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Autonomous collision avoidance system based on accurate knowledge of the vehicle surroundings

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Abstract: In this study, a collision avoidance system is presented, based on the information provided by a laser-scanner sensor, in which two actions could be taken in case of danger. Firstly, the system tries to stop the vehicle in order to avoid the accident. If a reduction in speed is not sufficiently effective, the control system takes control of the steering and deviates the vehicle's trajectory in order to escape from the hazardous situation. The control system evaluates the situation and decides the most appropriate action in each case considering free areas on the surroundings using the information of a detailed digital map. This system has been implemented in a vehicle and has been tested with pedestrians and vehicles circulating along the private test track with satisfactory results.

1 Introduction

Traffic accident data have shown a clear reduction in accidents during recent years. This reduction is being achieved by the introduction of solutions that affect all areas of road transport (infrastructure, vehicle and driver) [1]. Where these advances are probably most evident is in the vehicle-related area where numerous safety systems have been introduced. We can distinguish primary safety systems which are designed to avoid accidents, and secondary safety systems that attempt to reduce their consequences. Primary systems provide the vehicle with intelligent systems able to predict and prevent accidents that the driver alone could not control. The incorporation of advanced technologies into vehicles has improved protection afforded to vehicle occupants and pedestrians and reduced road accidents in the past decade despite the huge increase in the vehicle fleet and mobility. To improve integrated safety models, a phase of interaction between primary and secondary systems has been defined [2], called pre-collision systems, overlapping the previous ones, as they use the information provided by the primary systems to achieve both the primary and secondary systems' objectives. These systems use information captured by sensors of primary systems and they can act on the control and protection systems (secondary systems) in order to reduce the probability and consequences of the accident. They allow taking measures some seconds in advance. Some of the actions are automatic braking, automatic steering manoeuvre, pretensioner activation, preparation of airbags and actions that improves the compatibility between vehicles or minimise the effects of pedestrian accidents.

The first aspect to be taken into account by pre-collision systems is the detection and interpretation of the vehicle surroundings, analysing whether there are obstacles that may become potential obstacles in the path of the vehicle. Obstacle detection is a field of work that has led to enormous progress in the interaction between primary safety systems and primary–secondary safety systems [3]. The three technologies that are commonly used for large-range vehicle surroundings detection are computer vision (e.g. [4]), radar (e.g. [5, 6]) and laser-scanner (e.g. [7–9]). Sensor fusion is used to enhance the possibilities of understanding and representing the environment as well as for mitigating the deficiencies of each sensor, and several algorithms have been proposed in the past (e.g. [10–12]).

The second aspect is how the collision avoidance system warns the driver or acts. In the case of systems that warn the driver, it is critical the interface designs. A more advanced solution considers action on the brake pedal and the steering wheel, which lies in the field of autonomous vehicles [13]. The intelligent control of these vehicles is one of the most important current challenges of intelligent transportation systems. The application of artificial intelligence techniques for the automatic management of the actuators of the vehicle enables driver assistance systems to perform management in a similar way to human drivers [14]. There are several initiatives of X-by-Wire systems use as a low-level control layer for autonomous vehicle control (e.g. [15, 16]) and there is a wide range of advanced driver assistance systems that require the automatic management of the vehicle actuators in order to correctly comply with their mission. Some examples are as follows, where some products are presently available as car equipment, developed by (original equipment manufacturer) OEMs:

– Adaptive cruise control [17–20].
– Parking assistant [21–23].

– Collision avoidance assistant [24, 25].
– Automatic intersection manager [26–29].
– Automatic lane change and lane keeping systems [30–33].

In the case of collision avoidance systems, the action that the vehicle takes is only on the brake pedal. More specifically, EuroNCAP has established that autonomous emergency braking systems will be included in the vehicle assessment scheme [34]. In this paper, we present a step forward: a collision avoidance system, based on the information provided by a laser-scanner sensor, in which two actions could be taken in case of danger instead of only braking. Firstly, the system tries to stop the vehicle in order to avoid the accident. If a reduction in speed is not sufficiently effective, the control system takes control of the steering and deviates the vehicle's trajectory in order to escape from the hazardous situation. The control system evaluates the situation and decides the most appropriate action in each case considering free areas on the surroundings using the information of a detailed digital map. This system has been tested in real testbed vehicles circulating along a test track.

2 System architecture

The developed system basically consists of two levels. First, the system should capture and analyse the environment of the subject vehicle to determine if there is any risk of collision. Moreover, the second level includes the warning and action modules on the vehicle, including braking and automatic steering manoeuvres. These assistance systems can react in less time than a driver, but require complex systems for detecting the environment in order to evaluate the most convenient alternative action.

Fig. 1 shows the vehicle control system architecture scheme. A high-level layer discriminates threats by using data acquired by a laser-scanner. Moreover, satellite positioning on a digital map is used as an additional sensor to supplement the information provided by the vehicle sensors [35, 36]. Thus, the system is able to discriminate the obstacles that are potential threats and those that are not because they are outside the area of interest. This area is defined using the information of global positioning system positioning of the vehicle and the information of a detailed digital map that includes information of accurate road geometry, number of lanes, lane widths etc. It is also possible to determine the free areas available to perform collision avoidance manoeuvres using the positioning system on a detailed digital map. With the above information, the system analyses the most suitable braking and/or steering manoeuvre that is necessary (or possible) to avoid an accident or minimise its consequences in the event of it being inevitable. The decision logic begins evaluating simple solutions to avoid a collision based on partial or full braking. In those cases in which this solution is not adequate, steering manoeuvres are evaluated. In both cases, the control system considers the physical limits imposed by vehicle dynamics, so only safe manoeuvres are proposed. When a decision is taken, the low-level system receives signals from the high-level system. It also receives information regarding steering wheel position and vehicle speed to close the control loops. Finally, it acts on the pedals and the steering wheel. Both high- and low-level control systems have been implemented at two personal computers on board with the purpose of adjusting parameters and recording data, but algorithms have been optimised so they could run in real time at other platforms more suitable for implementation on a vehicle.

