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Navigation system for a smart wheelchair

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Abstract: Recent results on the development of a navigation system for a smart wheelchair are presented in this paper. In order to reduce the development cost, a modular solution is designed by using commercial and low cost devices. The functionalities of the tracking control system are described. Experimental results of the proposed assistive system are also presented and discussed.

Key words: Smart wheelchair, Guidance system, Path planning, Tracking control
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INTRODUCTION

Assistive technology is defined as any item, piece of equipment, or product, whether acquired commercially, off the shelf, modified, or customized, that is used to increase, maintain, or improve the functional capabilities of individuals with disabilities.

To date, assistive technology is being a more important area where robotic devices can be used to strengthen the residual abilities of individuals with motor disabilities or to substitute their missing functions thus helping them to increase their level of independence, at least for accomplishing their everyday activities. The ideal would be to give each user the system that exactly meets his or her individual requirements. This is particularly crucial when powered wheelchairs have to be designed. A smart wheelchair typically consists of either a standard power wheelchair base to which a computer and a collection of sensors have been added or a mobile robot base to which a seat has been attached. Smart wheelchair should be designed that provide navigation assistance to the user in a number of different ways, such as assuring collision-free travel, aiding the performance of specific tasks (e.g., passing through doorways), and autonomously transporting the user between locations. The design of smart wheelchairs that meets the needs of many can be achieved by designing lowest common denominator solutions at the expenses of sub-optimal solutions for most users, or, alternatively, by resorting to integrated systems (Cherry *et al.*, 1996).

During the past years, smart powered wheelchairs have been the subject of intensive research activities. The VAHM project (Bouhris and Pino, 1996; Bourhis and Agostini, 1998; Bourhis *et al.*, 2001) was aimed at improving the control of powered wheelchairs by adding possibilities of autonomous mobility. Different operating modes have been defined, with different levels of autonomy, for adapting the system to various situations. The NavChair assistive wheelchair navigation system (Levine *et al.*, 1999; Simpson and Levine, 1999) is based on a commercial wheelchair system and employs different operating modes and has applications for development of shared control systems where the machine can automatically adapt to human behaviors. The ARPH system (Hoppenot and Colle, 2001) is composed of a control station and a manipulator arm mounted on the wheelchair and uses a succession of control modes, which may be either automatic or manual. In this case, the user and the system contribute their skills to executing missions by means of task sharing. The Hephaestus smart wheelchair (Simpson *et al.*, 1999; 2002) is an example of a modular system based on commercially available wheelchairs with various levels of autonomy. The SmartChair (Rao *et al.*, 2002; Parikh *et al.*, 2003; 2004) with shared control framework allows the user to interact with the chair while it is performing an autonomous task. An approach to coordinating human motion with a robotic wheelchair moving in a populated, continuously changing, natural environment was described in (Prassler *et al.*, 2001). In all the above smart wheelchairs, the autonomy and security aspects are guaranteed by a set of sonar sensors. Different sensor devices, such as vision systems, are also used in the Wheelesley and TAO intelligent wheelchairs (Wheelesley, 1997; TAO, 1997; Yanco and Gips, 1997; Gomi and Griffith, 1998). Intelligent navigation systems for commercial wheelchairs are also important in order to increase the autonomy and the security of users with motor disabilities (Fioretti *et al.*, 2000).

This paper presents recent results on the development of a navigation system for a smart wheelchair. Different functionalities are introduced for matching the user needs; e.g. the assistive robotic system can be controlled on board by the user in a direct way, or in a remote way by a workstation. These aspects of usability have to be managed without affecting security and efficiency of the robotic system's control module. The paper considers the aspects of physical safety and operating robustness, for some significant applications of these devices, in order to aid users in some activities of daily life.

