phi_d^*)$ exponentially decreases.

In particular, as r gets closer to m, the forward velocity u has an increasing impact on ϕ_d. Thus we observe an increase in the servoing error: this is due to the fact that we do not have any estimation of the actual forward velocity of the wheelchair and we assume it remains constant for the control law computation. But as soon as the control law switches (i.e when $r = m$), the feature error again asymptotically converges to zero. Figures 6 and 7 also show that the distance from the camera to the doorpost r reduces as desired and converges almost linearly to the margin $m = 0.2$ meters. Thus the above results validate the stability of the control law.

Furthermore, for Case II, Figure 8 shows a representative camera trajectory during the experimentation along with the images acquired by the camera at four instants during the servoing process. The red line represents the position of the doorpost acquired by the tracker from where the value of ϕ_d is computed. The green line represents the position (ϕ_d^*) in the image where the doorpost must be in order to achieve the desired trajectory. The cross represents the foot of the doorpost estimated by the system from which the distance r is computed. We can see that the foot of the doorpost is not visible as the wheelchair gets closer to the doorway (see Figure 8(c)). In that case we rely on odometry for estimating the position of this point.

Finally, when designing an assistive system for the task of doorway passage in a wheelchair, the main factor to take into account is that the wheelchair must not collide with the doorpost. We can clearly observe that the control law forces the wheelchair to respect the margin m by taking a circular motion around the doorpost (especially in Case II). The proposed control system is thus a feasible design as a first step in designing a semi-autonomous assistive system as well.

V. Conclusion

In this work, we proposed a visual servoing control scheme for autonomously passing a doorway in a wheelchair. The aim is to design a low-level control system which can be utilised, as a second step, in a semi-autonomous architecture where the user has considerable presence in the control loop.

A novel Lyapunov-based control scheme has been proposed to control the angular velocity of the wheelchair while maintaining a constant forward velocity as the wheelchair manages to pass through a doorway. Also, it has been taken into account that the wheelchair is able to position itself in front of the doorway no matter what its starting position is by respecting a margin m.

Experiments have been conducted on a robotized wheelchair. Results show the convergence of the control law and the feasibility of the system as a first step in designing a semi-autonomous assistive system. Future work aims at developing as mentioned a complete assistance system by taking into account the human-in-the-loop condition.

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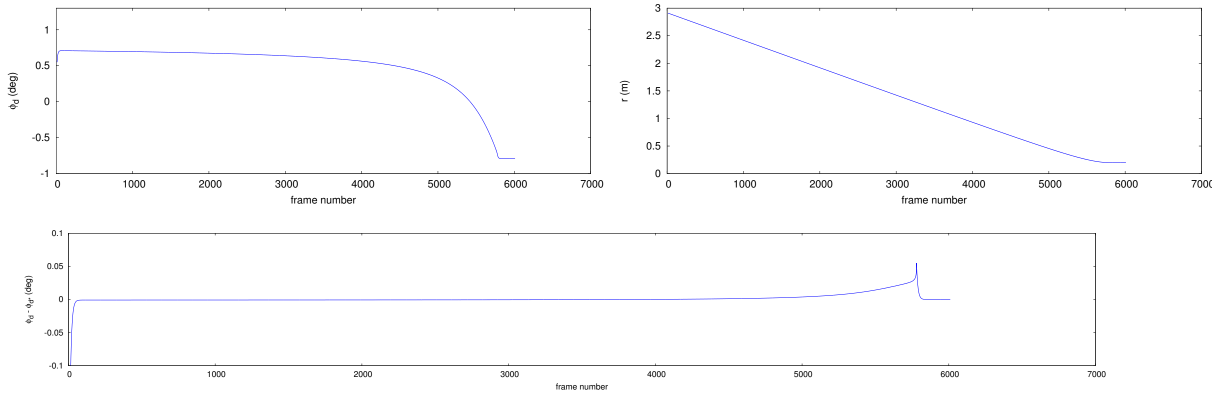

