

# A Collision Avoidance Strategy for Safe Autonomous Navigation of an Intelligent Electric-Powered Wheelchair in Dynamic Uncertain Environments with Moving Obstacles

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**Abstract**—We present a reactive navigation algorithm that guarantees the safety of automated intelligent wheelchairs for people with mobility impairments in dynamic uncertain environments. The proposed navigation algorithm restricts neither the natures nor the motions of the obstacles, the shapes of the obstacles can be time-varying (deforming obstacles). Furthermore, the proposed navigation algorithm does not require prior information about the positions and velocities of the obstacles to accomplish obstacle avoidance. Simulation and experimental results show that intelligent electric-powered wheelchairs are able to successfully avoid collisions with moving obstacles such as pedestrians or vehicles under the guidance of the proposed algorithm and reach the target.

## I. INTRODUCTION

Wheelchairs are one of the most commonly used independent mobility aids for people with mobility impairments [1], [2]. The movement ability of the users is raised with the assistances of the wheelchairs [1], [3], allowing them to attend more social activities, perform physical exercises, relieve mental burden [4], etc. Due to the growing number of the impaired persons over the past decades [5], [6], more and more users are benefited from using wheelchairs [4].

The primary objective for operating wheelchairs is to safely deliver users from the current location to a target location. The existing approaches to the safe navigation of wheelchairs can be generally classified into two categories: the user-wheelchair interaction and the autonomous navigation, respectively.

In the case of the user-wheelchair interaction approach, the users are responsible for observing the environments, making decisions to avoid the obstacles, and controlling the wheelchair by various means, e.g. hand gesture [7], head position and movement [8], voice command [9], or brain signals [10]. Thus information about the environments is acquired by the user's perception and the decisions are made by the user's reaction. However, these perception and

reaction can be easily plagued by many factors such as bad perceptual condition (tiredness, stress) or poor operating environment (darkness, noise). Inaccurate information about the environment can dramatically increase the chances of misjudgments, which lead to inappropriate decisions, and so the safety of the users is not guaranteed. Furthermore, a clinical survey shows that forty percent of the users found it difficult to perform steer tasks using these intelligent wheelchairs, and a number of users cannot operate the intelligent wheelchairs due to various reasons [11]. This is an indication that most of user-wheelchair interaction methods cannot be learned easily and require a fair amount of practice and training in order to properly operate the wheelchair.

According to the autonomous navigation approach, algorithms take over the control of the wheelchair from the users. The advantages of this approach are that the wheelchair can be operated in poor perceptual environments and responses to the changes in the environment are generally faster. There are many well known autonomous navigation methods that can be implemented with intelligent wheelchairs. The Vector Field Histogram (VFH) [12] and Vector Force Field [13] are implemented in the NavChair Assistive Wheelchair navigation system, the obstacle avoidance strategy based on optimized Bayesian Neural Networks [14] and shared control strategy [15] are implemented in SAM (semi-Autonomous Machine). A biologically inspired approach [16], which was implemented with a mobile robot and which performance was confirmed by extensive real world experiments, can also be applied to intelligent wheelchairs. These navigation algorithms have demonstrated great successes in static environments. Furthermore, the velocity obstacle approach (VO) is implemented in a commercial wheelchair model SPRINT in [17], [18], the VO approach allows the SPRINT wheelchair to cope with environments with moving obstacles.

In this paper, we present a novel collision free navigation strategy for an electric-powered wheelchair in cluttered dynamic environments. Unlike the bulk of recent research on the problem of wheelchair obstacle avoidance, which basically deals with static environments, the proposed navigation strategy is more relevant to real world scenarios, where the users of wheelchairs often find themselves involved in dynamic crowded environments with multiple moving obstacles such as pedestrians or vehicles. The intelligent wheelchair SPRINT [17], [18] is a rare example of a wheelchair that can operate in dynamic environments; the employed control algorithm is based on approximation of the obstacles by cir-

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cles to simplify calculation of control signals. Our proposed algorithm does not restrict the shapes of the obstacles: they are arbitrary and can be time-varying and deforming, like a train of trolleys or revolving door. This makes the proposed navigation algorithm more flexible and applicable for a large variety of environments. Furthermore, the proposed algorithm achieves the navigation task with limited information: it does not require a completed map of the environment or full information about positions and velocities of the obstacles. This decreases the implementation cost of the entire navigation system of the wheelchair. Applicability and performance of the proposed navigation algorithm are confirmed by computer simulations and extensive real world experiments with an intelligent electric-powered wheelchair.

