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# Semi-autonomous Navigation of a Robotic Wheelchair

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**Abstract.** The present work considers the development of a wheelchair for people with special needs, which is capable of navigating semi-autonomously within its workspace. This system is expected to prove useful to people with impaired mobility and limited fine motor control of the upper extremities. Among the implemented behaviors of this robotic system are the avoidance of obstacles, the motion in the middle of the free space and the following of a moving target specified by the user (e.g., a person walking in front of the wheelchair). The wheelchair is equipped with sonars, which are used for distance measurement in preselected critical directions, and with a panoramic camera with a 360 degree field of view, which is used for following a moving target. After suitably processing the color sequence of the panoramic images using the color histogram of the desired target, the orientation of the target with respect to the wheelchair is determined, while its distance is determined by the sonars. The motion control laws developed for the system use the sensory data and take into account the non-holonomic kinematic constraints of the wheelchair, in order to guarantee certain desired features of the closed-loop system, such as stability. Moreover, they are as simplified as possible to minimize implementation requirements. An experimental prototype has been developed at ICS–FORTH, based on a commercially-available wheelchair. The sensors, the computing power and the electronics needed for the implementation of the navigation behaviors and of the user interfaces (touch screen, voice commands) were developed as add-on modules and integrated with the wheelchair.

**Key words:** wheelchairs, robot navigation, non-holonomic mobile robots, person following, sensor-based control, panoramic cameras.

## 1. Introduction

People with impaired mobility are faced with multiple challenges when moving in environments designed for people without such problems. Existing assistive devices, such as wheelchairs, are primarily useful to people whose mobility problems are not combined with limited fine motor control of their upper extremities or reduced ability for perception of their environment, which render control of a wheelchair problematic. Such combinations of mobility, motor control and perception problems are not uncommon. Thus, the advances in robotic technology, that initially targeted mobile robot navigation [8], become relevant in building more effective assistive devices.

The present work considers the enhancement of a commercially-available power wheelchair (usually driven manually through a joystick) by the computational and sensory apparatus necessary for automating certain frequently-occurring navigation tasks. The implemented tasks are:

- Motion in the middle of the free space defined by the obstacles and the environmental layout.
- Following of a target (e.g., a moving person) specified by the user.
- Obstacle avoidance.
- Motion towards a desired direction which is specified by the user using appropriate man–machine interfaces (e.g., touch screen, voice commands).

Some of these tasks are carried out in cooperation with the user, hence the term *semi-autonomous navigation.* The difference from the usual mode of operation of such a wheelchair is that the user is relieved from its continuous control via the joystick during the execution of such a task and has merely to issue some high-level commands, usually when the task is initiated (e.g., to select the person to be followed by pointing on a touch screen, to select the direction of motion by appropriate voice commands, etc.).

Various approaches to robotic navigation range considerably in the degree of autonomy they support. On one end lies “manually-controlled” platform motion, whereas, on the other lies fully autonomous navigation in unstructured environments. For the case of robotic wheelchairs, the former approach has already led to market products. Regarding autonomous navigation approaches, they are currently far from being both reliable and cheap enough in order to be introduced in this sector. However, there is a clear demand for technology that would increase the independence of people with special needs [5, 4]. Towards this end, the proposed approach for assistive navigation presents a good compromise regarding the autonomy/reliability trade-off. It relieves the user from the continuous operation of the wheelchair, involving him/her only in higher level decisions. The current implementation of the above navigation behaviors does not support navigation in non-visible areas, nor recognition of the target objects. It is, however, of utmost importance that the enhanced navigation capabilities are offered without compromising robustness and reliability in platform operation.

The sensory modalities used for the development of the robotic wheelchair are odometry, sonars and panoramic vision. The sonars measure range in preselected critical directions around the wheelchair. The panoramic camera provides visual data from a 360° field of view and constitutes an important source of sensory information for some of the developed navigation capabilities.

The rest of the paper is organized as follows: Section 2 presents issues related to panoramic cameras that constitute essential background to this work. Section 3 discusses the system’s navigation behaviors. Section 4 provides some details on the experimental prototype that was built. Finally, Section 5 summarizes the paper.

## 2. Panoramic Vision

Panoramic cameras have been extensively studied in previous works [9, 12]. Their main advantage in robotic navigation is their ability to "look" simultaneously in arbitrary directions and thus, robotic tasks requiring movement in one direction and observation of environmental features in a different one, are greatly facilitated. In mobile robotics, the main alternative to panoramic cameras are moving cameras mounted on pan-and-tilt platforms or multiple-camera systems mounted on the robot. The use of a moving, limited-f.o.v. camera on a wheelchair necessitates its precise orientation, especially when the wheelchair is also moving; this can be a challenging control problem [15]. Looking in a direction outside the current field of view of the camera requires repositioning the sensor, which, in turn, involves a delay that may be unacceptable when the environment also changes. This problem becomes more severe when the direction where the camera needs to look next is not known a priori; time-consuming exploratory actions are then necessary. In the case of multiple-camera systems, the lack of a common nodal point of the cameras and the elaborate calibration required, complicate their use. Also, the duplication of optical and electronic components increases the cost of the system. Moreover, the system lacks flexibility in observing an arbitrary direction of interest. In contrast to the above, panoramic cameras offer the capability of extracting information simultaneously from all desired directions of their visual field. Neither moving parts,

*Figure 1.* Sample panoramic image of an indoors environment.