The navigation system of the mobile base is designed for accomplishing the navigation task either when the user direct control is required or when remote control of the vehicle is needed. It must interact with the user in order to involve him in the guidance of the vehicle without limiting the functionality and security of the system. Innovative aspects on the control system are introduced and discussed, and feasible improvements are also presented. The results contribute to improving the physical safety and operating robustness for effective applications of these devices for supporting users activities.

SYSTEM ARCHITECTURE

On the basis of our experiences in previous research projects (Fioretti *et al.*, 2000) and related results (Dallaway *et al.*, 1995), the developed solution introduces autonomy and user interaction with the necessary functionality and security. To reduce the development cost, a modular solution has been adapted by using commercial and low cost devices. The solution with commercial products meets also security aspects. For example, aspects concerning stability and manoeuvrability of the wheelchair were tackled at the origin by devices producers.

The developed assistive robotic system is composed of a commercial mobile base TGR Explorer (http://www.tgr.it/Welcome.html) and the motion control system. By a local bus, the control system interacts with the robotic devices, the set of sensors and the user interface. The system architecture is shown in Fig.1.

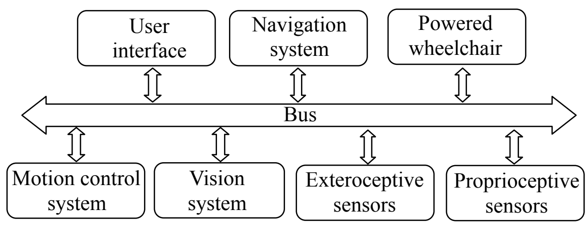

Fig.1 System architecture

The motion control system performs environment monitoring and manages user commands in order to realize different autonomy levels. The motion assistance can work in two principal modalities:

1. Assisted motion control of the robotic system: It leaves to the user the greatest freedom of action and acts only in case of danger. This can be performed in two modes: in the filtered mode the user commands are filtered depending on his disabilities and collision detection is implemented in order to stop the vehicle in case of danger; in the corrected mode the control unit can either suspend the task for the vehicle (in case of danger, unexpected obstacle in front to the vehicle) or correct the user commands for the mobile base in order to avoid collisions.

2. Automatic motion control of the robotic system: The user sets the configuration to be reached by the vehicle. This functionality can be used for automatic delivery and carrying tasks.

The interface allows the user to control the robotic system motion and its structure depends on the autonomy level of the user. Remote control of the vehicle is introduced to improve the functionalities of the developed system. For example in this modality the integration of a robotic arm on the wheelchair allows performance of tele-manipulation tasks. In this modality the introduction of exteroceptive sensors, such as vision systems, is necessary in order to acquire the information of the remote environment which interacts with the robotic system.

MOBILE BASE

The mobile base used in this project is a commercial powered wheelchair (TGR Explorer) equipped with a car-like locomotion system. It has two rear driving wheels and one front leading wheel that can rotate around its vertical axes. A PC/104 architecture manages the entire system.

The dead-reckoning system (proprioceptive sensors system) is based on odometric and inertial sensors that allow the estimation of the mobile base position with respect to a starting reference configuration. This is simply carried out by two incremental optical encoders aligned with the axes of the driving wheels. The external/environmental sensor system (exteroceptive sensor system) is based on a proper set of ultrasonic range finders used for detecting obstacles in the environment.

The reliability and accuracy of sonar measures are improved by a proper fusion of these measures in a probabilistic local map of the environment. The solution proposed in (Angeloni *et al.*, 1996), and based on the probabilistic approach, is implemented. This solution is able to find a trade-off between accuracy and computation cost.

In the developed navigation system, the usability criterion was pursued by designing the navigation module with different levels of autonomy and making use of the M3S protocol for the design of the user interface (Fioretti *et al.*, 2000). The use of this protocol allows a rapid and low-cost substitution of the user command devices, which depends on the types of remaining functional abilities of the user, without the need to re-adapt the other modules of the system. Moreover, the different autonomy levels of the navigation module allow the tailoring of the system to different levels of users' disabilities.