3 Obstacle detection

The first step of the system is obstacle detection. Sensors and algorithms need to be developed to detect any imminent collision [37], estimate the time until it happens, and finally decide when it becomes unavoidable. One key aspect in these systems is the decision whether a collision is unavoidable or not, as it conditions the type of action the vehicle should take automatically (reversible or irreversible steps). To this end, from real-time analysis of the situation, the system should calculate time-to-collision (TTC) and compare it with time-to-avoidance. Other information of interest is the relative speed of impact, its probability, its

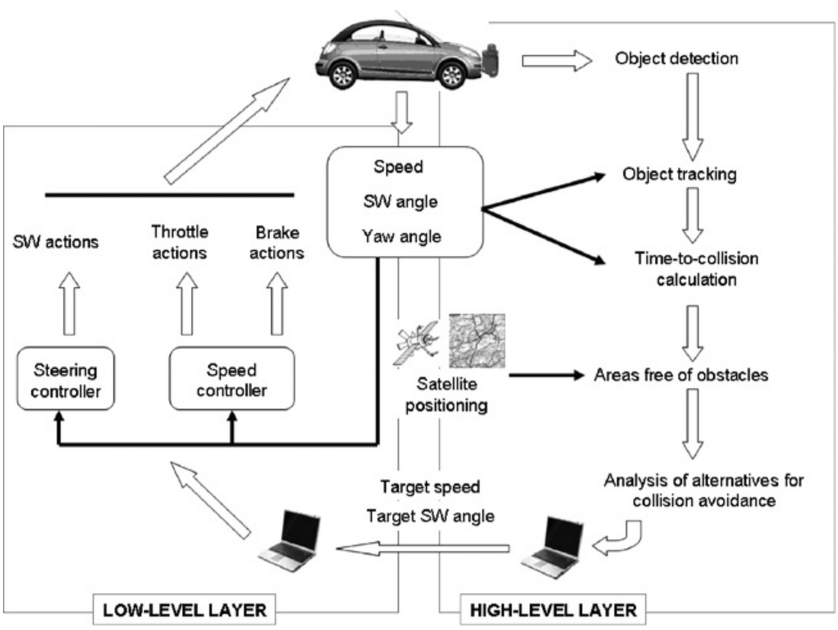

Fig. 1 *General scheme of the collision avoidance system*

Table 1 Main characteristics of Sick LRS 1000 laser-scanner

operating voltage	24 V DC ± 15%
maximum power consumption	36 W
radial range	up to 250 m
angular range	up to 360° (configured at 180°)
angular resolution	between 0.125 and 1°
acquisition frequency	up to 10 Hz
data interface	RS232/controller area network (CAN)/Ethernet
enclosure rating	IP 65

location, the characteristics of mass and stiffness of the obstacle and its identification [3].

Obstacle detection implies the following phases:

– Segmentation: identification of the piece of information that corresponds to an obstacle.
– Ego-motion estimation.
– Object classification.
– Object tracking: analysis of the obstacle's movement over time.

Several algorithms have been developed and they depend on the type of sensor. In this proposal, a single-layer laser-scanner Sick LRS 1000 is used. Table 1 shows its main characteristics. Some interesting algorithms examples in the case of laser-scanners can be found in [38–41]. However, the algorithms may be very sensitive to errors of measurement or complex road environments, which reduce the robustness and accuracy of the algorithms and their results. For this reason, the algorithm that is used by the collision avoidance system takes into account the ideas presented in [37] and introduces some relevant innovations compared with other solutions:

– Iterative segmentation algorithm to avoid false groupings or the division of obstacles in complex environmental scenarios.
– Algorithm that determines the main axes of the obstacle detected and provides accurate speed calculation of obstacle displacement.
– Accurate algorithm for TTC calculation.

3.1 Discrimination of obstacles

First of all, the detected points by the scanner should be grouped in order to identify which ones belong to the same obstacle. The common criterion assumes that two consecutive points belong to the same obstacle if they are not separated by a distance greater than a pre-set tolerance $\Delta d(r_i, r_{i+1}) = s_0 + s_1 \min(r_i, r_{i+1})$ that depends on the distance r between the laser-scanner and the obstacle detected. s_0 is a constant parameter used for noise reduction, and a lower bound for s_1 can be calculated by $s_{1\,\min} = \sqrt{2 - 2\cos\Delta\alpha}$ where $\Delta\alpha$ is the angular resolution of the laser-scanner [40]. Other more complex formulations consider the vehicle's speed [36].

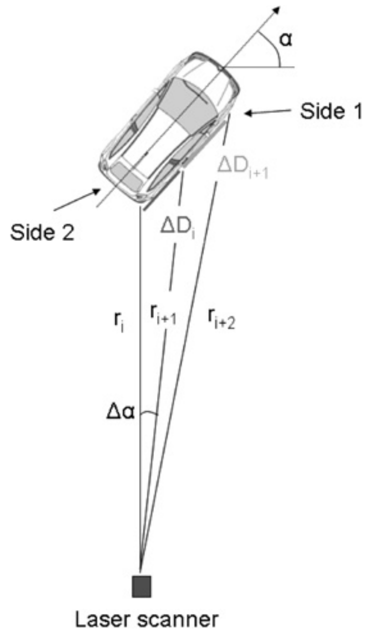

Fig. 2 *Distance between the consecutive detected points of an obstacle*

The problem of this method resides in the fact that the distance between two consecutive points of a detected obstacle can be very variable also depending on its orientation. Considering Fig. 2 and bearing in mind that the expected obstacles in road environments usually have a rectangular base (vehicles) or are theoretically equivalent to pedestrians or posts [36, 39], the distance between consecutive detected points is given by the following expressions presented in [37] (see (1) and (2))

where
if $n = 1$

$$r = d \quad (3)$$

if $n > 1$

$$\text{side 1: } r_n = r_{n-1}\frac{\cos(\alpha + (n-2)\Delta\alpha)}{\cos(\alpha + (n-1)\Delta\alpha)} \quad (4)$$

$$\text{side 2: } r_n = r_{n-1}\frac{\sin(\alpha + (n-2)\Delta\alpha)}{\sin(\alpha + (n-1)\Delta\alpha)} \quad (5)$$

Thus, a given value of tolerance Δd can sometimes provide satisfactory results, but not always. This requires an iterative process to perform collision detection so that Δd is modified according to the detected orientation of the obstacle, a parameter that is obtained in steps that must be addressed after the segmentation process.