The remainder of the paper is organized as follows. Section II presents the mathematical model of the wheelchair and the statement of the problem. Section III introduces and discusses the proposed autonomous reactive navigation algorithm. The results of computer simulation and experiments with real intelligent wheelchair are given in Sections IV and VI, respectively. They are interspersed by a detailed description of the real wheelchair employed for experiments in Section V.

The mathematically rigorous analysis of the proposed algorithm will be given in the journal version of the paper.

## II. SYSTEM MODEL AND PROBLEM STATEMENT

We consider a wheelchair (WC) that travels in a plane and has two independently actuated driving wheels mounted on the common axle and castor wheels. The position of WC is represented by the absolute Cartesian coordinates  $x, y$  of the reference point located at the center of the axle, whereas its orientation is given by the angle  $\theta$  between the WC centerline and the abscissa axis. The driving wheels roll without sliding. WC is controlled by the angular velocities  $\omega_l$  and  $\omega_r$  of the left and right driving wheels, respectively, which are limited by a common and given constant  $\Omega$ . The relevant mathematical model of kinematics of WC is as follows:

$$\begin{aligned} \dot{x} &= v \cos \theta, & v &= \frac{v_l + v_r}{2}, & x(0) &= x_0, \\ \dot{y} &= v \sin \theta, & u &= \frac{v_r - v_l}{2L}, & y(0) &= y_0, \\ \dot{\theta} &= u & v_i &= R_w \omega_i, & \theta(0) &= \theta_0 \end{aligned} \quad (1)$$

where  $R_w$  is the radius of the driving wheels,  $2L$  is the length of the axle, and  $\omega_i = \omega_i(t) \in [-\Omega, \Omega]$ ,  $i = l, r$ . To simplify the matters, we treat  $v$  and  $u$  as control variables. They uniquely determine the rotational velocities  $\omega_r = (v + Lu)/R_w$ ,  $\omega_l = (v - Lu)/R_w$  and obey the bound:

$$|v| + L|u| \leq V := R_w \Omega. \quad (2)$$

This bound implies restrictions on the forward and rotational movements of the wheelchair. In particular, its speed cannot exceed  $V$ , and for given  $v \in (-V, V)$ , the turning radius of the wheelchair is bounded from below by

$$R = \frac{L|v|}{V - |v|}. \quad (3)$$

The motion of many wheeled mobile robots, missiles, unmanned aerial vehicles and other autonomous systems such as electrically-powered wheelchairs, can be described by this model; see e.g. [19], [20] and the references therein.

WC travels in an uncertain environment with multiple disjoint static and dynamic obstacles. At time  $t$  each of them occupies a certain domain  $D_i(t)$ , where  $i = 1, 2, \dots, n$  is the serial number of the obstacle. The positions of the obstacles are not known in advance and the obstacles may undergo arbitrary motions. Moreover, the shapes of the obstacles are not specified and may be time-varying.

The only information that is available to WC is the current distance  $d(t) := \mathbf{dist}_{D(t)}[r(t)]$  to the closest obstacle  $D(t)$  and the rate  $\dot{d}(t)$  at which this measurement evolves over time. Here  $r := [x, y]^\top$  is the vector of the absolute coordinates of the wheelchair and

$$\mathbf{dist}_D(r) := \min_{r' \in D} \|r - r'\| \quad (4)$$

where  $\|\cdot\|$  denotes the standard Euclidean vector norm and the minimum is achieved if  $D$  is closed.

There also is a steady point-wise target  $\mathbf{T}$  and WC has access to the heading  $H(t)$  towards  $\mathbf{T}$ . The objective is to guide WC through the obstacle-free part of the plane and reach the target  $\mathbf{T}$  at a certain time  $t_f > 0$ :

$$r(t_f) = \mathbf{T}; \quad r(t) \notin \bigcup_{i=1}^n D_i(t) \quad \forall t \in [0, t_f].$$

Moreover, the distance between WC and any obstacles should constantly exceed a given safety margin  $d_{\text{safe}} > 0$ :

$$\mathbf{dist}_{D_i(t)}[r(t)] \geq d_{\text{safe}} \quad \forall t \in [0, t_f], i = 1, \dots, n. \quad (5)$$

## III. AUTONOMOUS NAVIGATION ALGORITHM

In this section, we present a summary of the proposed reactive navigation algorithm. The algorithm combines obstacle avoidance strategy, which is activated in a close proximity of every en-route obstacle, with motions towards the target in a straight line when there is no threat of collision.