The choice of commercial products designed for the specific purpose of locomotion for user with disabilities also took into account the security aspects. Aspects concerning stability and manoeuvrability of the wheelchair were tackled at the origin. Further security aspects were added to the standard levels allowed by the commercial wheelchair integrating internal and external/environmental sensors which can capture environment information with a high level of reliability. This allowed the introduction of various autonomy levels that assure avoidance of the various obstacles present in an unstructured user environment, thus enhancing the security levels of the whole system.

The choice of a commercial powered wheelchair was also made for reasons of cost reduction. Though the whole system is not cheap, attention was paid to reduce the cost of adapting the system to the user's level of disability as well as the costs of re-adapting the system in case of changes in the users' functional abilities in time.

Three different levels of autonomy of the navigation module have been developed. In the first and second level of autonomy the user interacts with the navigation system (Fioretti *et al.*, 2000).

In the first level of autonomy, the navigation module performs simple filtering of the user's commands and in front of a detected obstacle the module performs a 'Stop+Wait' action. The navigation module stops the mobile base and waits for the obstacle to disappear, while the user interface shows a warning message. After a time-out period, if the obstacle does not disappear, the module stops the wheelchair or activates the 'Stop+Invocation' of User Help action. In this case the navigation module invokes the help of the user who can command to ignore the obstacle (just try to push it away) or to abort the current trajectory and start a new one in a direction free of obstacles. The feasibility of the new motion direction is evaluated by means of the environment map (Conte and Zulli, 1995).

In the second level of autonomy, the navigation module introduces some local corrections on the user commands by a simple obstacle avoidance algorithm. If the obstacle is detected inside the security area, a correction on the steering angle is automatically introduced until the security area is free of obstacle. In this autonomy level, the user cannot control the amplitude of the correction but can always activate the 'Stop' action of the system. The obstacle avoidance algorithm is based on a fuzzy-logic approach that represents an extension of the algorithm proposed in (Leo *et al.*, 1995).

In the last level of autonomy, the navigation system implements a high level of autonomy. This level is used in the modality of automatic motion control of the robotic system. The innovative and technical aspects of this level denoted by automatic guidance system are introduced in the following subsection.

Automatic guidance system

In this modality the user sets a goal within the workspace. The navigation system plans a feasible free-obstacle trajectory joining a start and goal configuration and implements the tracking actions necessary for reaching the desired configuration.

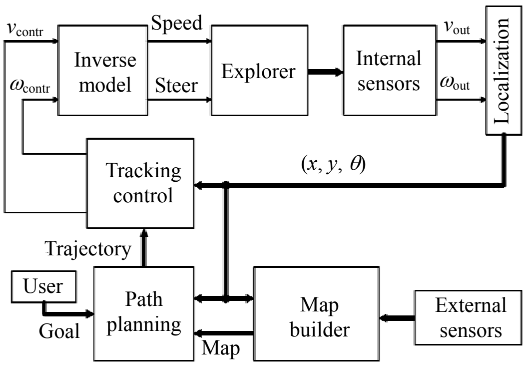

Fig.2 Automatic guidance system

Path planning

The path-planning module computes a collision-free path for a rigid object moving freely among static obstacles (Latombe, 1991). The approach based on the configuration space is considered.

In the configuration space (*C*-space) the robot is represented by a point and the configurations characterized by the presence of obstacles form a region called the obstacle configuration space (C_0). The complementary part of the C_0 with respect to the *C*-space is called the free configuration space (C_{free}). The developed path-planning is an off-line procedure which calculates in the *C*-space a collision-free path from a start configuration (*S*) to a goal configuration (*G*). In this approach a proper discretization of the configuration space and a planning method based on a research algorithm are considered (Conte and Zulli, 1995).

