SCALED EXPERIMENTAL STUDY OF AN AUTOMATIC COLLISION AVOIDANCE SYSTEM FOR PASSENGER CARS

Antonella Ferrara

Dipartimento di Informatica e Sistemistica
Università di Pavia - Via Ferrata 1 - 27100 Pavia - Italy
e–mail: antonella.ferrara@unipv.it

Abstract: In this paper, an automatic pre–crash collision avoidance strategy for cars is presented. It produces a collision avoidance manoeuvre, if feasible, or, otherwise, an emergency braking to reduce the energy at the impact. The manoeuvre is generated relying on the use of sliding mode control. The performances of the proposed collision avoidance system are tested on a scaled radio–controlled car and the results are here discussed.

Keywords: automotive systems, nonlinear systems, sliding–mode control, variable–structure systems.

1. INTRODUCTION

In recent years, a number of European Commission funded projects (see, for instance, the IST projects PROTECTOR, CHAMELEON and SAVE–U) have investigated how the objective of increasing pedestrian safety can be attained by means of intelligent driver assistance systems. The results collected up to now show that, while in the long range case, a warning system to alert the driver as soon as a vulnerable road user (VRU), i.e., a pedestriant, a cyclists or a motorcyclist, is detected and classified by the sensors can be sufficient to reduce the number of accidents, an active intervention system is mandatory in pre–crash situations.

There are two types of automatic actions that a driver assistance system can accomplish so as to attain collision avoidance or injury severity mitigation: an emergency braking or a collision avoidance manoeuvre. The effect of collision velocity on injury severity is well–known. Nevertheless, the benefits of an emergency braking have been analyzed on a statistical basis in (Neunzig and Sala, 2003), under the assumptions that the driver assistance system is able to react faster than the attentive driver, and capable of performing a full braking, while the average driver usually exploits only the 60% of the maximum deceleration of the vehicle. In a previous work, the second type of automatic action, namely the generation of collision avoidance manoeuvres, has been analyzed with reference to a passenger car (Ferrara and Giacomini, 2004). The car is supposed to be equipped with sensors able to measure the relative position and relative velocity between the car and a number of moving VRUs.

In the present paper a more general automatic pre–crash collision avoidance system is considered, even if the focus is still on automatic manoeuvres generation. The system is based on the assumption that the car is equipped with front and lateral sensors (radar, laser or stereo vision systems, for instance), so that both the pedestrians crossing the road and other moving or static objects (like cars arriving in the opposite direction or from behind, parked cars, pavements or road borders) can be detected. The automatic strategy

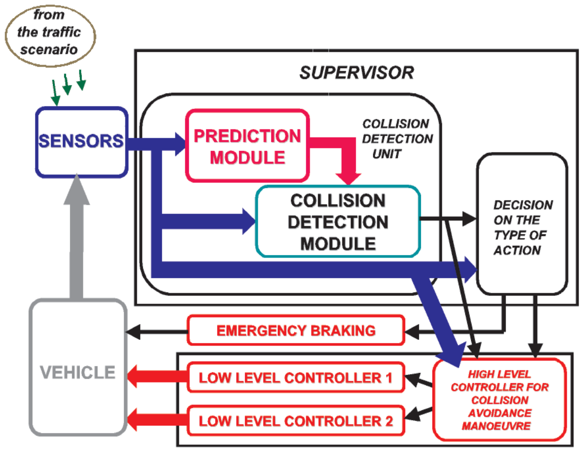

Fig. 1. Scheme of the automatic control system

is realized only when, on the basis of the data available at the current time instant, it turns out that a future collision is going to occur in $1sec$ or less, assuming that the time necessary to practically generate the automatic action is around 0.3–0.4sec. Otherwise, it is supposed that a warning generation strategy could be activated, for instance, according to (DeNicolao *et al.*, 2002).

The designed control system, depicted in Fig. 1, is characterized by a supervisor which receives the data from the car sensors, detects the possible collision, and makes the decision on which action, between the emergency braking and the collision avoidance manoeuvre, is the appropriate choice in the current situation. In case a collision avoidance manoeuvre is necessary and feasible, the supervisor activates a high level controller which, on the basis of the data received at any sampling instant form the sensors, and of some computed quantities, establishes if the car has to perform the movement to avoid the obstacle, or if it has to return to the original driving direction, since the obstacle has been avoided. This implies that there are two low level controllers capable of attaining the two different aims. Both of them are designed through a sliding mode control approach (Utkin, 1992), acting on two control variables: traction/braking torque and wheels steering angle. The variations of both the control variables have to comply with safety rules and physical limits.