$$\Delta D_{n\ \text{side 1}} = \sqrt{r^2\left(1 + \frac{\cos^2(\alpha + (n-1)\Delta\alpha)}{\cos^2(\alpha + n\Delta\alpha)} - 2\frac{\cos(\alpha + (n-1)\Delta\alpha)}{\cos(\alpha + n\Delta\alpha)}\cos\Delta\alpha\right)} \quad (1)$$

$$\Delta D_{n\ \text{side 2}} = \sqrt{r^2\left(1 + \frac{\sin^2(\alpha + (n-1)\Delta\alpha)}{\sin^2(\alpha + n\Delta\alpha)} - 2\frac{\sin(\alpha + (n-1)\Delta\alpha)}{\sin(\alpha + n\Delta\alpha)}\cos\Delta\alpha\right)} \quad (2)$$

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3.2 Calculation of obstacle orientation

Once the obstacles have been detected, it is necessary to know their kinematics (speed and direction). The simplified methods are based on tracking the centroid points identified as belonging to an obstacle along the different frames provided by the laser-scanner. This method provides good results in the case of small obstacles such as pedestrians. However, significant errors can occur in the case of other obstacles such as vehicles. In such cases, a more accurate algorithm is proposed. Larger obstacles tend to be detected as rectangular shapes. In those cases, 1 or 2 sides can be detected, so it is necessary to discriminate the points corresponding to each side. There are different methods in this literature that attempt to perform these operations [38, 41]. However, the above methods present deficiencies that can have a negative impact on the results, such as:

– Accuracy in detected points measurements is crucial for a correct identification of both sides, if one of those points is expected to be the corner.
– Methods usually rely on tolerances that are quite difficult to set in a general way.

The avoidance system uses the method proposed in [37] that attempts to solve the limitations of the other methods and ensures the orthogonality of both sides at any instant. This method assumes that, in general, at least three points have been detected and can be fit by two perpendicular straight lines

$$r_1 \equiv y = mx + b \tag{6}$$

$$r_2 \equiv y = \frac{-1}{m}x + c \tag{7}$$

A quadratic error minimisation process is performed (giving equal weighting to the error of each side) in order to find the axes, varying the number of points belonging to each of the straight lines r_1 and r_2 (n_1 and n_2, respectively, and with $n_1 + n_2 = N$).

$$\varepsilon^2 = \frac{1}{n_1}\sum_{i=1}^{n_1}(y_i - mx_i - b)^2 + \frac{1}{n_2}\sum_{i=1}^{n_2}\left(y_i + \frac{1}{m}x_i - c\right)^2, \quad \text{if } n_1 \neq 0 \ y \ n_2 \neq 0 \tag{8}$$

$$\varepsilon^2 = \frac{1}{N}\sum_{i=1}^{N_1}(y_i - mx_i - b)^2, \quad \text{if } n_1 = 0 \ ó n_2 = 0 \tag{9}$$

The method that minimises the quadratic error leads to the following expressions from which the gradient of the straight line r_1 can be deduced (see (10) and (11))

For any possible values of m, we find b and c using the expressions in the case of $n_1 \neq 0 \ y \ n_2 \neq 0$

$$b = \frac{1}{n_1}\sum_{i=1}^{n_1}\left(y_i - mx_i\right) \tag{12}$$

$$c = \frac{1}{n_2}\sum_{i=1}^{n_2}\left(y_i + \frac{1}{m}x_i\right) \tag{13}$$

If $n_1 = 0$ or $n_2 = 0$, (12) is used, substituting n_1 for N and calculating the second straight line as a perpendicular through the most extreme point.

3.3 TTC calculation

In [42], a procedure to calculate the TTC between two vehicles is presented, assuming that the vehicles are two ideal points. The data that are considered are the initial positions of the vehicles, their speeds and directions. Once the intersection point has been found, a procedure is established to calculate the collision time, which consists in calculating the time it takes each of the two vehicles to reach the intersection. When these two times coincide, then that is TTC. To take into account a safety margin that compensates the simplifications made, a δ factor is considered, so it is assumed that a collision occurs when the difference between the calculated time is lower than that parameter. Note that the higher δ is the more conservative the algorithm.

This procedure is simple and works well in the event of the detected obstacle being a pedestrian, but the results may become very dependent on the δ parameter when dealing with vehicles. Thus, using the previous methodology, the algorithm implemented in the avoidance system assumes the vehicle geometry to be rectangular. When two vehicles crash, it can be seen that the corner of one of them is the first area that comes into contact. Two possible initial configurations can be distinguished by taking into account the angle β between the motion vectors of both vehicles: $\beta < 90°$ and $\beta > 90°$ (Fig. 3) and only 10 accident configurations are possible. Figs. 4 and 5 illustrate them, including the time conditions that should be satisfied in each one and which configuration could take place if those time conditions are not satisfied. The notation *TXYZ* is used to denote the time the point *XY* takes to reach point *Z*, where *X* is the number of the vehicle corner, *Y* is the vehicle number and *Z* is the intersection point number.

For TTC calculation, two cases can be distinguished: (i) the corner of a vehicle hits the side of another vehicle and (ii) the corner of a vehicle hits the front or the rear part of the other vehicle. In the first situation (cases A, D, G and J), the crash point is located at one of the intersections of the

$$m^4\left[n_2\sum_{i=1}^{n_1}\left(-x_i^2 + \frac{1}{n_1}\sum_{j=1}^{n_1}x_ix_j\right)\right] + m^3\left[n_2\sum_{i=1}^{n_1}\left(x_iy_i - \frac{1}{n_1}x_i\sum_{j=1}^{n_1}y_j\right)\right] + m\left[n_1\sum_{i=1}^{n_2}\left(x_iy_i - \frac{1}{n_2}x_i\sum_{j=1}^{n_2}y_j\right)\right] + n_1\sum_{i=1}^{n_2}\left(x_i^2 - \frac{1}{n_2}\sum_{j=1}^{n_2}x_ix_j\right) = 0, \quad \text{if } n_1 \neq 0 \ y \ n_2 \neq 0 \tag{10}$$

$$\frac{1}{m^2}\sum_{i=1}^{n_2}\left[\left(y_i + \frac{1}{m}x_i - \frac{1}{n_2}\sum_{j=1}^{n_2}\left(y_j + \frac{1}{m}x_j\right)\right)x_i\right] = 0, \quad \text{if } n_1 = 0 \ ó n_2 = 0 \tag{11}$$