We employ the following obstacle avoidance strategy:

$$u(t) = \frac{V - v(t)}{L} \cdot \text{sgn}\{\dot{d}(t) + \chi[d(t) - d_0]\}, \quad \text{where} \quad (6)$$

$$v(t) = \Upsilon[d(t)]$$

$$\chi(z) := \begin{cases} \gamma z & \text{if } |z| \leq \delta \\ v_* \text{sgn}(z) & \text{if } |z| > \delta \end{cases} \quad (v_* := \gamma \delta) \quad (7)$$

is the linear function with saturation (see Fig. 1(a)), the smooth function  $\Upsilon(\cdot) : [0, \infty) \rightarrow (0, V)$  determines the wheelchair speed depending on the current distance to the obstacle, whereas  $\gamma > 0, \delta > 0$ , and  $d_0 > d_{\text{safe}}$  are the controller parameters, with  $d_0$  being the desired distance to the obstacle when bypassing it. The function  $\Upsilon(\cdot)$  smoothly varies between two speeds  $v_0$  and  $v_{\text{cr}}$ , i.e.,  $\Upsilon(d) = v_0 \forall d \leq d_0^X$ ,  $\Upsilon(d) = v_{\text{cr}} \forall d \geq d_{\text{cr}} > d_0^X$ ; see Fig. 1(b). The speed  $v_0 \in (0, V)$  is used when bypassing obstacles, so  $d_0 < d_0^X$ ; the larger  $v_{\text{cr}} > v_0$  "cruise" speed is employed where there is no collision threat. We assume that  $v_{\text{cr}} < V$  to leave the wheelchair maneuverability in the "cruise" regime.

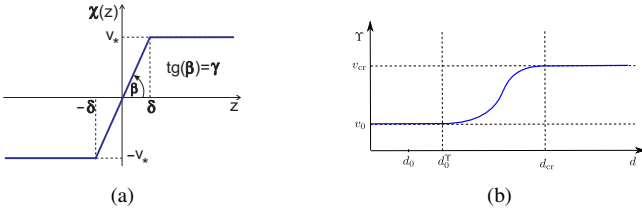


Fig. 1. (a) Linear function with saturation; (b) Wheelchair speed as the function of the distance to the obstacle

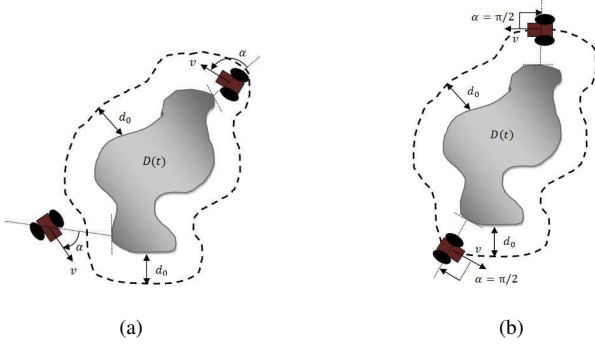


Fig. 2. (a) Sliding motion towards the equidistant curve; (b) Motion along the equidistant curve

The proposed obstacle avoidance strategy belongs to the class of sliding mode control algorithms; see e.g. [21]. The intuition behind this strategy is that in the sliding mode, the equation  $\dot{d} + \chi(d - d_0) = 0$  of the sliding surface is satisfied, according to which WC is steered towards the desired distance  $d_0$  to the obstacle. For this to take effect, the sliding mode maneuver should be at least realistic. Since  $\dot{d}$  does not exceed  $|\dot{d}| \leq v_r$ , the relative speed  $v_r$  of WC with respect to the obstacle, this means that in (7), the saturation level  $v_*$  should not exceed this speed. This can be achieved by proper tuning of the controller parameters  $\gamma$  and  $\delta$  based on available estimates of the speeds of the obstacles. If initially WC is not on the sliding surface, the control law (6) drives it to this surface after a short initial turn, so sliding motion is the main part of the obstacle avoidance maneuver.