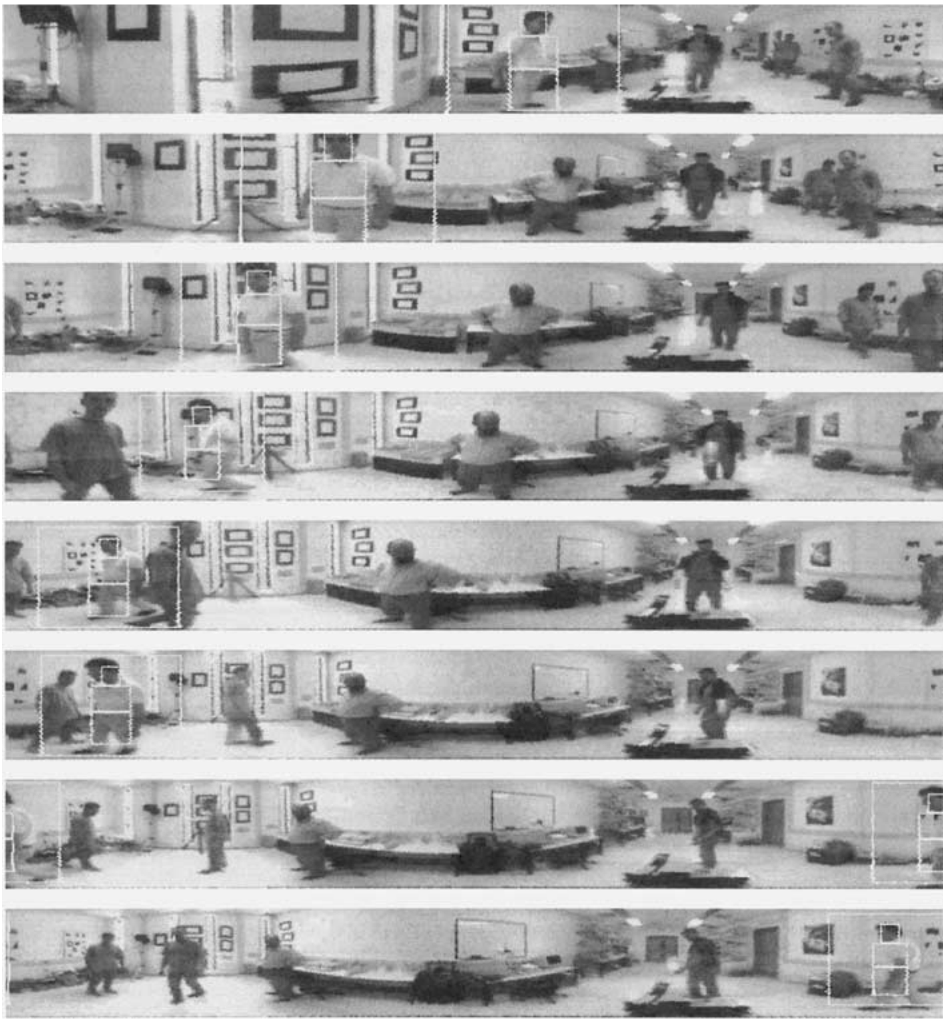


*Figure 2.* Unfolded panoramic images: person tracking sequence.

nor elaborate control mechanisms or expensive hardware is required to achieve this capability.

A panoramic image can be “unfolded” giving rise to a cylindrical image, using a polar-to-Cartesian transformation. Different columns of the resulting cylindrical image correspond to different viewing directions. Figure 1 shows an example of a panoramic image and Figure 2 shows examples of unfolded ones. Note that the leftmost and rightmost parts of each image correspond to the same visual direction. The property of the resulting image is that the full 360° field of view is mapped on its horizontal dimension. In the remainder of this paper, unless otherwise stated, the term panoramic image refers to an unfolded one.

Let F denote a feature of the environment and let $\phi$ be the bearing angle of feature F in the panoramic image. Since we deal with panoramic images, the bearing angle of feature F can easily be computed as: $\phi = 2\pi x/s$, where $x$ is the $x$-coordinate of the feature in the image, and $s$ is the width of the panoramic image (both measured in pixels). Thus, recovering the orientation of an environmental feature with respect to the panoramic camera becomes trivial, once the feature has been identified in the panoramic image.