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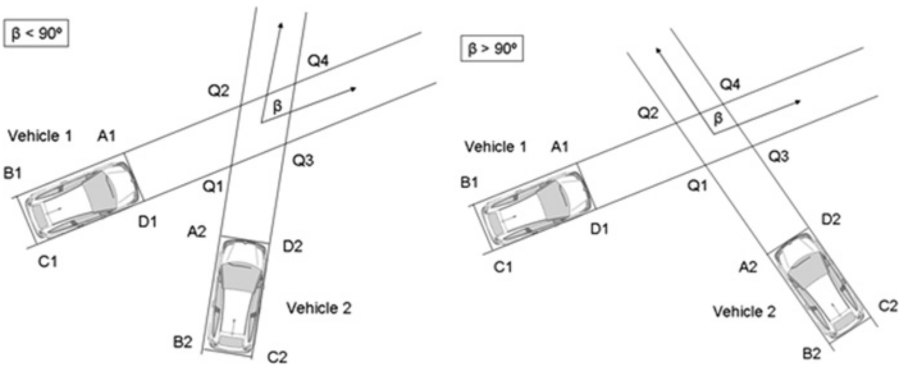
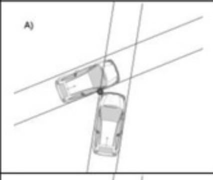
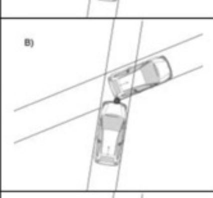
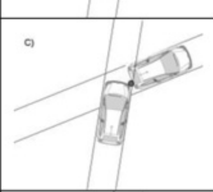
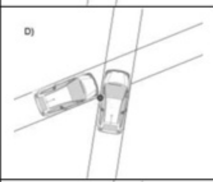
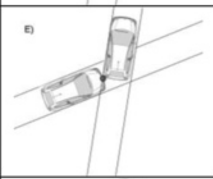
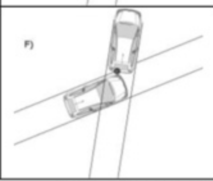


Fig. 3 *Initial configurations (β < 90°; β > 90°)*

	Situation	Diagram	Time conditions (Situation in the event the condition is not satisfied)	TTC
A)	Corner Vehicle 2 hits side Vehicle 1		TC11 > TA21 > TD11 B D	TA21
B)	Front part Vehicle 2 hits corner Vehicle 1		TC13 > TD23 > TA21 > TC11 C * A	Between TA21 and TD23
C)	Corner Vehicle 2 hits rear part Vehicle 1		TB14 > TD24 > TD23 > TC13 X * B	Between TD23 and TD24
D)	Corner Vehicle 1 hits side Vehicle 1		TB21 > TD11 > TA21 E A	TD11
E)	Front part Vehicle 1 hits corner Vehicle 2		TB22 > TA12 > TD11 > TB21 F * D	Between TD1 and TA12
F)	Corner Vehicle 1 hits rear part Vehicle 2		TC24 > TA14 > TA12 > TB22 X * E	Between TA12 and TA14

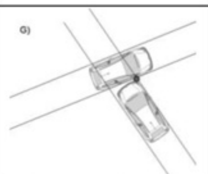
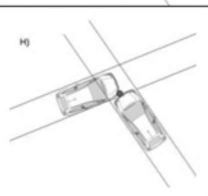
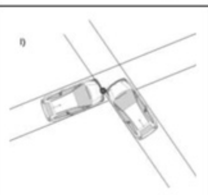
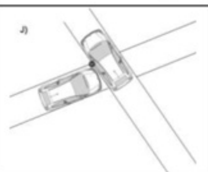
* = Always occurs X = No accident

Fig. 4 *Accident configurations when β < 90°*

* = always occurs
X = no accident

prolongation lines of the sides of the vehicles. In the second case, it should be analysed how the corner moves along that segment where the collision will take place and how the other vehicle is entering that segment (more specifically, how the last point of the area of the other vehicle where the crash occurs evolves). In this respect, two situations can be distinguished:

– When $\beta < 90°$, both the corner and the last point of the other vehicle that enters the segment move in the same direction.

	Situation	Diagram	Time conditions (Situation in the event the condition is not satisfied)	TTC
G)	Corner Vehicle 2 hits side Vehicle 1		TC13 > TD23 > TD13 X H	TD23
H)	Corner Vehicle 1 hits front part Vehicle 2		TD13 > TD23 G TA21 > TD11 I TA21 > TD23 * TD13 > TD11 *	Between max(TD11,TD23) and min(TA21, TD13
I)	Corner Vehicle 2 hits front part Vehicle 1		TD11 > TA21 H TA22 > TA12 J TD11 > TA12 * TA22 > TA21 *	Between max(TA21,TA12) and min(TD11, TA22
J)	Corner Vehicle 1 hits side Vehicle 2		TB22 > TA12 > TA22 X I	TA12

* = Always occurs X = No accident

Fig. 5 *Accident configurations when $\beta > 90°$*

* = always occurs
X = no accident

Furthermore, the order of the four time spots involved is unequivocally specified in the time conditions.

– When $\beta > 90°$, the points move in opposite directions. In this case, the order of the four time spots involved is not completely specified in the time conditions, because some of the relationships depend on each particular case.

4 Vehicle automation

Within the collision avoidance system, the obstacle detection algorithm acts as a high-level layer that generates orders to the low-level layer that acts on the vehicle's controls. The developed vehicle control architecture has been implemented and installed in a Citroen C3 Pluriel vehicle that equips an automatic gearbox, whose actuators (accelerator, brake and steering wheel) have been automated. When the system detects a collision risk, it assesses and performs the best action, but the driver maintains control of the vehicle, so control is switched from manual to shared mode and the driver is alerted of this. Then, the driver could take control at any moment to correct any action of the automatic system. Furthermore, vehicle automation has been performed so that it is possible externally to stop the vehicle at any time via a remote control. Fig. 6 shows a scheme of the control layer. The following sections show the different parts of the control architecture.

4.1 Speed control

The Citroen C3 Pluriel equips an electronically actuated throttle. The engine central unit controls the fuel inlet by considering the voltage signal that it receives depending on the accelerator position. The solution used is to bypass the electrical signal given from the pedal by one generated from an Advantech USB-4711A acquisition card. To switch between the manual action and autonomous one, a switching relay is used.

The vehicle brake has no electric power assistance. The solution that has been implemented for automating this system is direct action on the brake pedal via an external actuator. The braking module consists of a set of a Maxon RE35 DC motor and an ENC HEDL 5540 encoder, controlled by the Maxon EPOS 24/5 position controller that receives the target from the low-level control system. The motor acts on a pulley that moves the pedal. This solution allows the driver to always have control of the brake.

