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Automatic car driving based on fuzzy logic and GNSS

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Abstract: The goal of Intelligent Transport Systems (ITS) is to fully automate driving. ITS is the application of technology to vehicles and roadways to increase safety. Adaptive Cruise Control (ACC) and other assistants are all part of ITS. There is consensus among professionals that developments will move progressively from ACC to automatic driving. In this paper, we resent an approximation to automatic driving, which differs from other developments mainly in that it is based upon global navigation satellite system and artificial vision information. Also the computation for navigation is based on a set of fuzzy logic controllers that manage the vehicle actuators. Mass-produced cars have been instrumented to behave automatically when circulating in private circuits. A fuzzy controller has been designed to manage the vehicle actuators: steering wheel, throttle and brake. Automatic driving tests have been performed, resulting in very human-like vehicle management, in steering as well as speed control.

Keywords: fuzzy control; global positioning system; intelligent control; road vehicle control.

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Ricardo García received a PhD in Physics from Bilbao University, Spain. He was a Founder of Instituto de Automatica Industrial, Spanish Research Council, where he has worked in intelligent robotics until nowadays. He was named in 2002 for the 'Barreiros' Research on Automotive Field Prize for his AUTOPIA project on ITS.

Teresa de Pedro received a PhD in Physics from the Universidad Complutense of Madrid in 1976. Since 1971 she has been working on artificial intelligence applied to automation in the Instituto de Automática Industrial belonging to the Spanish Research Council. Now she is interested on fuzzy models for unmanned vehicles and she is the Head of a Spanish team involved in the Integration of Sensors to Active Aided Conduction (ISAAC) project.

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1 Introduction

Computers have been a vehicle component for many years. Until recently, however, their role has been relegated to auxiliary tasks, such as regulating the cabin temperature, and warning about low fuel, motor oil or battery charge levels, and open doors. At most, computers have monitored internal devices, but they have not been involved in any task related to environment perception or in driving. Recently, computers have been in charge of some tasks related to driving in some commercial models, such as maintaining a reference velocity or keeping a safe distance, improving night vision with IR cameras, building maps, providing alternative routes. In experimental models, the involvement of computers in driving is increasing and becoming a major subject for manufacturers to such a point that some of them are beginning to look at vehicles as computers with wheels. Although the use of computers in vehicles is not new, their role is shifting from controlling auxiliary devices, irrelevant to driving, to operating the main driving devices, such as the steering wheel, throttle and brake.

However, the automatic control of commercialised actuators is limited at present to research projects aiming at gauging the real scope of the available technology and developing a new generation of vehicle equipment.

The first automated car in the world was presented by Tsugawa's team at the Mechanical Engineering Laboratory in Japan in 1977 (Tsugawa et al., 1979). This vehicle's behaviour was very limited and it could only execute short routes due to technological constraints. Nevertheless, it is demonstrated that a car can be automatically controlled without human intervention by just a sensor, in this case artificial vision, an onboard computer and the instrumentation of the vehicle actuators. This group is continuing its research, applying new technology to modern vehicles. In Kato et al. (2002), they present an automatic driving system based on GPS information for tracking a road route and using inter-vehicle communication to locate all the vehicles circulating on the road.

Two US research projects focus on automatic driving: Navlab and PATH. The first is the acronym for the Carnegie Mellon University's Navigation Laboratory that has been doing research in this field since 1984. Several unmanned vehicle prototypes have been developed at this laboratory. The most famous one was Navlab 5, which was involved in the 'no hands across America' experiment, whose aim was to complete a route from Washington to California driving along US public highways. The steering wheel of the Navlab 5 vehicle was automated and controlled by the RALPH system (Pomerleau, 1995), based on artificial vision and neural networks. This project is still going today and is developing unmanned vehicles that can be used to test a wide variety of sensors and control techniques to approximate automatic driving.

California Partners for Advanced Transit and Highways (PATH) bases its work on the development of automatic vehicles circulating in platoons along private lanes beside public roads (Sheikholeslam and Desoer, 1990). These vehicles have automated steering and speed and they can enter or leave the platoon when the human user decides to return to manual driving and rejoin the public highway (Shladover, 1991).

In Europe, the unmanned vehicle research started during the PROMETHEUS project (PROgraM for European Traffic with HighEst and Unprecedent Safety), as part of which some autonomous prototypes were developed (Dickmanns et al., 1993; Bloseville et al., 1994; Broggi et al., 1999). It is continued today by several fifthand sixth framework research programmee projects. The Cybercars project, which recently came to a conclusion, aimed to develop unmanned vehicles to meet citizens' needs (Michel, 1997) and the focus of the Chauffeur project is on the automatic driving of trucks in hazardous conditions (Fritz et al., 2004).

The ultimate aim of this technology is, therefore, for vehicles to be driven without human intervention.

Some traffic situations are complex and difficult to manage even for people, not to mention a computer system. As Prof Zadeh has often remarked and most recently in Zadeh (2001), 'we cannot automate driving in city traffic' (he cites Istanbul as an extreme case), though humans can do this without any measurements and any computations. The task of driving belongs to a class of problems in which the overall capability depends on the underlying systems for logical reasoning and dealing with uncertainty.