Fig. 6. Evolution of ϕ_d, r, $\phi_d - \phi_d^*$ - Case II

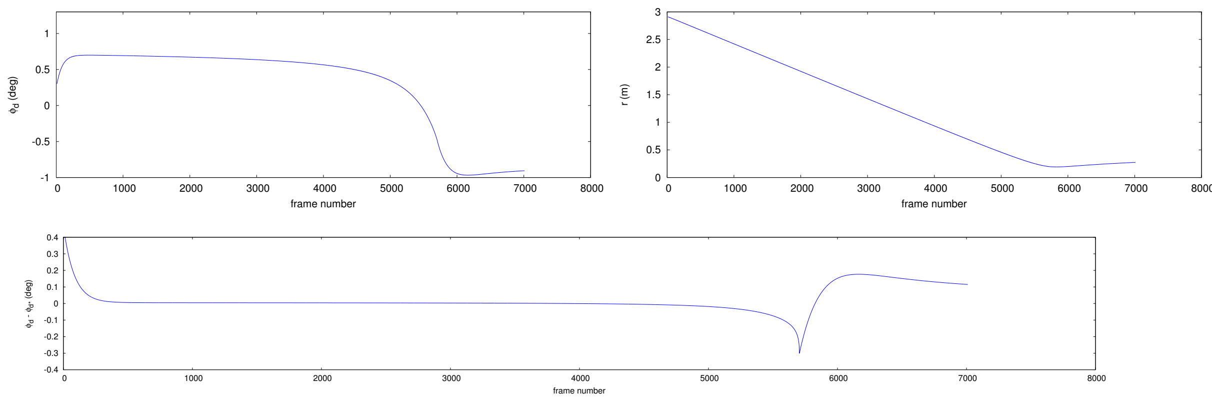

Fig. 7. Evolution of ϕ_d, r, $\phi_d - \phi_d^*$ - Case I

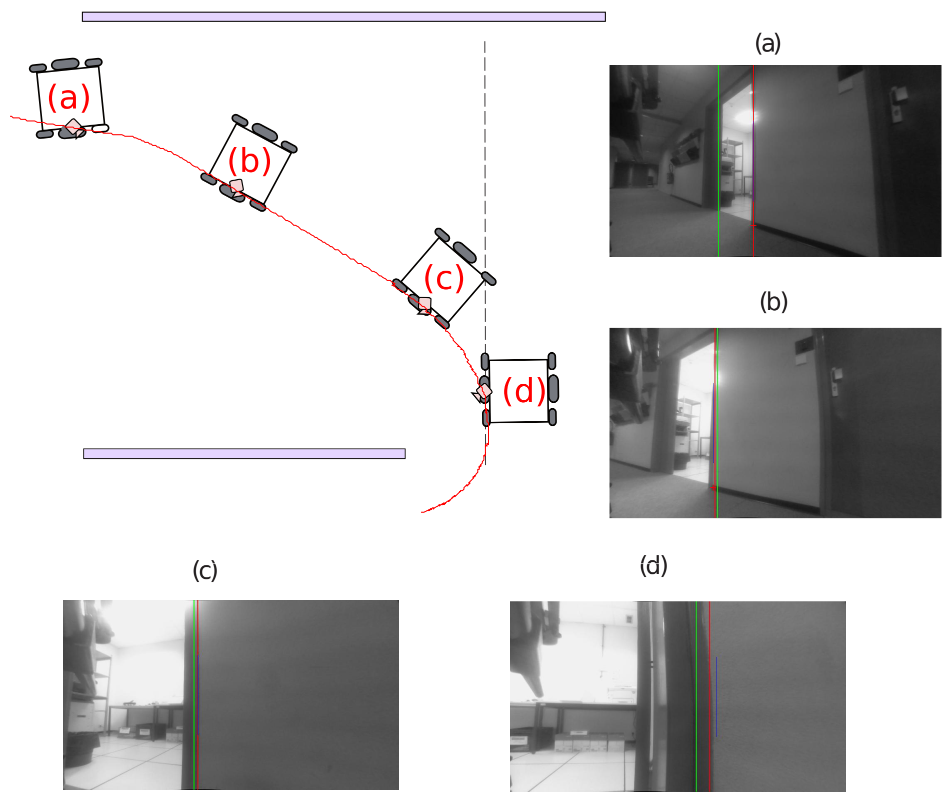

Fig. 8. Reconstructed trajectory with the camera view - Case II

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