The proposed automatic pre–crash collision avoidance system has been verified in simulation and tested on a scaled (1:10) radio–controlled (R/C) car. Some results of this experimentation are here reported. Even if the clear limitations of the experimental set–up at disposal and its differences with respect to a real car let the necessity of experimentation on a car prototype open, this study has been important to have a first confirmation of the possibility of actually applying an automatic system to the peculiar context of collision avoidance and collision mitigation in cars.

2. COLLISION DETECTION

The collision detection task is performed relying on the so–called collision cone, under the assumptions that: $A1$) both the vehicle and the obstacles are moving on a two-dimensional space; $A2$) their velocities (modulus and direction), during the sampling interval, can be regarded as constant quantities.. The theory underlying the construction of this cone can be briefly summarized as follows. Let us consider two point objects moving by translation on a plane (Fig. 2): let O represent the car, and F the obstacle to be avoided; let V_F and V_O be the respective velocities. In a polar–coordinates reference frame centered on the vehicle O, the motion of the object F with respect to the car O is described by the two speed components V_r and V_θ

$$\begin{cases} V_r = \dot{r} = V_F \cos(\beta-\theta) - V_O \cos(\alpha-\theta) \\ V_\theta = r\dot{\theta} = V_F \sin(\beta-\theta) - V_O \sin(\alpha-\theta) \end{cases} \quad (1)$$

which describe also the kinematic behavior of the segment OF. Relying on the assumption of constant speed, it is easy to prove that

$$V_r^2 + V_\theta^2 = V_{r0}^2 + V_{\theta 0}^2 \quad (2)$$

V_{r0} and $V_{\theta 0}$ being the initial conditions, so that it can be claimed that the possibility that a collision occurs depends only on the initial conditions. More specifically, it is possible to prove that, under the assumption that the two considered points O and F are moving with constant velocities, $V_{\theta 0} = 0$ and $V_{r0} < 0$ are a necessary and sufficient condition for collision (Chakravarthy and Ghose, 1998). So, if one considers an initial geometry defined by the two points O and F, with specified values for r_0 and θ_0, V_O and V_F, and β, it is possible to determine the value of α such that a collision can occur in the future.

In the more complete case of collision detection between a point object O and a circular one $\mathcal{F}$, characterized by a ray R (Fig. 2), the entire range of values of α which verify the condition of future collision takes the name of *collision cone*. In this case, the collision between the two objects will occur if there exists a point C belonging to the circle $\mathcal{F}$ which verifies the collision condition previously mentioned. Thus, rewriting (1) for the line OC, one has

$$\begin{cases} (V_r)_{OC} = V_{\mathcal{F}} \cos(\beta - (\theta+\phi)) - V_O \cos\big(\alpha \\ \qquad - (\theta+\phi)\big) \\ (V_\theta)_{OC} = V_{\mathcal{F}} \sin(\beta - (\theta+\phi)) - V_O \sin\big(\alpha \\ \qquad - (\theta+\phi)\big) \end{cases} \quad (3)$$

With reference to Fig. 2, to determine the collision cone, it is necessary to consider all the possible collision points C, but in particular the extreme

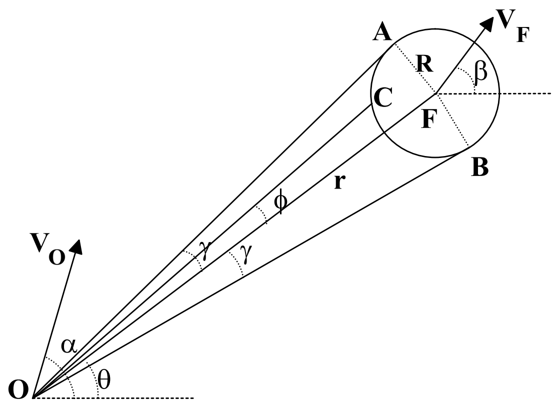

Fig. 2. The collision cone

points A and B, so that the condition $(V_\theta)_{OC} = 0$ found in the previous simpler case is now replaced by the new condition $(V_\theta)_{OA}\,(V_\theta)_{OB} \leq 0$. This latter can be rewritten as

$$r^2\,(V_\theta)^2_{O\mathcal{F}} \leq R^2 \left\{ (V_r)^2_{O\mathcal{F}} + (V_\theta)^2_{O\mathcal{F}} \right\} \tag{4}$$