The speed control loop is closed by the speed measurement from the vehicle CAN bus.

4.2 Steering wheel control

The Citroen C3 Pluriel equips an electrically assisted steering system. This system consists of a DC electric motor attached to the steering rack through a gear. This motor exerts a power over the steering that is proportional to the power exerted by the driver over the steering wheel, measured through a torque sensor located in the steering bar. This signal is received by a controller that sends a pulse width modulation signal to assist the steering movement so that very little effort is required of the driver. This system has been used for automating the steering system of the vehicle. Thus, the acquisition card generates a signal which passes through the Maxon ADS 50/10 4-Q-DC Servoamplifier that is responsible for controlling

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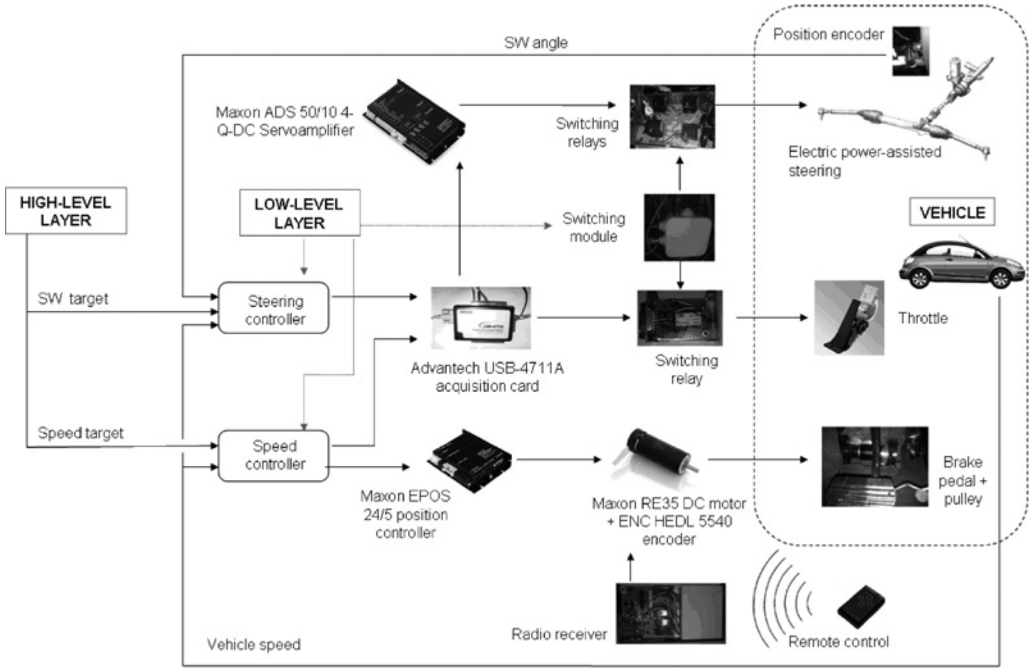

Fig. 6 *General scheme of the vehicle autonomous control architecture*

the vehicle steering motor. The feedback loop control is performed through the signal provided by the steering wheel rotation sensor. Switching between manual and automatic controls is achieved by bypassing the assistance steering unit and replacing it with the signal coming from the amplifier itself through a power relay box.

4.3 Low-level control system

The low-level control system manages the vehicle actuators in order to comply with the commands sent by the high-level controllers. The selected architecture guarantees interoperability with any high-level driver assistance system by making transparent the actuators' management.

Two low-level control systems have been designed: steering controller and speed controller. The first must be able to receive steering angle commands and to send coherent signals to the actuators to meet these orders. Similarly, the second controller must be able to receive the desired speed commands and to send the necessary orders to the accelerator and brake pedals to achieve this speed. Both controllers work at 100 Hz because this is the frequency speed and steering wheel information can be read from the internal communication bus of the vehicle which enables a quick response of the closed-loop control systems.

An important feature of both systems is their non-linear behaviour. Steering and speed are influenced by many internal and environmental factors that give rise to complex dynamics that are difficult to model with a classic method. The solution adopted to manage these elements is the application of fuzzy logic. This is able to deal with uncertain models as well as to model human behaviour when developing a complex task as driving. Soft computing deals with inaccuracy, uncertainty, partial truths and approximation in order to achieve tractability, robustness and low-cost solutions for complex systems [43]. Two fuzzy controllers have been designed:

– Steering controller involves two input variables and one output variable. The input fuzzy variables are the position error (difference between the target steering position and the real position) and the steering position. The output

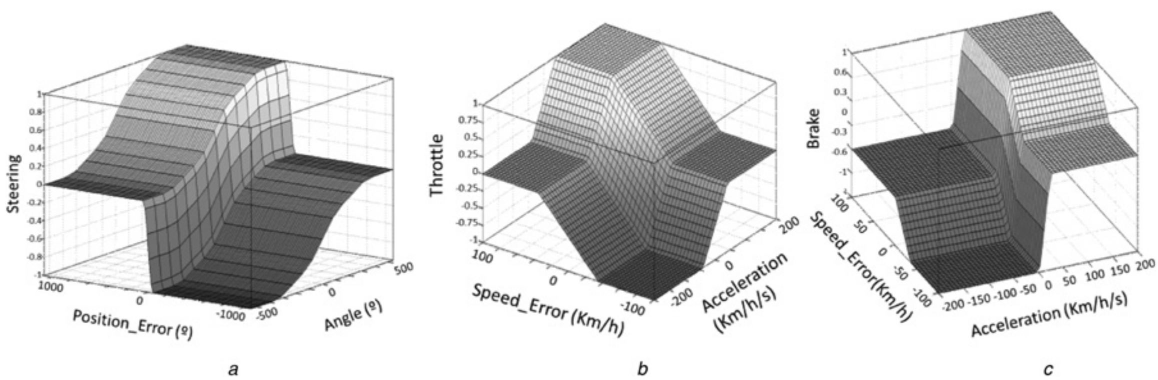

Fig. 7 *Control surfaces of the fuzzy controllers*

a Steering controller
b and *c* Speed controller (throttle and brake)