In more details, this motion looks as follows. The equation  $\dot{d} + \chi(d - d_0) = 0$  means that the angle  $\alpha$  between the relative velocity of WC  $\vec{v}_r$  and the line of sight at the nearest point of the obstacle equals  $\alpha = \arccos \frac{\chi(d - d_0)}{v_r}$ . It follows that the angle  $\alpha$  is obtuse for  $d < d_0$  and acute for  $d > d_0$  (see Fig. 2(a)), and so WC is driven towards the desired distance  $d_0$  to the obstacle. In doing so, the angle  $\alpha$  is kept constant  $\alpha = \arccos \left[ \frac{v_* \operatorname{sgn} \chi(d - d_0)}{v_r} \right]$  in the saturation zone  $|d - d_0| > \delta$ . As  $d$  leaves this zone and approaches  $d_0$ , the angle goes to  $\frac{\pi}{2}$ . In the limit where  $d = d_0$ , the relative velocity  $\vec{v}_r$  is oriented parallel to the obstacle border  $\alpha = \pi/2$ , which means traveling along the  $d_0$ -equidistant curve, see Fig. 2(b).

The control law (6) is activated in a close proximity of en-route obstacles. Whenever WC is far away from them, it is driven towards the target in a straight line:

$$u(t) \equiv 0, \quad v(t) = \Upsilon[d(t)]. \quad (8)$$

Switching (8)  $\mapsto$  (6) occurs when the distance to the nearest obstacle does not exceed a given threshold  $d_{av} \in (d_0, d_0^*]$  and  $\dot{d} + \chi(d - d_0) \leq 0$ ; switching (6)  $\mapsto$  (8) occurs when WC is oriented towards the target and  $\dot{d} + \chi(d - d_0) \geq 0$ .

The second relation in (8) means that WC moves at the cruise speed  $v_{cr}$  far enough from the obstacles  $d \geq d_{cr}$  and starts to slow down when the distance to them reduces to the "alert" level  $d_{cr}$ . If after this the distance reduces to and below the "dangerous" level  $d_{av}$  and  $\dot{d} + \chi(d - d_0)$  becomes non-positive, the avoidance maneuver is started and then performed at the reduced speed  $v_0$ . After bypassing the obstacle, WC accelerates to the cruise speed  $v_{cr}$ . If the distance does not reduce to  $d_{av}$  or constantly  $\dot{d} + \chi(d - d_0) > 0$ , WC bypasses the obstacle along a straight line, with braking near the obstacle.

In the last case, WC not only bypasses the obstacle without collision but also respects the safety margin  $d_{safe}$ . If the distance does not reduce to  $d_{av}$ , this is true thanks to the inequalities  $d_{av} \geq d_0 > d_{safe}$ . Otherwise the claim holds by the following lemma whose proof will be given in the full version of the paper.

**Lemma 3.1:** Suppose that  $\dot{d} + \chi(d - d_0) \geq 0 \forall t \in [t_0, t_1]$ . Then  $d(t)$  lies between  $d_0$  and  $d(t_0)$  during this time interval.

When the distance to the obstacle reduces to the dangerous level  $d_{av}$ , the derivative  $\dot{d}$  is typically strictly negative. So the switch (8)  $\mapsto$  (6) does not occur at this moment only if in the sum  $\dot{d} + \chi(d - d_0)$ , the second positive addend exceeds the absolute value of the first one. Since  $|\chi(d - d_0)| \leq v_*$  and  $v_*$  from Fig. 1(a) is tuned to be less than WC speed relative to the obstacle, this may hold only if the relative velocity is nearly tangential to the  $d_{av}$ -equidistant curve. This means that the collision threat is not urgent and explains the decision to postpone the switch to the collision avoidance law (6).

The second relation from (8) does not mean that WC should have constant access to the distance  $d(t)$ : it suffices that this distance can be measured only in a vicinity of the en-route obstacle  $d(t) \leq C$ , where  $C \geq d_{cr}$ .

Practically the discrepancy  $d_{cr} - d_{av}$  and the profile of  $\Upsilon(\cdot)$  on  $[d_{av}, d_{cr}]$  are chosen with regard to the acceleration capability of the wheelchair.

The detailed theoretical studies will be given in the journal version of the paper.

#### IV. COMPUTER SIMULATION

In this section, we illustrate the performance of the proposed navigation algorithm in dynamic environments via computer simulations performed in MATLAB.

We depict WC as a brown disk and obstacles by grey circles, respectively. In Fig. 3(a), motion of WC is obstructed by one separate moving obstacle and a tight group of several obstacles moving in a common direction similar to a chain of trolleys. (The group is treated as one obstacle in this case). As can be seen from Fig. 3(b) and Fig. 3(c), WC tracks the  $d_0$ -equidistant curve of the obstacles after the avoidance mode is activated. Then WC resumes pursuing the target.