The subscript $O\mathcal{F}$ may be omitted for a simpler notation. In this case, it is possible to prove (Chakravarthy and Ghose, 1998) that a point and a circle moving with constant velocities will collide if and only if their initial conditions satisfy

$$V^2_{\theta 0} \leq p^2 V^2_{r0} \text{ and } V_{r0} < 0 \tag{5}$$

with $p = R/\sqrt{r_0^2 - R^2}$. The collision cone, with respect to a fixed reference frame, is defined by all those values of $\eta = \alpha - \theta_0$ that satisfy (5): this can be transformed into three conditions, each one corresponding to an interval of values of η, so that the collision cone is given by the intersection between the three intervals, i.e.,

$$\mathcal{N} = \mathcal{N}_1 \cap (\mathcal{N}_{21} \cap \mathcal{N}_{22}) \tag{6}$$

with $\mathcal{N}_1 = \{\eta : V_{r0} < 0\}$, $\mathcal{N}_{21} = \{\eta : V_{\theta 0} \leq -pV_{r0}\}$, and $\mathcal{N}_{22} = \{\eta : pV_{r0} \leq V_{\theta 0}\}$. A further step is to analyze the collision problem when both $\mathcal{O}$ and $\mathcal{F}$ are two circular objects, with ray $R_{\mathcal{O}}$ and $R_{\mathcal{F}}$ respectively. In this case the collision cone is simply defined by (5) with p replaced by a value computed as if $\mathcal{O}$ were a single point and $\mathcal{F}$ were enlarged to account for $R_{\mathcal{F}} + R_{\mathcal{O}}$. To extend the collision cone approach to the case in which more than one pedestrian is crossing the road in front of the car, and other moving or static objects (like cars arriving in the opposite direction or from behind, parked cars, pavements or road borders) can be detected, the idea is to determine the "relevant" collision cone, that is the collision cone, among those of all the pedestrians and obstacles visible by the car sensors at the current time instant, which has to be used to determine the escaping manoeuvre. This cone is the cone associated with the obstacle which is likely to collide with the car in the shortest time.

Finally, to give a better evaluation of a future collision situation, one needs to know the possible behavior of the obstacle. The idea is to make a one-step-ahead prediction of all the quantities necessary to construct the collision cone relying on an autoregressive model (ARM) as suggested in (Elnagar and Gupta, 1998), so as to be able to determine a "predicted" collision cone. Then, the output of the "Collision detection unit" of the supervisor (Fig. 1) can be based on a weighted evaluation of the collision cone and of the "predicted" collision cone.

3. THE CONTROL MODULE

To design the multi–level controller, one needs to refer to a simple mathematical model of the car, to identify the different control phases, and to design the two low level controllers capable, respectively, to generate the movement to avoid the obstacle, and to make the car recover the original driving direction. These issues will be briefly described in the following subsections.

3.1 A Simple Car Model

For the sake of simplicity, let us rely on the so–called bicycle model (Guldner *et al.*, 1999) of the car vehicle

$$\dot{u} = \frac{1}{M}\Big(Mvr - Mfg + u^2\,(fK_1 - K_2) \tag{7}$$

$$- c_f \frac{v + ar}{u}\delta + T\Big) \tag{8}$$

$$\dot{v} = \frac{1}{M}\Big(- Mur - (c_f + c_r)\,\frac{v}{u} + \big(bc_r \tag{9}$$

$$- ac_f\big)\,\frac{r}{u} + c_f\delta + T\delta\Big) \tag{10}$$

$$\dot{r} = \frac{1}{J_z}\Big(- Mfh_g ur - (ac_f - bc_r)\,\frac{v}{u} \tag{11}$$

$$- \big(b^2 c_r + a^2 c_f\big)\,\frac{r}{u} + ac_f\delta + aT\delta\Big) \tag{12}$$

$$\dot{X} = u\cos(\Psi) - v\sin(\Psi) \tag{13}$$

$$\dot{Y} = u\sin(\Psi) + v\cos(\Psi) \tag{14}$$

$$\dot{\Psi} = r \tag{15}$$

where M is the mass of the vehicle, f, c_f and c_r are friction coefficients, K_1, K_2 are aerodynamics-related quantities, h_g is the height of the center of mass, and all the other quantities are as in Fig. 3. The two control signals are δ, the wheels steering angle, and T, the traction force at the contact point between the tire and the ground. These two signals are saturated for physical and comfort reasons, i.e., $-\delta_{\max} \leq \delta \leq \delta_{\max}$ and $T_{\min} \leq T \leq T_{\max}$. For δ_{max} it can be found an explicit expression function of the geometry of the vehicle and the environment parameters, such as the status of the road surface (Genta, 1997).