All the movements generated during the research have to satisfy the nonholonomic constraints of the considered car-like robot. To overcome this problem the research algorithm uses only a finite number of predefined feasible movements that guarantees constraints fulfillment. A good trade-off between computational burden and effectiveness is to use three forward basis movements (turn left, go straight, turn right) and three analogous backward basic movements.

The research algorithm must also consider obstacles and vehicle geometry during the planning task. Expanding obstacles based on vehicle orientation is an effective method to deal with this requirement. A three dimensional matrix $\boldsymbol{M}(i, j, k)$ is considered and the cell (i, j, k) is denoted as occupied or free depending on the vehicle with orientation $\beta=k\cdot\Delta\theta$ and position $(i\cdot\Delta x, j\cdot\Delta y)$ bump or not with an obstacle respectively, where Δx, Δy and $\Delta\theta$ are the space discretization steps. Once defined start configuration (x_s, y_s, θ_s) and goal configuration (x_g, y_g, θ_g), the research algorithm operates as follows:

1. Discretize the workspace and generate a three dimensional map $\boldsymbol{M}$ whose cells are labelled as occupied if the corresponding configuration belongs to C_0 or free if it belongs to C_{free}.

2. Start the goal node and let make a breadth expansion of free and not yet analyzed nodes until one of them coincides with the start one or all nodes are expanded.

3. Go back over the tree in order to reconstruct the followed path.

This algorithm uses a heuristic approach (a cell is expanded only one time) to reduce the exponential complexity of the research problem to a polynomial complexity. In addition, if a solution exists in the tree associated with the performed discretization, the proposed method will find the shortest solution in the sense of the minimum number of basic movements.

To permit the user to supervise the motion, in the proposed algorithm, the maximum backward motion velocity has been reduced, so that in the planned trajectory the travel distance in the backward motion has been minimized. The computed obstacle-free path is a discrete path characterized by a sequence of discrete configurations which require an interpolation procedure for obtaining a time reference and then a trajectory.

For simplifying the tracking task and to make more comfortable movements, the interpolation procedure introduces acceleration and deceleration ramps and provides deceleration before turns.

Tracking control

The kinematic model of the powered wheelchair has the following form:

$$\begin{cases} \dot{x} = v\cos\theta \\ \dot{y} = v\sin\theta \\ \dot{\theta} = \omega \end{cases} \tag{1}$$

where the triplet $[x(t),\ y(t),\ \theta(t)]$ describes the position and orientation of the mobile base with respect to a fixed frame. The vehicle inputs are the translational velocity v and the angular velocity ω. Although this is a simplified model of the vehicle's motion, it is sufficient to capture the nonholonomy property defined by the constraint:

$$-\dot{x}\sin\theta + \dot{y}\cos\theta = 0 \tag{2}$$

Usually a car-like vehicle is subject to another constraint that limits the maximum steering angle and then, in an indirect way, the maximum angular velocity of the mobile base. Such a constraint can be formulated as:

$$\dot{x}^2 + \dot{y}^2 - \left(\frac{L}{\tan\phi_{\max}}\right)^2 \dot{\theta}^2 \geq 0 \tag{3}$$

where L is the distance between front and rear wheels of the car-like vehicle and $\phi_{\max}$ is the maximum steering angle.

Now consider a reference trajectory of the form:

$$\begin{cases} \dot{x}_r = v_r\cos\theta_r \\ \dot{y}_r = v_r\sin\theta_r \\ \dot{\theta}_r = \omega_r \end{cases} \tag{4}$$

where x_r, y_r and θ_r characterize the desired wheelchair trajectory, and v_r and ω_r are the linear and angular reference velocities respectively (Fig.3).