The next simulation deals with the case where the obstacles are two large crosses depicted in Fig. 4(b). One of

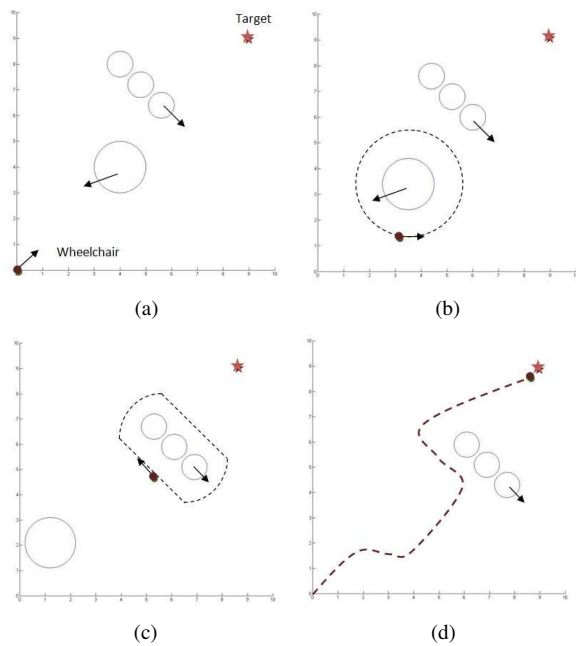


Fig. 3. Wheelchair navigating among dynamic obstacles

them slowly rotates around its center point (similar to a revolving door), and the other simultaneously rotates and moves forward. Figs. 4(c) and 4(d) depict the situations at the moments when WC bypasses the moving obstacles. Fig. 4(d) displays the overall path of WC. This simulation shows that the proposed navigation algorithm can cope with obstacles undergoing complex motions.

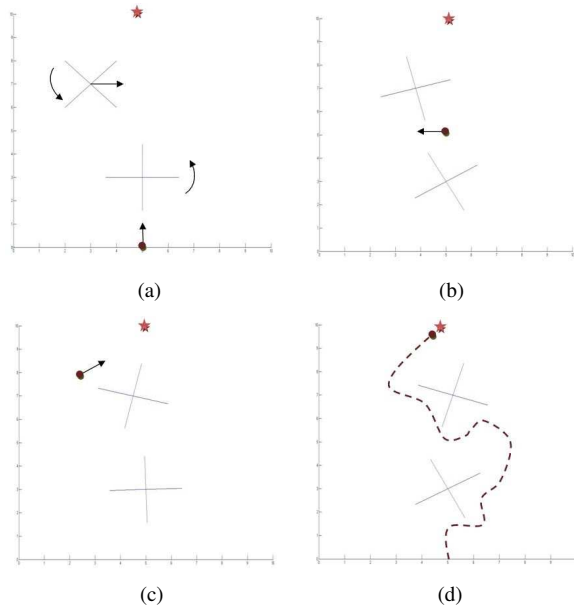


Fig. 4. Wheelchair avoids rotating obstacles

## V. DESCRIPTION OF THE REAL WHEELCHAIR SYSTEM

All experiments were carried out with SAM (Semi-Autonomous Machine) wheelchair. Motion of this WC can

be controlled in many ways, e.g. by a joystick, EEG signals [22], head movement [14] etc. For a systematic survey of the available control methods, we refer the reader to [15], [23]–[25]. The SAM WC features two rear driving wheels and two front caster wheels, the motor is powered by a 24V battery. SAM is equipped with many accessories including an on-board computer, DC/AC converter, laser range finder, LCD monitor, encoders, data acquisition devices, etc. Some of these accessories should be emphasized since they were key components in our experiments:

- A notebook with the proposed algorithm implemented in LabWindows. This is the core of the entire intelligent wheelchair control system. All data are sent to the notebook, where the control signals are computed and then sent to the driving system.
- The URG-04LX laser. It is mounted on a rack at the front of WC. This laser is used to measure the distance  $d(t)$  to the obstacles.
- USB1 adapter (by USDigital). It receives information from the encoder which measures the distances travelled by both wheels and sends them to the notebook for estimation of the position and orientation of WC via odometry.
- National Instrument DAQ device (NI USB-6008). It is used to send the control signals computed by the notebook to the motor of WC.

## VI. EXPERIMENTAL RESULTS WITH A REAL WHEELCHAIR

We implemented the proposed navigation algorithm at the SAM WC described in the previous section and carried out a variety of experiments to demonstrate its performance.