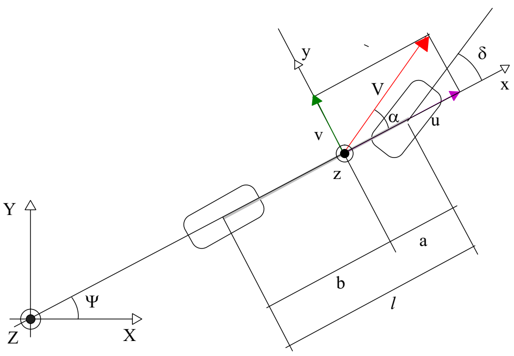

Fig. 3. The bicycle model

3.2 The Control Actions

A collision avoidance control systems for pre–crash application is a critical system, in the sense that a number of physical aspects and constraints need to be considered to generate a safe manoeuvre. This is the reason why a supervisor has been included in the control scheme: its aim is to predict, on the basis of the information available at each sampling instant, if a collision with some VRU or which some other obstacle detected by the sensors is going to occur in the close future, as well as to establish if a collision avoidance manoeuvre is applicable (or, in contrast, if, by making the manoeuvre, a collision with a different obstacle is likely). If the manoeuvre is not feasible, an emergency braking is produced so as to reduce, at least, the energy at the impact. The emergency braking action can be open–loop, because of its emergency nature. In particular, in our case, we assume that if this kind of action needs to be performed, it is realized by making the car brake with the maximum admissible deceleration. Otherwise, if the collision avoidance manoeuvre is feasible, a high level controller in charge of the generation of the manoeuvre is activated. To produce a correct manoeuvre, the controller requires that a reference trajectory is available at any time instant during the bypassing movement. To simplify the reference trajectory generation, the movement of the car during the collision avoidance manoeuvre has been divided into two phases: *Phase 1*, collision avoidance movement; *Phase 2*, re–entry movement.

3.3 The Sliding–Mode Based Low Level Controllers

The two low level controllers in Fig. 1 have been designed relying on a sliding–mode control approach (Utkin, 1992). The controller which is activated in Phase 1 (*low level controller 1*) makes the car track the collision avoidance curve approximated, during the interval between the arrivals of two subsequent pieces of data from the sensors, with its tangent line. Such a curve is determined on the basis of the knowledge of the current "relevant" collision cone. Indeed the position of the current velocity vector of the vehicle inside the cone gives indications on how a collision could be avoided: the idea is to steer the car and to vary the magnitude of the velocity vector in such a way that the driving direction moves outside the cone. The controller which is activated in Phase 2 (*low level controller 2*) makes the car track the reference trajectory given by a line parallel to the road border and distant from it of an offset equal to $1.5m$. Moreover, both the controllers produce an action on the traction/braking torque so that an appropriate reference velocity u_d is tracked during both phases.

3.4 Steering angle control in Phase 1

To generate the steering command in Phase 1, introduce the sliding quantity

$$S_1 = \dot{\xi} + \lambda_{11}\xi + \lambda_{12}\int_0^t \xi \mathrm{d}\tau \tag{16}$$

where λ_{11}, and λ_{12} are design parameters on which the dynamics of the vehicle depends once the sliding manifold is reached, and ξ represents the error between the actual car direction and the border of the collision cone closer to the actual car direction: both quantities are expressed in terms of the angle with respect to the original driving direction, i.e.,

$$\xi = \alpha_{car} - \alpha_c \tag{17}$$

The control law can be chosen as

$$\delta = -\frac{K_{S_1}}{\Delta} sign\,(\Delta)\, sign\,(S_1) \tag{18}$$

where K_{S_1} is a design parameter which takes into account the physical and passenger comfort limit δ_{max}, and

$$\Delta = \frac{a(c_f + T)}{J_z} \tag{19}$$

Note that, since in practical application of sliding–mode control the so–called chattering phenomenon may arise, it is advisory to enlarge the collision cone with a safety margin, and so consider a slightly "expanded" cone to be sure that the actual car direction during the obstacle avoidance manoeuvre is forced outside the true collision cone.