## 3. Navigation Behaviors

The main navigation capabilities developed on the robotic wheelchair are the motion in the middle of the free space defined by obstacles or environment features, the following of a target (e.g., a moving person) specified by the user and the motion towards a desired direction which is specified by the user using a touch screen or voice commands. In this section we present the first two behaviors in more detail. It should also be noted that a low-level obstacle avoidance behavior is implemented, which assumes the control of the platform as soon as an imminent collision with obstacles in the environment is predicted through sonar data processing.

### 3.1. MOTION IN THE MIDDLE OF FREE SPACE

The wheelchair employed is kinematically equivalent to a mobile robot of the unicycle type. We suppose that it is moving on a planar surface inside a "corridor" formed by obstacles, which can be locally approximated by two straight parallel walls. We further suppose that appropriate sensors able to specify distance to the walls are mounted on the wheelchair (e.g., sonars) (Figure 3).

Consider an inertial coordinate system $\{F_O\}$ centered at a point $O$ of the plane and aligned with one of the walls, a moving coordinate system $\{F_M\}$ attached to the

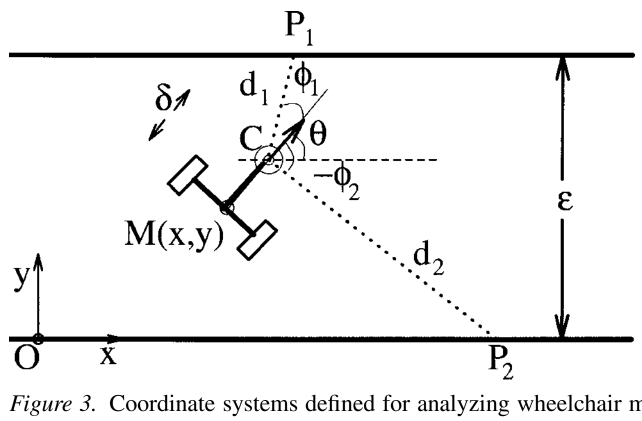



*Figure 3.* Coordinate systems defined for analyzing wheelchair motion in the middle of free space.

middle $M$ of the wheelchair's wheel axis and another moving one $\{F_C\}$ attached to the nodal point $C$ of the range finder. Let $(x, y)$ be the position of the point $M$ and $\theta$ be the orientation of the wheelchair with respect to the coordinate system $\{F_O\}$. Let $\delta \geqslant 0$ be the distance of the point $C$ from $M$ and $\epsilon > 0$ the width of the corridor. We suppose that the wheels of the mobile platform roll without slipping on the plane supporting the system. This induces a *non-holonomic constraint* on the motion of the wheelchair, due to the fact that the instantaneous velocity lateral to the heading direction of the mobile platform has to be zero. From this, we get the usual unicycle kinematic model [2] for the mobile platform

$$\dot{x} = v\cos\theta, \qquad \dot{y} = v\sin\theta, \qquad \dot{\theta} = \omega, \tag{1}$$

where $v \stackrel{\text{def}}{=} \dot{x}\cos\theta + \dot{y}\sin\theta$ is the heading speed and $\omega$ is the angular velocity of the unicycle. Consider the rays $d_1$ and $d_2$ in the forward directions $\phi_1$ and $-\phi_2$ with respect to the heading direction of the wheelchair (Figure 3). We suppose that $d_1$ intersects the left wall, while $d_2$ intersects the right wall of the corridor and that $y \in (0, \epsilon)$ and $\theta \in (-\phi, \phi)$, with $0 < \phi < \pi/2$. Let $\phi_1 = \phi_2 = \phi$.

The task of staying in the middle of the corridor consists of using the angular velocity $\omega$ of the system to drive the lateral distance of the wheelchair from the walls, as well as its orientation, to desired values. This amounts to asymptotically stabilizing the state $(y, \theta)$ of the subsystem

$$\dot{y} = v\sin\theta, \qquad \dot{\theta} = \omega \tag{2}$$

of the unicycle kinematics of Equation (1) to $(y_\star, \theta_\star) = (\epsilon/2, 0)$, using only the angular velocity $\omega$ as the control of the system. The heading speed $v(t)$ cannot be controlled, but we suppose that it is known at all times (for details on stability concepts and methods, see [7, 16]).

When reconstruction of the state $(y, \theta)$ from the sensory data is possible, a path-following control scheme, similar to the one developed in [10] can be applied to the system.