Table 2 Summary of tests carried out to verify the system performance

	Scenarios			Expected automatic actions	Results
	Vehicle B[a]	Vehicle C[a]	Pedestrian		
1	—	moves along the left lane of the main road (opposite direction to vehicle A)	crosses the main road from the left-hand side	vehicle A stops completely	satisfactory (Fig. 6)
2	—	moves along the left lane of the main road (opposite direction to vehicle A)	crosses the main road from the right-hand side	vehicle A stops completely	satisfactory
3	is stopped at the right lane of the main road	—	—	vehicle A reduces speed and performs a double lane change	satisfactory
4	is stopped at the right lane of the main road	moves along the left lane of the main road (opposite direction to vehicle A)	—	vehicle A stops completely	satisfactory
5	is moving slowly along the right lane of the main road (in the same direction of vehicle A)	—	—	vehicle A overtakes vehicle B	satisfactory
6	is moving slowly along the right lane of the main road (in the same direction of vehicle A)	moves along the left lane of the main road (opposite direction to vehicle A)	—	vehicle A reduces speed	satisfactory
7	enters the crossing from the secondary road	—	—	vehicle A reduces speed or stops completely	satisfactory (Fig. 7)
8	enters the crossing from the secondary road	moves along the left lane of the main road (opposite direction to vehicle A)	—	vehicle A reduces speed or stops completely	satisfactory
9	—	—	crosses the main road from the left-hand side	vehicle A stops completely or reduces speed and performs a double lane change	satisfactory[b]
10	—	—	crosses the main road from the right-hand side	vehicle A stops completely or reduces speed and performs a double lane change	satisfactory[b] (Fig. 8)

Subject vehicle A is initially moving along the right lane of the main road
[a]Vehicles B and C are considered as obstacles
[b]Evasive manoeuvre is performed only if the distance between pedestrian and the left lane is large enough (larger than half the lane width) when the automatic action begins

fuzzy variable of this controller is the power that must be generated by the steering servoamplifier to make the position error zero.
– Speed controller is capable of controlling two actuators, accelerator and brake pedals. Consequently, this is a multiple input multiple output controller whose fuzzy input variables are the speed error (difference between the target and the real speed) and the acceleration, whereas the fuzzy output variables are the position of the two actuators to meet this desired speed. The speed control considers both pedals in order to follow the speed command so it chooses at every moment which one is more suitable to use.

Owing to the relevance of the controllers' tasks, stability analysis is required. In classical control theory, a common tool is Lyapunov asymptotic stability analysis. However, in intelligent control is not possible to apply it directly [44]. The other way to demonstrate the stability of an intelligent controller is making an experimental validation, considering the control responses taking into account the full range of input variables to demonstrate that the output always maintains in range and to assure the absence of instabilities. In our case, we have calculated the control surfaces for the three controllers (Fig. 7). It is shown that the surfaces are stable, without instabilities in the full operative range of the input variables, providing the expected output and assuring a safe behaviour of the fuzzy controllers in any possible circumstances. A more complete description of the fuzzy logic controllers can be found in [45].

5 System functioning tests

To test the correct functioning of the system, some tests have been carried out at the University Institute for Automobile Research test track. The experiments are presented in order to demonstrate the feasibility and performance of the presented system. In the test track an x-crossing was simulated.

The experiments consisted of an obstacle detection and avoidance in different scenarios. It should be noted that controlled scenarios are presented because obstacles detection algorithms have been proved in the past in more complex situations [37] and results compared with other methods proposed in the past [38, 41], so it is assumed their correct and robust behaviour. Table 2 contains the tests configurations and main results. The conclusion is that the system works correctly in all the situations tested, the system decisions have been appropriate and the automatic

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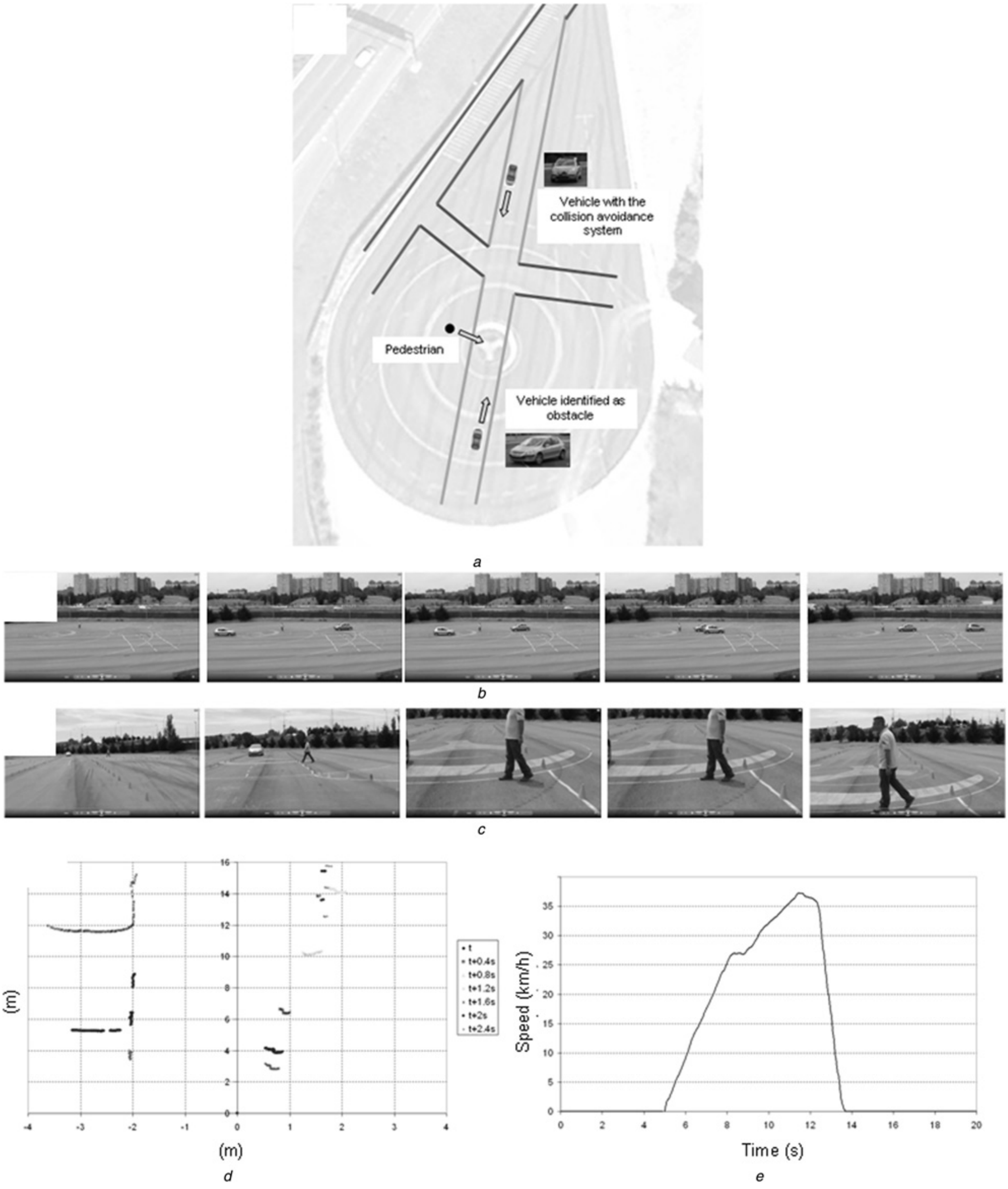