First, we showed that WC is able to perform basic navigation tasks. In these scenarios, WC has to arrive at various target positions without any collision. The most challenging part of the experiment was to maintain a given margin between WC and the obstacles (mainly the walls). The following snapshots capture crucial moments of the experiment and demonstrate maintaining a given margin to the wall (Fig. 5(a)), straight motion to the target (Fig. 5(b)), crossing a narrow passage (similar to a door passage, Fig. 5(c)), and arrival at the target (Fig. 5(d)); the corresponding points are indicated by special marks in Fig. 5(e). Fig. 5(e) also depicts the complete paths for all experiments.

We also added some occasional obstacles (bike, chairs, personal) in the scene and examined the resultant performance of the proposed navigation algorithm. The initial position of the wheelchair is shown in Fig. 5(a); Figs. 6(b), 6(c), and 6(d) correspond to the moments when the wheelchair avoids a specific obstacle. The overall path is shown in Fig. 6(e). As can be seen, the wheelchair is still able to reach the target while respecting the required safety margin.

In the next experiment, WC encounters a moving obstacle (personal) just after bypassing the chain of chairs. This moving obstacle traverses the path from WC to the target and moves at a reasonable speed. In this scenario, WC is

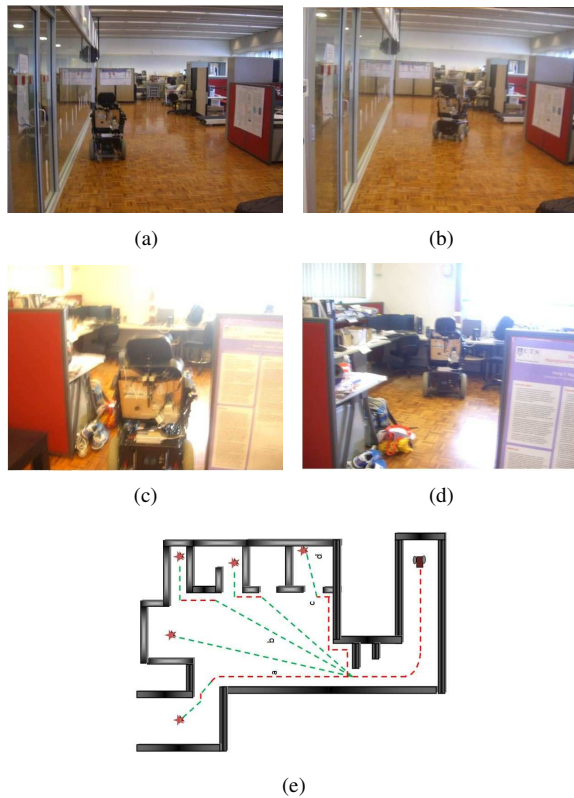


Fig. 5. Wheelchair performs basic navigation tasks

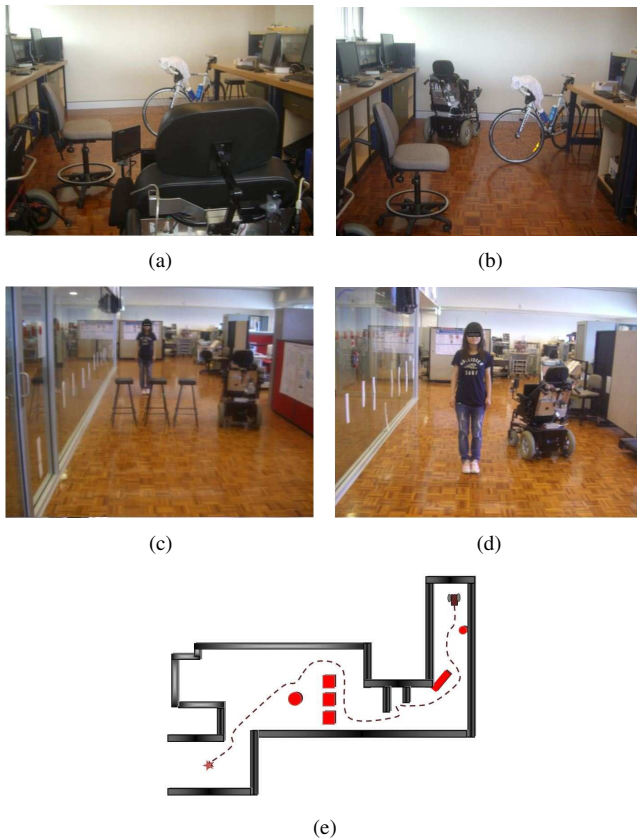


Fig. 6. Wheelchair avoids random obstacles

still able to track the  $d_0$ -equidistant curve of the moving obstacle, see Fig. 7(b) and 7(c). The complete path of this experiment is shown in Fig. 7(d).