In the case that reconstruction of the state $(y, \theta)$ from the sensory data is not desirable or possible, a motion control scheme based on the scaled difference of inverse depths from the corridor walls is possible (cf. [14] for details.) In the case that $v$ is time-varying, but strictly positive ($v(t) > 0, \forall t \geqslant 0$), the angular velocity control

$$\omega = -k_1 v \sin\phi\left(\frac{1}{d_1} - \frac{1}{d_2}\right), \tag{3}$$

with positive gain $k_1$, can be shown to locally asymptotically stabilize the system of Equation (2) to $(y_\star, \theta_\star)$. An input scaling procedure [10] can be used to reduce the linearization of the closed-loop system around the desired equilibrium to a linear time-invariant system whose asymptotic stability can be established by classical results like the Routh–Hurwitz test. Linear theory tools can also be employed to select the gain $k_1$ (e.g., for critical damping of the trajectory).

PROPOSITION 1. *Let the heading speed v of the unicycle of Equation (1) be time-varying and assume that it is strictly positive at all times, piecewise continuous and bounded. Let $d_1$ and $d_2$ be the distances from the walls as specified in Figure 3. The angular velocity $\omega$ of Equation (3) with gain $k_1 > 0$, stabilizes locally asymptotically the subsystem of Equation (2) of the unicycle kinematics to the equilibrium* $(y_\star, \theta_\star) = (\epsilon/2, 0)$.

When $v$ is negative, a similar approach, employing "backwards looking" rays can be employed.

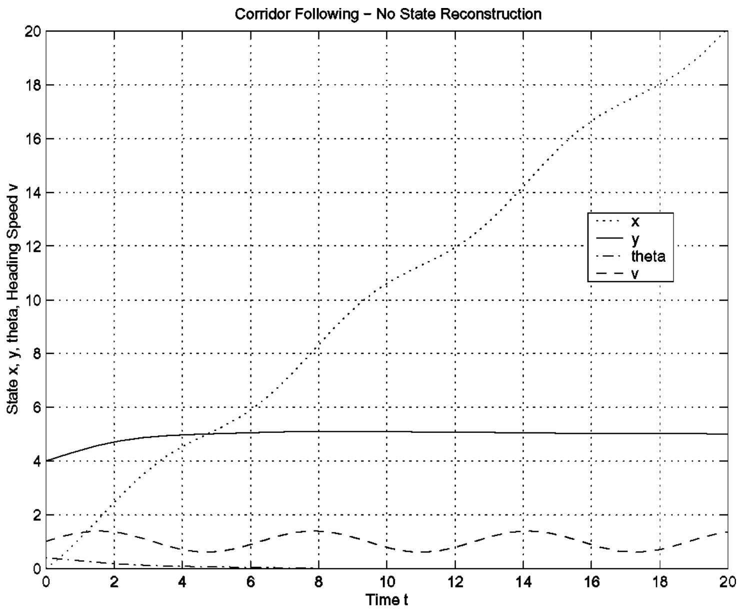
Figure 4 shows MATLAB simulations of the system for the controls of Equation (3) and for the case where the heading speed of the mobile robot is strictly positive and varies periodically with time. The state $(y, \theta)$ is not being reconstructed in this case. The control $\omega$ is used to achieve stabilization of $(y, \theta)$ to the desired values $(5, 0)$ starting from the initial state $(4, 0.4)$.

In the experimental prototype developed, this behavior is implemented using sonars. However, in [14] we have shown that by computing optical flow in selected areas of a panoramic image, we can derive the quantity $(1/d_1 - 1/d_2)$, and use panoramic vision for implementing this behavior. The method presented in [14] is based on the method proposed in [1] and it is inspired by experiments on the navigational capabilities of bees [3, 11].

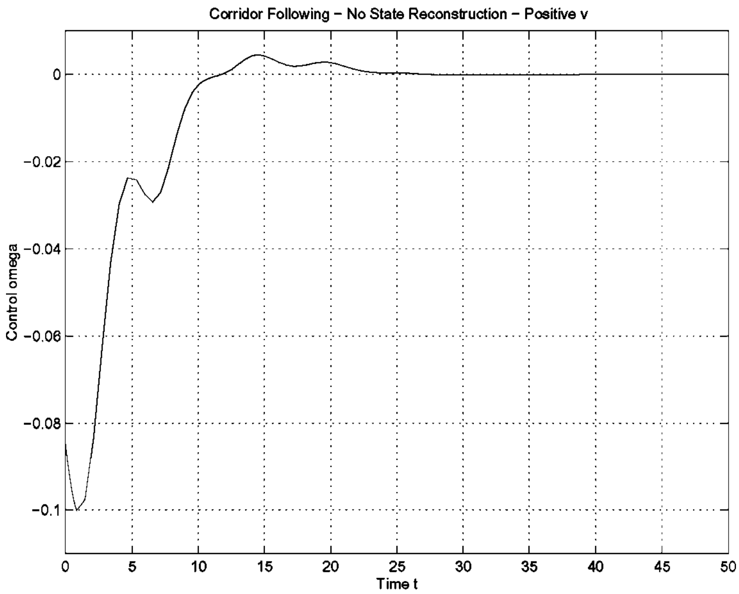
### 3.2. PERSON FOLLOWING

In order to implement the person-following behavior, both the color panoramic camera and the ring of sonars of the wheelchair are used. By processing the images acquired by the camera, the orientation of the moving target with respect to the wheelchair is computed. Sonar data provide the distance between the wheelchair and the moving target.