3.5 Steering angle control in Phase 2

To generate the steering command in Phase 2, introduce the sliding quantity

$$S'_1 = \dot{y}_s + \lambda'_{11} y_s + \lambda'_{12} \int_0^t y_s \mathrm{d}\tau \tag{20}$$

where λ'_{11}, and λ'_{12} are design parameters on which the dynamics of the vehicle depends once the sliding manifold is reached, and y_s represents the reference lateral distance from the road border. The control law can be chosen as

$$\delta = -K_{S'_1} sign\,(S'_1) \tag{21}$$

where $K_{S'_1}$ is a design parameter that takes into account the the physical and passenger comfort limit δ_{max}. In our case a suitable value is $0.49 rad$.

3.6 *Velocity control in Phase1 and 2*

As for the velocity control, suppose to set a piecewise constant reference velocity u_d, and define the error variable $\dot{\varepsilon} = u - u_d$ and the sliding surface

$$S_2 = \dot{\varepsilon} + \lambda_{21}\varepsilon + \lambda_{22} \cdot \int_0^t \varepsilon \mathrm{d}t \tag{22}$$

where λ_{21}, and λ_{22} are again design parameters. Then, a discontinuous control law can be designed as

$$T = -K_{S_2} sign\,(S_2) \tag{23}$$

with K_{S_2} sufficiently high to attain $S_2 = 0$ in finite time.

4. EXPERIMENTAL RESULTS WITH A SCALED R/C CAR

The automatic pre–crash collision avoidance system has been tested on the scaled (1:10) radio–controlled (R/C) car in Fig. 4. The control law for T is that indicated in (23), yet, it has been necessary to transform this variable into a suitable voltage to drive the electric engine of the R/C car. The car speed is measured via an incremental encoder placed on the engine shaft. The relative distance between the car and the pedestrians and the pedestrians' speeds are reconstructed from the images captured by the camera through image processing. The experimental results relevant to a first experiment with three still pedestrians are reported in Figs. 5–8, while those relevant to a second experiment with three pedestrians moving with random speeds are reported in Figs. 9–12. In the experimental tests the control approach has shown satisfactory performances, even though, because of sensor noise, unpredictable time–varying actuator offsets, and limitations imposed on the sampling time by image processing, the car trajectory is less smooth than in simulation.

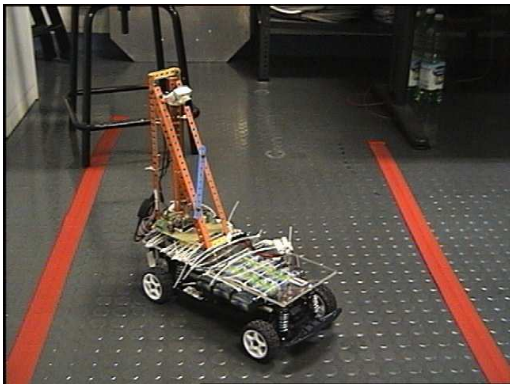

Fig. 4. The scaled (1:10) radio–controlled car

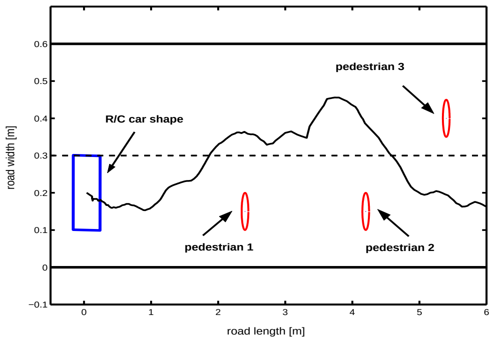

Fig. 5. Trajectory of the controlled car and of the pedestrians during the first experiment