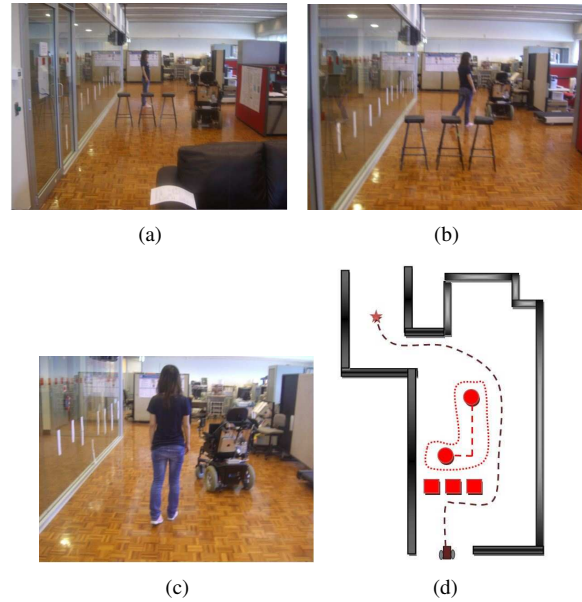


Fig. 7. Wheelchair navigating among static and dynamic obstacles

Finally, the capability of the proposed navigation algorithm to avoid multiple moving obstacles was examined. Fig. 8 shows snapshots of these experiments. Though the obstacles move in random directions, the wheelchair is still able to arrive at the target while avoiding all obstacles.

## REFERENCES

- [1] J. N. Russel, G. E. Hendershot, J. H. Felicia LeClere, and M. Adler, "Trends and differential use of assistive technology devices: United states, 1994," *Advanced Data*, no. 292, pp. 1–9, 1997.
- [2] M. Finlayson and T. van Denend, "Experiencing the loss of mobility: perspectives of older adults with ms," *Disability and Rehabilitation*, vol. 25, no. 20, pp. 1168–1180, 2003.
- [3] S. Kinne, "Correlates of exercise maintenance among people with mobility impairments," *Disability and Rehabilitation*, vol. 21, no. 1, pp. 15–22, 1999.
- [4] R. C. Simpson, E. F. LoPresti, and R. A. Cooper, "How many people would benefit from a smart wheelchair?" *Journal of Rehabilitation Research and Development*, vol. 45, no. 1, pp. 53–72, 2008.
- [5] A. B. Schultz, "Mobility impairment in the elderly: Challenges for biomechanics research," *Journal of Biomechanics*, vol. 25, pp. 519–528, May. 1992.
- [6] M. L. Jones and J. A. Sanford, "People with mobility impairments in the united states today and in 2010," *Assistive Technology*, vol. 8, pp. 43–53, 1996.
- [7] Y. Zhang, J. Zhang, and Y. Luo, "A novel intelligent wheelchair control system based on hand gesture recognition," in *Proc. IEEE/ICME International Conference on Complex Medical Engineering (CME)*, May. 2011, pp. 334–339.
- [8] Z. Hu, L. Li, Y. Luo, Y. Zhang, and X. Wei, "A novel intelligent wheelchair control approach based on head gesture recognition," in *Proc. 2010 International Conference on Computer Application and System Modeling (ICCSAM)*, vol. 6, Oct. 2010, pp. 159–163.
- [9] M. Qadri and S. Ahmed, "Voice controlled wheelchair using dsk tms320c6711," in *Proc. International Conference on Signal Acquisition and Processing (ICSAP)*, Apr. 2009, pp. 217–220.