In order to specify the orientation of the moving person with respect to the wheelchair from panoramic vision, color information from the panoramic images is exploited. More specifically, a modification of the Color Indexing Scheme [13], has been employed. This algorithm identifies an object by comparing its color characteristics to the color characteristics of objects in a database. In our system, first the user selects the person to be tracked. This is done through a touch screen and an appropriate software interface. Based on this selection, the system builds an internal human body representation, consisting of three image regions that correspond to the head, torso and legs of the person to be tracked. For each of these regions, a normalized color histogram is built. Normalization is performed in order to make the system less vulnerable to changes in the global image illumination due to changes in lighting conditions. In subsequent image frames, a window is defined, in which the above–mentioned regions are searched for. This is done by comparing the color histograms of a reference model to every possible location in the search window. The locations of several of the best matches for each one of the




(a) State $(x,\ y,\ \theta)$ and heading speed $v$.




(b) Control $\omega$

*Figure 4.*

model regions are stored. The locations are optimized globally, in the sense that they should obey certain geometric relations (e.g., head above torso, torso above legs, etc.). The best location for the model regions defines the best estimate for the location of the person being tracked and, thus, its orientation with respect to the wheelchair. Finally, the models of the head, body and torso parts of the moving person are updated (both with respect to color information and to the size of the corresponding image areas), in order to accommodate changes in the appearance of the moving person.

This tracking method assumes that the processing of the image sequences proceeds fast enough to guarantee that the appearance of the moving person between subsequent image frames does not change significantly. In practice, we have been able to acquire and process panoramic frames at 3 Hz on a typical Pentium III processor, which proved sufficient for our case. The system fails in cases where moving persons are dressed in colors very similar to the scene background (e.g., people dressed in white in a room with white walls). Figure 2 shows a sequence of eight panoramic images, where the person inside the white windows is being tracked, as it moves from the middle of the scene in the first image to the left of it in the last one.

The rest of this section describes the design of a sensor-based control law implementing this behavior. Consider again an inertial coordinate system $\{F_O\}$ centered at a point $O$ of the plane and a moving coordinate system $\{F_M\}$ attached to the middle $M$ of the wheelchair's wheel axis. Let $(x, y)$ be the position of the point $M$ and $\theta$ be the orientation of the wheelchair with respect to the coordinate system $\{F_O\}$. Point $T$ in Figure 5 is the target of interest moving along an (unknown) trajectory. The target coordinates with respect to the coordinate system $\{F_O\}$ are $(x_T, y_T, \theta_T)$. The goal of the control system is to specify the wheelchair velocities $u \stackrel{\text{def}}{=} (v, \omega)$ that will keep the target in a constant position with respect to the

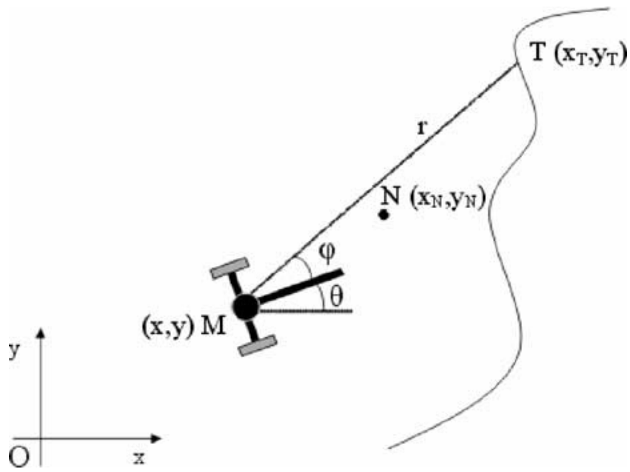



*Figure 5.* Person following by the robotic wheelchair.

wheelchair. This constant position can be represented by a virtual point $N$ (cf. Figure 5), with constant relative coordinates $(x_{MN}, y_{MN})$ with respect to the coordinate system $\{F_M\}$ and with coordinates $(x_N, y_N)$ with respect to the coordinate system $\{F_O\}$. The control goal can then be expressed as minimizing the deviation of point $N$ from point $T$ or as minimizing the *tracking error*

$$e \stackrel{\text{def}}{=} (e_x,\ e_y) = (x_N - x_T, y_N - y_T).$$

It can be easily seen that

$$x_N = x + x_{MN}\cos\theta - y_{MN}\sin\theta, \qquad y_N = y + x_{MN}\sin\theta + y_{MN}\cos\theta.$$