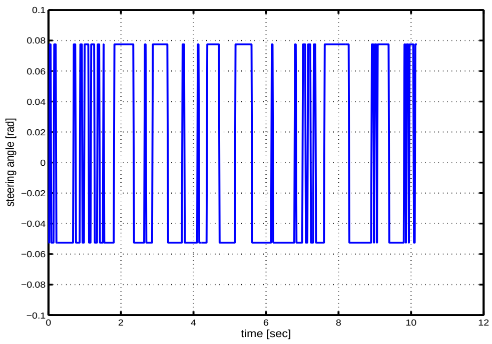

Fig. 6. The steering control input during the first experiment

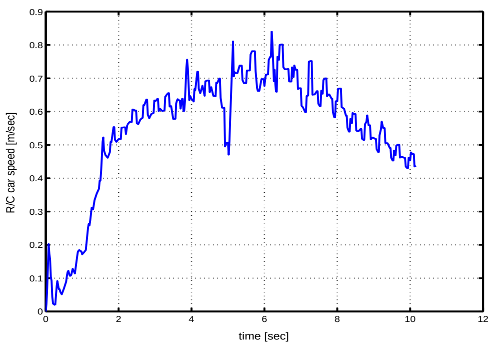

Fig. 7. The speed of the controlled car during the first experiment

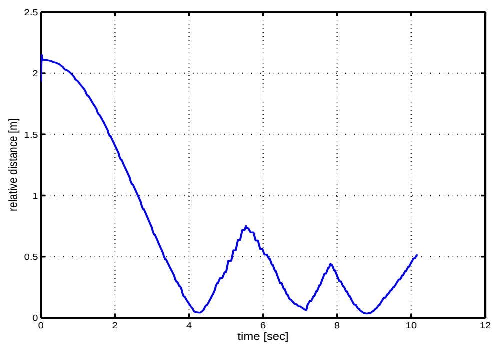

Fig. 8. The minimum value of the distances with respect to the pedestrians during the first experiment

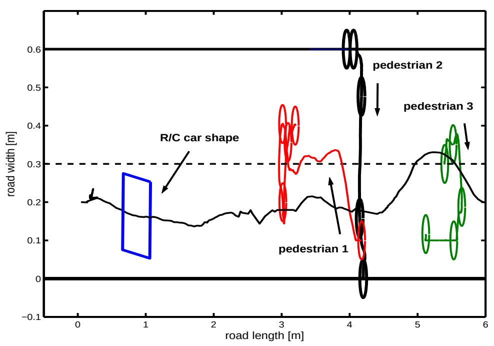

Fig. 9. Trajectory of the controlled car and of the pedestrians during the second experiment

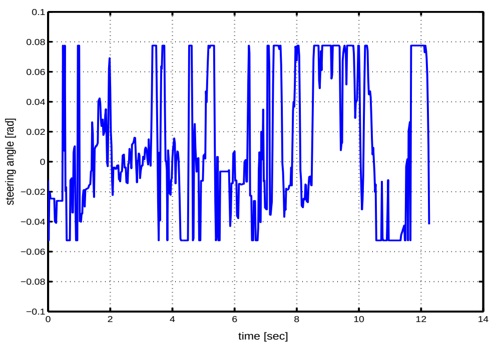

Fig. 10. The steering control input during the second experiment

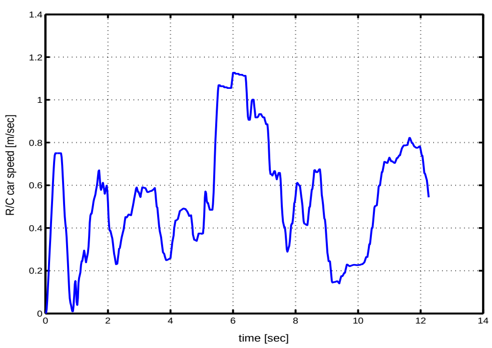

Fig. 11. The speed of the controlled car during the second experiment

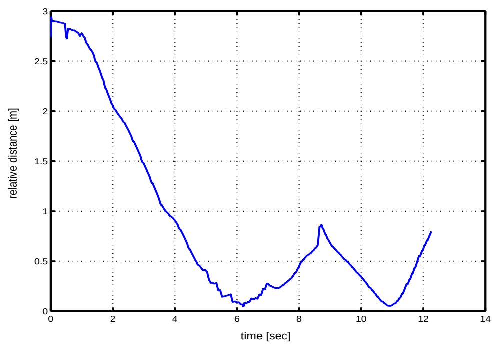

Fig. 12. The minimum value of the distances with respect to the pedestrians during the second experiment

5. CONCLUSIONS

The present paper explores the possibility of designing a pre–crash automatic collision avoidance system for cars. Satisfactory experimental results on a scaled vehicle have been provided in this paper. Yet, this work is in progress, and a number of crucial aspects still need to be analyzed before starting the required experimentation on a car prototype.

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