Fig. 8 *Test 1*

a Test layout
b Subject vehicle and obstacle movement
c Perception of the obstacle from the vehicle
d Laser-scanner obstacle information
e Subject vehicle speed

manoeuvres have been performed as desired. Figs. 8–10 show three of the most relevant scenarios and include several frames during the manoeuvre as well as data of the subject vehicle that equips the collision avoidance system (green vehicle in the figures) such as trajectory, speed and action over the steering wheel.

In Fig. 8, the pedestrian that enters the lane along which the vehicle with the system is moving is detected with enough

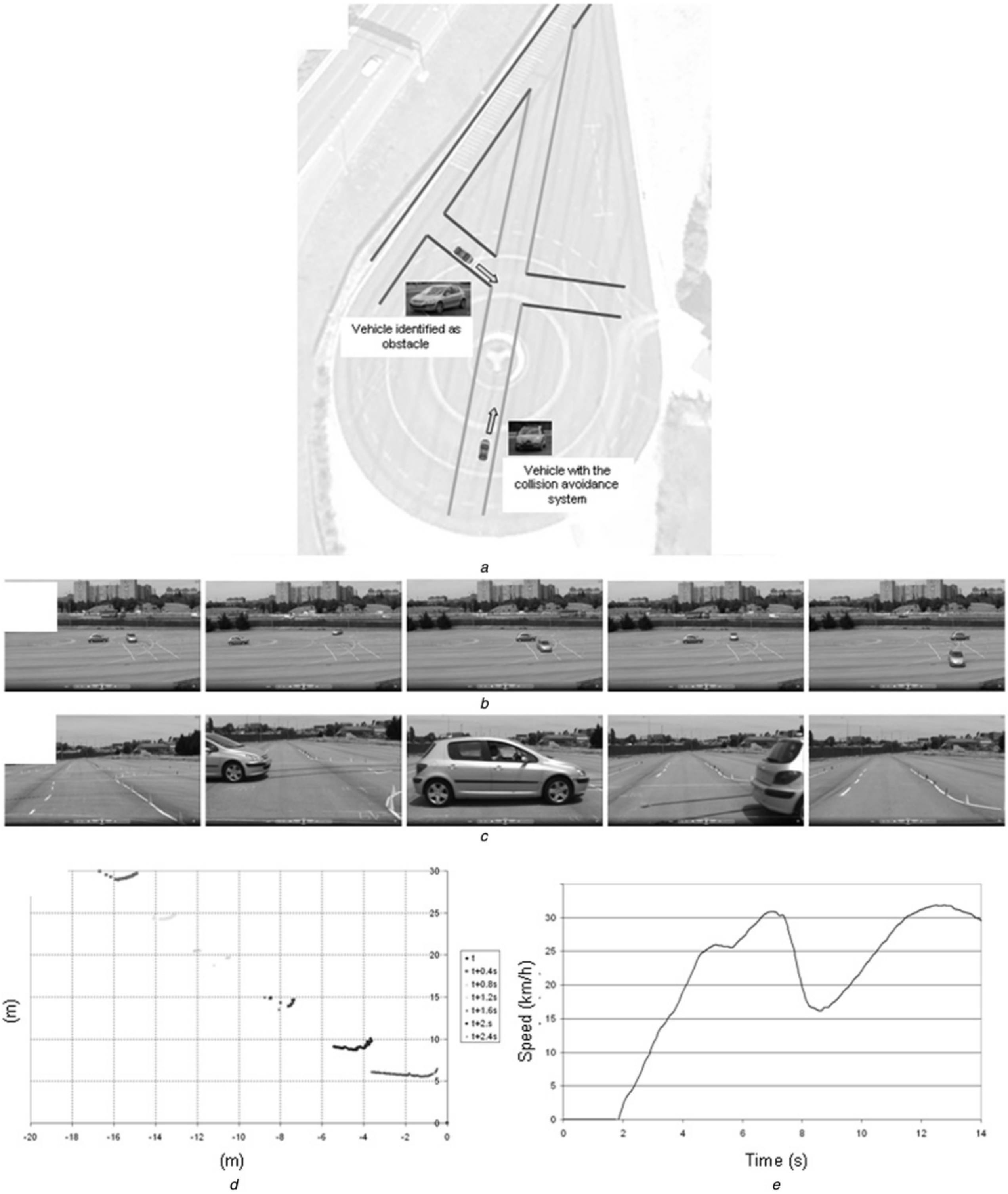

Fig. 9 *Test 7*

a Test layout
b Subject vehicle and obstacle movement
c Perception of the obstacle from the vehicle
d Laser-scanner obstacle information
e Subject vehicle speed

anticipation and the system stops the vehicle automatically to avoid collision because a lane change is not possible because of the presence of another vehicle (grey vehicle).

In Fig. 9, the subject vehicle with the avoidance system detects that an intruder vehicle (the grey one) is going to enter the crossing without braking and a collision may occur if no action is performed. In this situation, the system decides that it is not necessary to stop the vehicle completely but to reduce its speed. Therefore a force is applied to the brake pedal until the new target speed is achieved.