Since the motion of the wheelchair is subject to the non-holonomic constraints of Equation (1), the change of the tracking error during the motion *(error equations)* is

$$\dot{e} = B(\theta)u - \dot{\chi}_T, \tag{4}$$

with

$$B(\theta) = \begin{pmatrix} \cos\theta & -(x_{MN}\sin\theta + y_{MN}\cos\theta) \\ \sin\theta & x_{MN}\cos\theta - y_{MN}\sin\theta \end{pmatrix}, \tag{5}$$

where $\dot{\chi}_T \stackrel{\text{def}}{=} (\dot{x}_T,\ \dot{y}_T)$ is the translational velocity of the target. The matrix $B(\theta)$ is invertible whenever $x_{MN}$ is nonzero.

PROPOSITION 2. *Let $x_{MN}$ be nonzero. If the target translational velocity $\dot{\chi}_T$ is uniformly bounded and sufficiently small (but not necessarily zero when the error is zero), then the control law*

$$u(e, \theta) = B^{-1}(\theta)Ae, \tag{6}$$

*where $A$ is a Hurwitz matrix, will maintain the tracking error* ultimately uniformly bounded *(i.e., uniformly bounded after a finite initial time).*

The closed-loop system of Equations (4) and (6) can be seen as an exponentially stable nominal system with non-vanishing perturbation. Under the above conditions on $\dot{\chi}_T$, the proposition follows from known robustness results [7].

For simplicity, we choose $A = -k\mathbb{I}$, where $\mathbb{I}$ is the $2 \times 2$ unit matrix. The above state-feedback law then becomes $u(e, \theta) = -kB^{-1}(\theta)e$. This control law depends on the state $\theta$ and on the tracking error $e$. The first is not known and the second needs to be estimated from sensory data. It turns out that, while doing so, it is possible to eliminate the dependence of $u$ on $\theta$, as described below. Observe that the control law of Equation (6) does not depend explicitly on the target velocity which is treated as a perturbation.

Let $\phi$ be the relative orientation of the target with respect to the wheelchair and $r$ be the corresponding distance, as shown in Figure 5. Earlier in this section, a method for the estimation of $\phi$ from a sequence of color panoramic images was presented. The tracking error $e$ is related to the sensory information $\phi$ and $r$ by

$$\begin{aligned} e_x &= x_{MN}\cos\theta - y_{MN}\sin\theta - r\cos(\theta+\phi), \\ e_y &= x_{MN}\sin\theta + y_{MN}\cos\theta - r\sin(\theta+\phi). \end{aligned} \tag{7}$$

Using Equation (7), the previous control law is made to depend exclusively on the sensory information $(r, \phi)$ and takes the form

$$\begin{aligned} u(r,\phi) &= \begin{pmatrix} v(r,\phi) \\ \omega(r,\phi) \end{pmatrix} \\ &= \begin{pmatrix} -k\big[x_{MN}(x_{MN} - r\cos\phi) + y_{MN}(y_{MN} - r\sin\phi)\big]\big/x_{MN} \\ -k(y_{MN} - r\sin\phi)/x_{MN} \end{pmatrix}. \end{aligned} \tag{8}$$

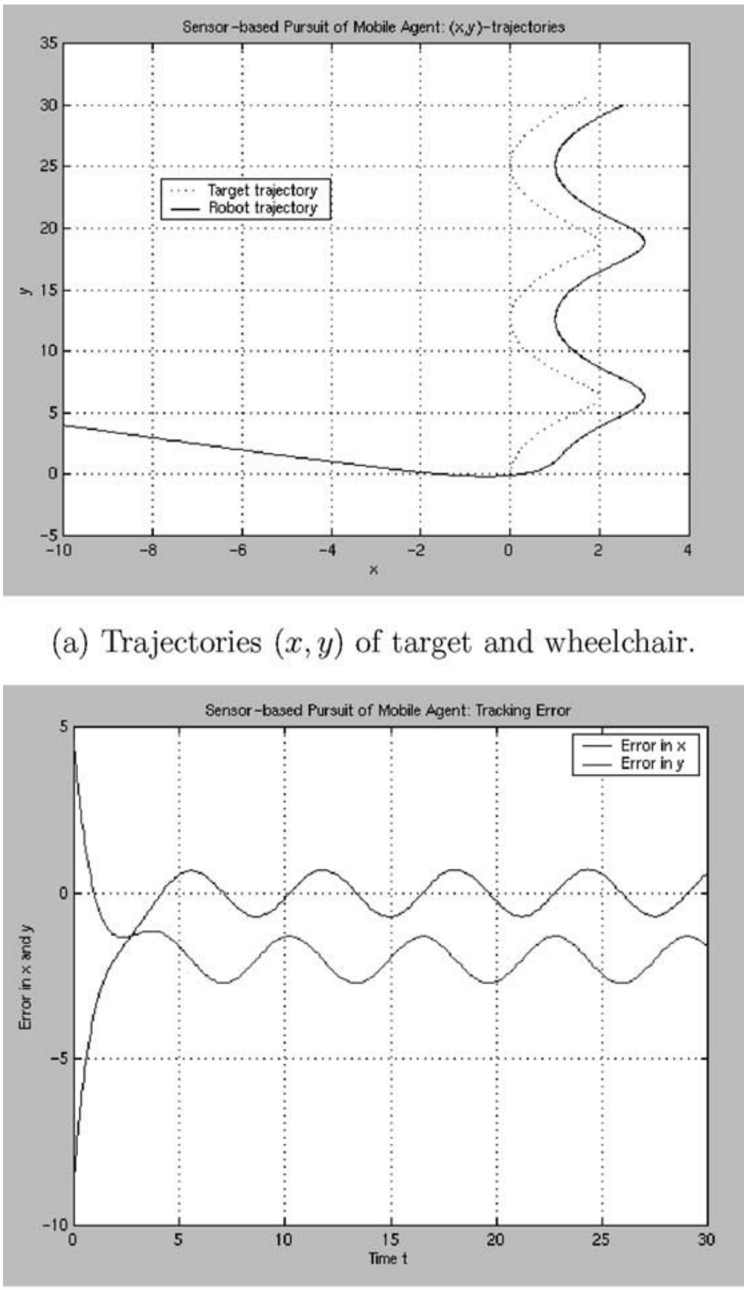
The quantities $x_{MN}$ and $y_{MN}$ are parameters determining the position where the target will be held with respect to the wheelchair.