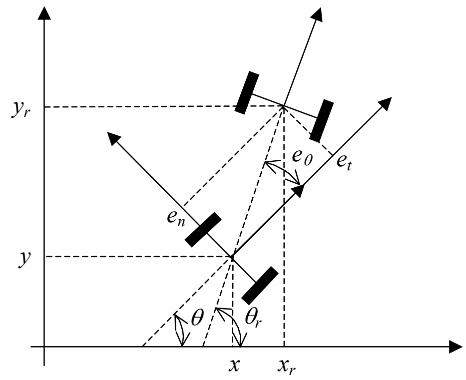

Fig.3 Real and reference configuration

Denoting by e_t, e_n and e_θ the tangent error, the normal error and the orientation error respectively, the tracking errors can be formulated as follows:

$$\begin{bmatrix} e_t \\ e_n \\ e_\theta \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} \tag{5}$$

The dynamics of the tracking errors has the following form:

$$\begin{bmatrix} \dot{e}_t \\ \dot{e}_n \\ \dot{e}_\theta \end{bmatrix} = \begin{bmatrix} 0 & \omega & 0 \\ -\omega & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} e_t \\ e_n \\ e_\theta \end{bmatrix} + \begin{bmatrix} v_r\cos e_\theta \\ v_r\sin e_\theta \\ \omega_r \end{bmatrix} + \begin{bmatrix} -1 & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{6}$$

In view of the experimental application of proposed control laws, the controller was designed in discrete time framework (Corradini *et al.*, 2003). Therefore the model Eq.(6) was discretized with a sampling time T_c. Integrating Eq.(6) from kT_c to $(k+1)T_c$ and assuming the control efforts $\boldsymbol{u}=[v\ \omega]^{\mathrm{T}}$ to be constant over the same time-interval, the following discrete-time model is obtained:

$$\begin{aligned} e_t(k+1) &= e_t(k)+f_1(e_n)\omega(k)+f_2(e_\theta, v_r)-T_c v(k) \\ e_n(k+1) &= e_n(k)+f_3(e_t)\omega(k)+f_4(e_\theta, v_r) \\ e_\theta(k+1) &= e_\theta(k)+f_5(\omega_r)-T_c\omega(k) \end{aligned} \tag{7}$$

where k denotes the variable evaluated in the $t=kT_c$ and

$$f_1(e_n)=\int_{kT_c}^{(k+1)T_c} e_n(\tau)\mathrm{d}\tau$$
$$f_2(e_\theta,v_r)=\int_{kT_c}^{(k+1)T_c} v_r(\tau)\cos(e_\theta(\tau))\mathrm{d}\tau$$
$$f_3(e_t)=\int_{kT_c}^{(k+1)T_c} -e_t(\tau)\mathrm{d}\tau$$
$$f_4(e_\theta,v_r)=\int_{kT_c}^{(k+1)T_c} v_r(\tau)\sin(e_\theta(\tau))\mathrm{d}\tau$$
$$f_5(\omega_r)=\int_{kT_c}^{(k+1)T_c} \omega_r(\tau)\mathrm{d}\tau$$

Consider the following control laws for the linear and angular velocities (Samson and Ait-Abderrahim, 1991):

$$\begin{aligned} v(k) &= k_t e_t(k) + v_r(k)\cos e_\theta(k) \\ \omega(k) &= \omega_r(k) + k_n e_n(k) v_r(k)\frac{\sin e_\theta(k)}{e_\theta(k)} + k_\theta e_\theta(k) \end{aligned} \tag{8}$$

where k_t, k_n and k_θ are the control gains. Under the assumption that the reference vehicle is not at rest all the time, this control law globally asymptotically stabilizes the origin e=0 (de Wit *et al.*, 1993) either with constant or time varying v_r and ω_r.