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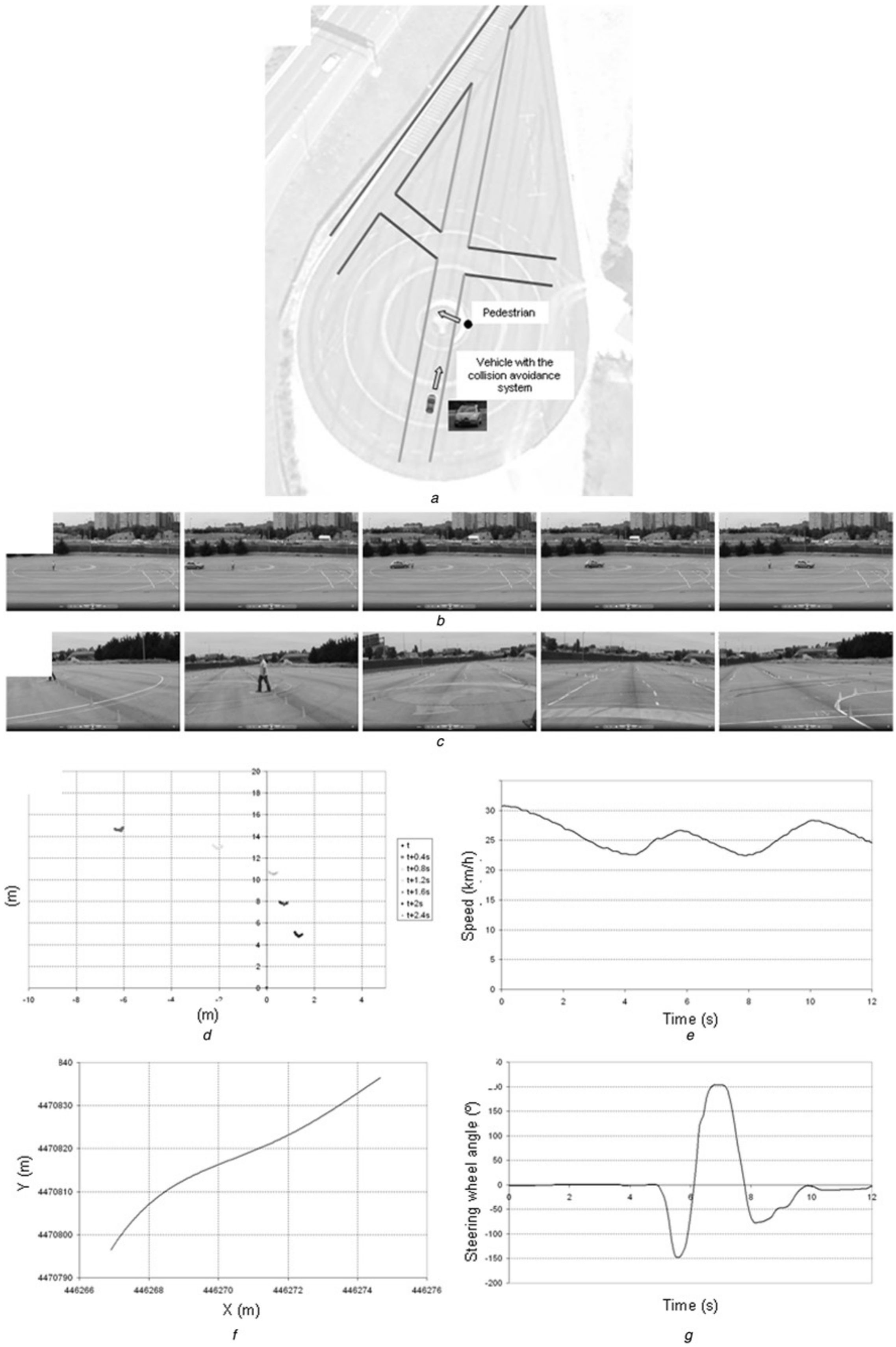

Fig. 10 *Test 10*

a Test layout
b Subject vehicle and obstacle movement
c Perception of the obstacle from the vehicle
d Laser-scanner obstacle information
e Subject vehicle speed
f Subject vehicle trajectory
g Steering wheel angle

Finally in Fig. 10, the pedestrian enters the lane in the same way as in the first case, but the distance between the vehicle and the pedestrian is not long enough to avoid the accident only by braking, so the system acts commanding the steering of the subject vehicle. In this case, the system knows from the information contained in the digital map that there is a lane on the left-hand side and the laser-scanner evaluates that it is free of obstacles, so lane change is a suitable and safe manoeuvre. As a result, the system takes control of the steering wheel and the brake and acts over them, reducing the speed as well as turning to the left the necessary angle to avoid the obstacle in a safe way.

6 Conclusions

In this paper, a novel automatic collision avoidance system, based on laser-scanner data, has been presented. This paper reflects the practical implementation of the collision avoidance system and employs results of the previous work regarding obstacles detection, imminent collision situations analysis and vehicle automation. The collision avoidance system has been modelled, implemented and tested. The analysis of the results of the experiments shows that the behaviour of the developed system fits with the expected one, guaranteeing the safety of the vehicle's passengers as well as the safety of the possible obstacles (i.e. pedestrians, other road users, other vehicles), selecting the best operation and actuator management in each situation. The system presents the novelty that steering manoeuvres are considered (not only braking) in order to avoid accidents and this fact implies that the control system should know the areas that are free of obstacles.

In the current practical implementation, a single-layer laser-scanner is used for detecting obstacles, and satellite positioning on a digital map provides the information on which vehicle movements are suitable for collision avoidance. The reliability of the avoidance collision system remains on an accurate detection of the surroundings of the vehicle. Of course, this perception system is not sufficiently complete to ensure that a specific steering manoeuvre is not dangerous for other road users. To obtain more information of the vehicle surroundings, other sensors are planned for future versions of the system using sensor fusion algorithms. In this case, the system would be able to evaluate whether there are obstacles near the vehicle's sides or whether a faster vehicle is going to pass us, in which case a lane change manoeuvre could be potentially dangerous. Furthermore, the laser-scanner works at 10 Hz detection frequency. This value is high enough in most circumstances, but higher values would be desirable in changeable scenarios.

Improved algorithms have been used for obstacle detection and TTC calculation. On the other hand, decision algorithms should be improved for future versions in order to take into account complex driving scenarios so that the response would be the most appropriate one in each case, combining braking and steering.

Finally, the developed fuzzy logic controllers imply an additional advantage: any high-level system connected to this low-level controller will perceive the car as a linear system that only needs to receive simple steering and speed commands to adapt its response. This feature facilitates the design of any kind of assistance system, and it should be noted that the system lets manual control be maintained even if the system considers that an automatic action is required.

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