Figure 6 shows the results of MATLAB simulations for the case where we attempt to track a target moving with velocity $\dot{x}_T = \sin t$, $\dot{y}_T = 2 + \cos t$, $\dot{\theta}_T = 0.3$, using the sensor-based control law of Equation (8) with parameters $x_{MN} = 1$, $y_{MN} = 1$ and $k = 1$. Figure 6(a) shows the $(x, y)$ trajectories of the wheelchair and of the target and Figure 6(b) shows the tracking error $(e_x,\ e_y)$. We observe that the error remains bounded, despite neglecting the target velocity in the control law design and despite the subsequent simplifications of this control law. In experiments with the robotic wheelchair prototype, this source of error is negligible.

## 4. The Experimental Prototype

An experimental prototype of a robotic wheelchair was built at ICS–FORTH (Figure 7). It is based on a commercially-available power wheelchair, where the sensors, the computing power and the electronics needed for the implementation of the navigation behaviors and of the user interfaces (touch screen, voice commands) were developed as add-on modules. The main hardware components of the robotic wheelchair (Figure 8) are:

- The *power wheelchair:* A MEYRA Eurosprint wheelchair is used as the base of the developed system. The wheelchair is actuated by two DC motors driving independently each rear wheel. Its motion is controlled by the user, either directly through a joystick, or indirectly through a computer, which communicates with the wheelchair through a serial port.
- The *sensors:* The sensory modalities employed are odometry, sonars and panoramic vision. A ring of 6 Polaroid sonars with a range of 6 m and beam width of 20° are used, as well as a Neuronics panoramic camera with a paraboloid mirror and a 360° field of view. The electronics interfacing the sensors to the computer system, as well as those necessary for controlling the sensors and for data collection, were built in-house.




(a) Trajectories $(x, y)$ of target and wheelchair.



(b) Tracking error.

*Figure 6.* Person-following by the robotic wheelchair.

*Figure 7.* Side view of the developed experimental robotic wheelchair prototype.

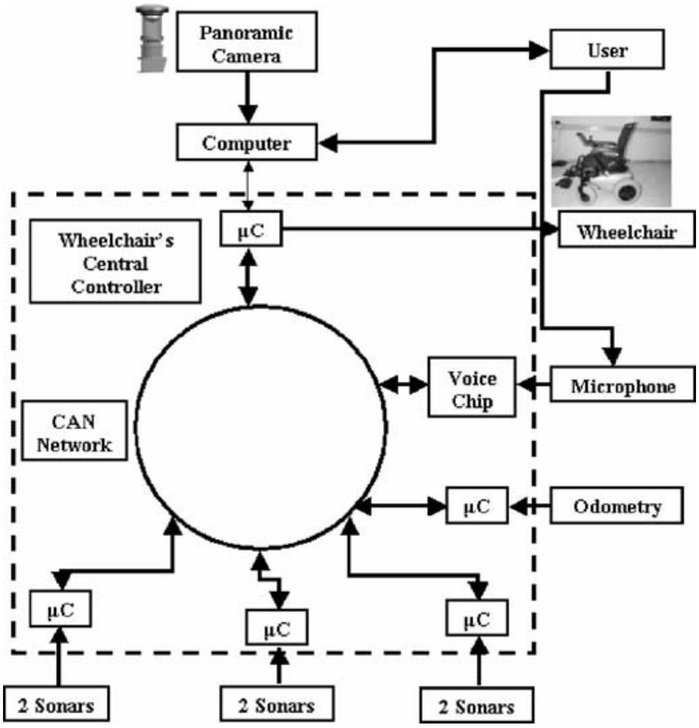



*Figure 8.* Hardware architecture of the robotic wheelchair.