Under the assumption that $v_r(k)$ is not zero and that a small sampling time T_c is chosen small enough to produce good estimations of simple integral terms with their trapezoidal approximations, the closed loop system described by Eqs.(7) and (8) around the equilibrium point (e_t=e_n=e_θ=0) has the following form:

$$\begin{bmatrix} e_t(k+1) \\ e_n(k+1) \\ e_\theta(k+1) \end{bmatrix} = \begin{bmatrix} 1-k_tT_c & 0 & 0 \\ 0 & 1 & v_r(k)T_c \\ 0 & -k_n v_r(k)T_c & 1-k_\theta T_c \end{bmatrix} \cdot \begin{bmatrix} e_t(k) \\ e_n(k) \\ e_\theta(k) \end{bmatrix} \tag{9}$$

Hence, the control gains k_t, k_n and k_θ of the control law Eq.(8) are chosen to impose the asymptotic stability of Eq.(9), i.e. the eigenvalues λ_1, λ_2 and λ_3 of system Eq.(9) are imposed in module less than one. This choice guarantees the local asymptotic stability of the closed loop system described by Eqs.(7) and (8). The eigenvalues λ_2 and λ_3 of Eq.(9) depend on $v_r(k)$, therefore the gain k_n must be related to the reference velocity $v_r(k)$ (velocity scaling). For example, eigenvalues λ_1, λ_2 and λ_3 are assigned to system Eq.(9) by the following choice of the gains:

k_t=$(1-\lambda_1)/T_c$, k_n=$(2-\lambda_2-\lambda_3)^2/(2v_rT_c)^2$, k_θ=$(2-\lambda_2-\lambda_3)/T_c$

EXPERIMENTAL RESULTS

The experimental testing of the proposed autonomous navigation system has been performed on the smart wheelchair TGR Explorer, available at the Robotics Lab of the Marche Polytechnic University. The wheelchair is provided with a proximity system composed of a half ring of 13 Polaroid ultrasonic sensors.

The result of a planning task for a defined environment is shown in Fig.4. Black/tick lines represent the known obstacles and the grey lines represent intermediate configurations assumed by the mobile base. In this case, discretization intervals of Δx=0.2 m, Δy=0.2 m and $\Delta\theta$=π/8 rad are used. The planning parameters are Δt=1 s, v_0=0.3 m/s, r=0.7, ϕ_0=43.3°, where Δt is the discretization time; v_0 and ϕ_0 are velocity and steering angle, respectively.

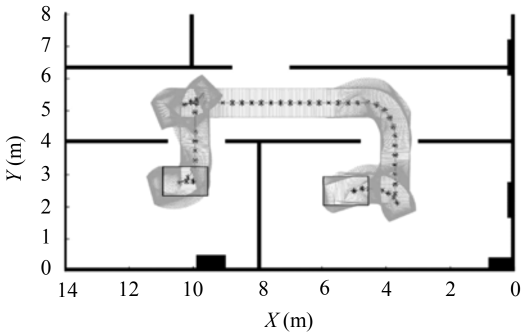

Fig.4 Planning path

The planner is able to operate within relatively complex workspaces with tight passages, corridors and doors. Note that, expanding the obstacles to a size larger than that of the maximum dimension of the vehicle, the door crossing will not be possible.

Due to the orientation quantization and to the interpolation procedure, the first values of the steering angles go beyond the physical limit of the TGR Explorer (Fig.5). Obviously, in this situation, the vehicle will inevitably commit larger tracking errors. Nevertheless the steering angle remains inside the limits for all the remainder of the path and the control system will always be able to drive the vehicle to the goal configuration with sufficient accuracy.

Estimation of mobile base position requires use of dead-reckoning system based on odometric and inertial sensors (Jetto *et al.*, 1998). This permits putting within bounds the incremental localization errors of the simulation trajectories. The tracking paths are shown in Figs.6 and 7.

Fig.7 shows that the final configuration will be reached with position errors lower than 2 cm and orientation error lower than 3 degrees whilst they are relatively larger when the velocity is bigger. This is due to the kinematic nature of the controller that neglects the mobile base dynamics. However, the proposed control law is robust in the sense that it guarantees the global stability of the tracking error system. In all performed tests, the performance of the path planner and of the tracking control system were satisfactory in terms of reliability and accuracy.