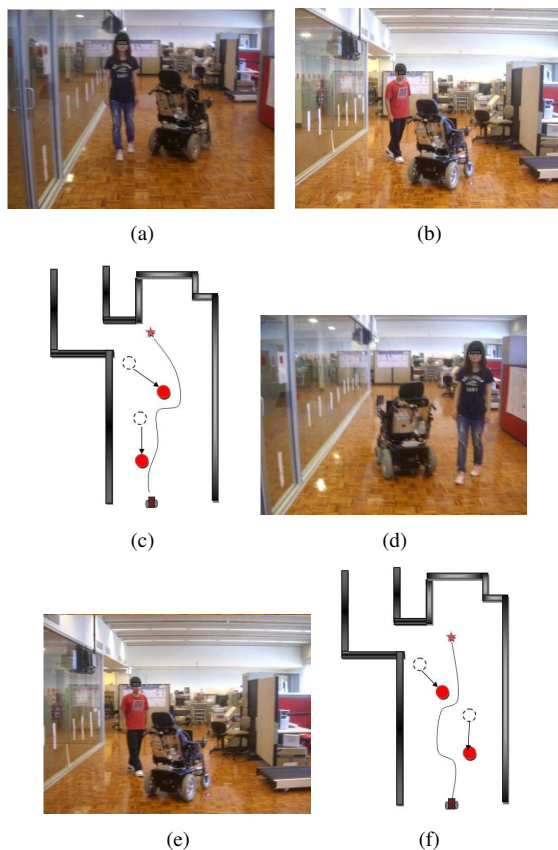


Fig. 8. Wheelchair avoids multiple moving obstacles

[10] B. Rebsamen, E. Burdet, C. Guan, H. Zhang, C. L. Teo, Q. Zeng, M. Ang, and C. Laugier, "A brain-controlled wheelchair based on p300 and path guidance," in *Proc. IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, Feb. 2006, pp. 1101–1106.

[11] L. Fehr, W. Langbein, and S. B. Skaar, "Adequacy of power wheelchair control interfaces for persons with severe disabilities: A clinical survey," *Journal of Rehabilitation Research and Development*, vol. 37, no. 3, pp. 353–360, 2000.

[12] J. Borenstein and Y. Koren, "Histogrammic in-motion mapping for mobile robot obstacle avoidance," *IEEE Transactions on Robotics and Automation*, vol. 7, no. 4, pp. 535–539, Aug. 1991.

[13] —, "The vector field histogram-fast obstacle avoidance for mobile robots," *IEEE Transactions on Robotics and Automation*, vol. 7, no. 3, pp. 278–288, Jun. 1991.

[14] H. T. Trieu, H. T. Nguyen, and K. Willey, "Advanced obstacle avoidance for a laser based wheelchair using optimised bayesian neural networks," in *Proc. 30th IEEE/EMBS Annual International Conference*, Aug. 2008, pp. 3463–3466.

[15] —, "Shared control strategies for obstacle avoidance tasks in an intelligent wheelchair," in *Proc. 30th IEEE/EMBS Annual International Conference*, Aug. 2008, pp. 4254–4257.

[16] H. Teimoori and A. V. Savkin, "A biologically inspired method for robot navigation in a cluttered environment," *Robotica*, vol. 5, pp. 637–648, 2010.

[17] E. Prassler, J. Scholz, and P. Fiorini, "A robotic wheelchair for crowded public environments," *IEEE Robotics and Automation Magazine*, vol. 8, pp. 38–45, Mar. 2001.

[18] E. Prassler, J. Scholz, and P. Fiorini, "Navigating a robotic wheelchair in a railway station during rush hour," *The International Journal of Robotics Research*, vol. 18, no. 7, Jul. 1999.

[19] A. S. Matveev, C. Wang, and A. V. Savkin, "Real-time navigation of mobile robots in problems of border patrolling and avoiding collisions with moving and deforming obstacles," *Robotics and Autonomous Systems*, vol. 60, no. 6, pp. 769–788, Jun. 2012.

[20] A. V. Savkin and C. Wang, "A simple biologically-inspired algorithm

for collision free navigation of a unicycle-like robot in dynamic environments with moving obstacles," *Robotica*, 2013.

[21] V. Utkin, *Sliding Modes in Control Optimization*. Berlin: Springer-Verlag, 1992.

[22] D. Craig and H. Nguyen, "Adaptive eeg thought pattern classifier for advanced wheelchair control," in *Proc. 29th IEEE/EMBS Annual International Conference*, Aug. 2007, pp. 2544–2547.

[23] S. Nguyen, H. Nguyen, P. Taylor, and J. Middleton, "Improved head direction command classification using an optimised bayesian neural network," in *Proc. 28th Annual IEEE/EMBS International Conference*, Sept 2006, pp. 5679–5682.

[24] T. N. Nguyen, S. Su, and H. Nguyen, "Robust neuro-sliding mode multivariable control strategy for powered wheelchairs," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 19, no. 1, pp. 105–111, Feb. 2011.

[25] N. Nguyen, H. T. Nguyen, and S. Su, "Optimal path-following control of a smart powered wheelchair," in *Proc. 30th IEEE/EMBS Annual International Conference*, Aug. 2008, pp. 5025–5028.