- The *computer system:* It is composed of a portable computer and of a set of 5 PIC micro-controllers interconnected through a CAN network. The portable computer processes the vision data and communicates with the user through the appropriate software interfaces. Among the micro-controllers, one is dedicated to the communication with the portable computer and with the wheelchair control unit through serial ports, three are dedicated to controlling the sonars and to receiving and processing their data and one to receiving and processing odometry data (cf. Figure 8).

Extensive tests have been performed with the developed prototype to evaluate its behavior in a variety of operating conditions. Movies of the robotic wheelchair prototype can be seen in [6]. Among its navigation capabilities, obstacle avoidance, the motion towards a specified direction and the motion in the middle of the free space work quite robustly at this stage. The following of a moving target works reliably under moderate lighting conditions. When significant variations in lighting occur during the movement of the wheelchair, the color-based visual tracking may lose the target or confuse it with another one. Further work to enhance the independence of the tracking scheme from lighting conditions is currently under way.

## 5. Concluding Remarks

The experimental prototype of a robotic wheelchair with the capability of semi-autonomous navigation was presented. Issues related to the processing and use of sensory information from sonars and a panoramic camera mounted on the wheelchair, to the control of the system based on the sensory information, as well as to the hardware and software architecture of the system were discussed. Such a system may potentially assist people with impaired mobility, who may have limited fine motor control.

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## References

1. Argyros, A. A. and Bergholm, F.: Combining central and peripheral vision for reactive robot navigation, in: *Proc. of Computer Vision and Pattern Recognition Conf. (CVPR'99)*, Fort Collins, CO, USA, 23–25 June 1999.
2. Canudas de Wit, C., Siciliano, B., and Bastin, G. (eds): *Theory of Robot Control*, Springer, Berlin, 1996.
3. Collett, T.: Measuring beelines to food, *Science* **287** (2000), 817–818.

4. Donna, E., Bacon, C., Rahman, T., and Harwin W. S. (eds): *Proc. 4th Internat. Conf. on Rehabilitation Robotics*, Applied Science and Engineering Lab., Univ. of Delaware/A.I. duPont Inst., Wilmington, DE, USA, 1994.
5. Foulds, R.: Interactive robotic aids – one option for independent living: An international perspective, *Monograph 37*, World Rehabilitation Fund, New York, 1986, pp. 7–17.
6. http://www.ics.forth.gr/~tsakiris.
7. Khalil, H. K.: *Nonlinear Systems*, Macmillan, New York, 1992.
8. Laumond, J.-P. (ed.): *Robot Motion Planning and Control*, Lecture Notes in Control and Information Sciences 229, Springer, New York, 1998.
9. Nayar, S. K. and Baker, S.: A theory of catadioptric image formation, Technical Report CUCS-015-97, Dept. of Computer Science, Columbia Univ., USA, 1997, p. 30.
10. Samson, C.: Control of chained systems: application to path following and time-varying point-stabilization of mobile robots, *IEEE Trans. Automat. Control* **40** (1995), 64–77.
11. Srinivasan, M. V., Zhang, S., Altwein, M., and Tautz, J.: Honeybee navigation: Nature and calibration of the 'odometer', *Science* **287** (2000), 851–853.
12. Svoboda, T., Pajdla, T., and Hlavac, V.: Epipolar geometry for panoramic cameras, in: *Proc. 5th European Conf. on Computer Vision*, Lecture Notes in Computer Science 1406, Springer, New York, 1998.
13. Swain, M. J. and Ballard, D. H.: Indexing via color histograms, in: *Proc. Internat. Conf. on Computer Vision*, 1990.
14. Tsakiris, D. P. and Argyros, A. A.: Corridor following by mobile robots equipped with panoramic cameras, in: *Proc. of the 8th IEEE Medit. Conf. on Control and Automation (MED'2000)*, Rio, Greece, 17–19 July 2000.
15. Tsakiris, D. P., Rives, P., and Samson, C.: Extending visual servoing techniques to nonholonomic mobile robots, in: G. Hager, D. Kriegman, and S. Morse (eds), *The Confluence of Vision and Control*, Lecture Notes in Control and Information Systems 237, Springer, New York, 1998.
16. Vidyasagar, M.: *Nonlinear Systems Analysis*, Prentice-Hall, Englewood Cliffs, NJ, 1978.