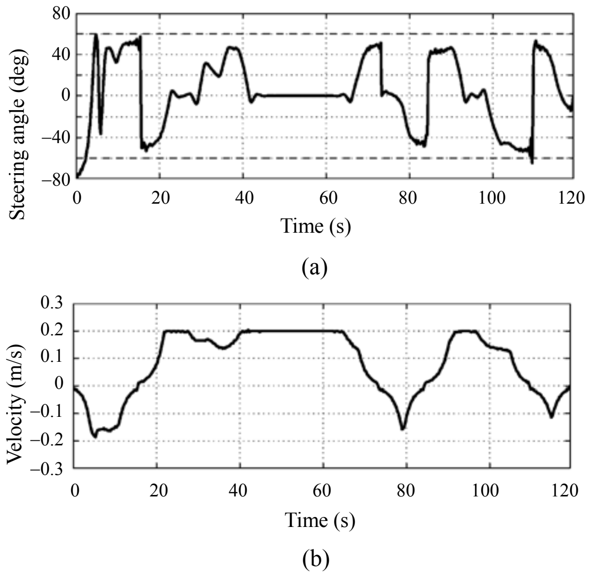

Fig.5 Planned steering angle (a) and velocity (b)

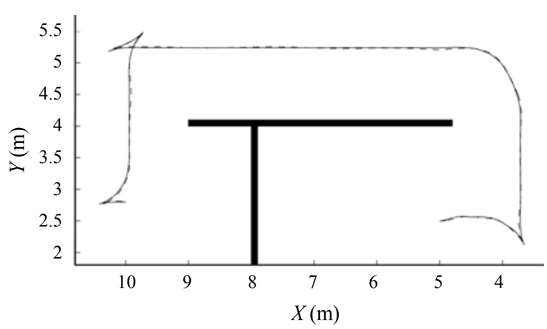

Fig.6 Controller performances: real trajectory (dashed) and reference trajectory (solid)

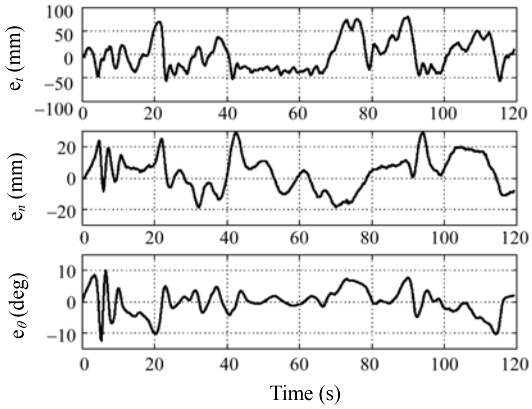

Fig.7 Tracking errors

CONCLUSION

This paper presents solutions to the problems related to smart wheelchair navigation. In order to improve usability, security and to meet the cost criteria, a modular architecture was considered. Different levels of autonomy of the designed system were proposed for strengthening the residual abilities of individuals with motor disabilities thus increasing their level of independence.

The usability of the developed robotic system has been improved by the introduction of the wheelchair's automatic motion control which plans a trajectory free of obstacles and tracks the vehicle along the planned path. This control modality transforms the wheelchair into an autonomous mobile robot which can be used for automatic delivery and/or automatic remote manipulation.

The developed automatic navigation system is composed of a searching based path planner and a nonlinear tracking controller which can deal with nonholonomic constraints and relatively complex workspaces. The achieved experimental results showed that the navigation system, together with the motion control module, enables the user to achieve sound/proper positioning of the mobile base, thus improving the manipulator functionalities. Moreover the proposed control law is robust because it guarantees the global stability of the tracking error system.

In order to introduce learning capabilities into the control system for reducing the tracking errors in the presence of environmental variations and disturbances, solutions based on neural networks are under investigation. Nevertheless more results about sensor fusion and/or fault-tolerance are needed.

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