The work described in this paper was done at the Instituto de Automática Industrial (IAI) and the University of Alcalá de Henares (UAL). Building on IAI's extensive experience in the development of autonomous robots and fuzzy control and UAL's knowhow in artificial vision, we set up the AUTOPIA Programme, a set of national research projects similar to other country's programmes (García and de Pedro, 2001). The goal of AUTOPIA is to transfer autonomous mobile robot control technologies to computer-aided vehicle driving. The aim of this programme is to develop a testbed infrastructure for experimentation with control systems, strategies and sensors applied to vehicle driving and it is open to groups interested in our research field. Our research objective is to implement automatic driving using real mass-produced cars tested on real roads, albeit for the time being within a private circuit for obvious safety reasons. This objective might be termed 'utopian' at this point in time, since fully automatic driving is unlikely to be a reality for at least 20 years. Nevertheless, this is a great starting point for exploring the future. The second aim of AUTOPIA is a spin-off of its ultimate goal: the development of driving assistants. Although full automation is not yet possible, the modular components of these automatic driving systems can now be applied in the automotive industry. A lot of applications can be developed from the experience gained using AUTOPIA systems.

Fuzzy logic was used to control these systems for two main reasons. The first is that fuzzy controllers do not need an exact mathematical model of the system to be controlled. This is a very important feature when dealing with systems, like cars, that are difficult to linearise. Fuzzy logic averts the use of approximate models, which, if realistic, are very complex and not very efficient or, if efficient, are not very realistic. The second feature of fuzzy control is that it aims not to use the mathematical representation of the systems, but to emulate the behaviour of human drivers and their experience, mimicking their reactions. Also users' subjective knowledge can be built into the system, which is definitely a very useful feature for emulating human behaviour (Mendel, 1995).

As part of AUTOPIA, three testbed cars (Figure 1) have been automated to perform speed and steering control from a computer with an embedded fuzzy logic-based control system. A VCD camera and high-precision GPS are the main sensorial inputs of the control system, which manages the car driving actuators: the steering, the throttle and the brake pedal of the cars that have been automated (Naranjo et al., 2003a,b,c).

Figure 1 AUTOPIA testbed vehicles

2 AUTOPIA instrumented vehicles

To run the automatic driving experiments, three vehicles – two Citroën Berlingo and one Citroën C3 Pluriel – have been instrumented and equipped to perform autonomous and cooperative driving. Two DC motors manage the steering wheel and the brake pedal of the Berlingos, whereas their throttles are controlled by an analogue signal. The steering of the C3 is controlled using the pre-installed Electronic Power Steering (EPS) system and its throttle is also managed by an analogue signal. All the vehicles include an onboard computer that runs the control system, a GPS receiver to ascertain the vehicle's road position and a WLAN link for broadcasting their GPS position within the driving zone.

One of the Berlingos (the one on the right in Figure 1) is also equipped with a laser scanner sensor to detect obstacles in the road and the other one is equipped with a VCD camera that provides input to an artificial vision system housed in a second onboard computer. Apart from detecting obstacles, this vision system can be used as the main navigation sensor, perceiving the edges even of unmarked roads.

The same automatic driving experiments can be done on all three vehicles, even though the brake pedal of the C3 has not yet been automated and it uses motor braking only for such operations. For this reason, we only refer to the two vans in this paper.

With this equipment, we can achieve unmanned driving manoeuvres on roads that are straight or have bends, as well as collaborative driving, like keeping a safe distance between cars, driving in traffic jams or overtaking.

3 Outline of the guidance system

The development of automated vehicles is progressing step by step towards what is expected to be a car being driven by a computer with minimal input from the user. Our ultimate goal is to build a modular system using fuzzy rules to control driving (the idea being that fuzzy rules are similar to human commands) with minimal input from the environment, as are human actions.

The first step was to get an unmanned car to run around an obstacle-free private circuit. The fuzzy controller rules provide the control actions on the throttle, the brake pedal and the angle of the steering wheel to do this. In this step, the fuzzy inputs are defined from the data acquired by a global navigation satellite system. The second step provides the same control actions, but the control rules can also react to the obstacles in the road, implementing the right behaviour. This step involves adding a sensor, a visual camera, to detect obstacles. The third step is to get several cars to move simultaneously around the circuit. In this case, the control rules permit the car to deal with a variety of situations, such as driving behind or parallel to another vehicle, overtaking (Naranjo et al., 2003a,b,c), Adaptive Cruise Control (ACC) (Naranjo et al., 2003a,b,c), giving way or stopping at junctions. This step requires communication among vehicles. Therefore, the wireless network used to transmit differential corrections of position from the GNSS base station to the cars is also used to broadcast information among the vehicles. The fourth step will be to drive along a road open to the public. To do this, further action will need to be taken to detect road limits, traffic signals, other cars on the road, etc. Other kinds of sensors will be needed to achieve this.

The first step has already been achieved and the testbed cars have been purchased and modified to accept accelerator, brake and steering commands from the computer. The car speedometer is used as feedback and a centimeter range Differential Global Positioning System (DGPS) is employed to determine the position.

The second step is almost complete and visual procedures to detect road edges and obstacles in the road have been tuned. This visual information is enough to guide the vehicle along the road, except at junctions where it has to be supplemented with information from the GNSS.

The third step has just been completed. In this step, each car knows the position of the other cars in the circuit and drives taking this into account.

For the fourth step, a lot of work remains to be done before our vehicles can drive along public roads, but the tools and the results achieved so far lead us to expect to be able to drive a fleet of vehicles for specific applications on roads that are not open to public traffic.

Finally, real experiments to test the first, second and third steps of the driving system have been completed. The real experiments have been carried out in a 1 km long, 6 m wide circuit with two electric vans. The circuit reproduces an urban district with sharp bends and junctions. The maximum velocity attained on the straight has been 60 km $hour^{-1}$ and the behaviour of the fuzzy controllers and sensorial systems are very promising.

4 Kinematic foundations of the fuzzy vehicle controller

At the most abstract level, the movements of a vehicle can be modelled by a sequence of states in a vectorial space. The elements of this space are vectors whose components define the current state of the vehicle, its position, velocity and acceleration, respectively, according to classic control theory:

$$S = \left(\vec{z}, \vec{z}', \vec{z}''\right)$$

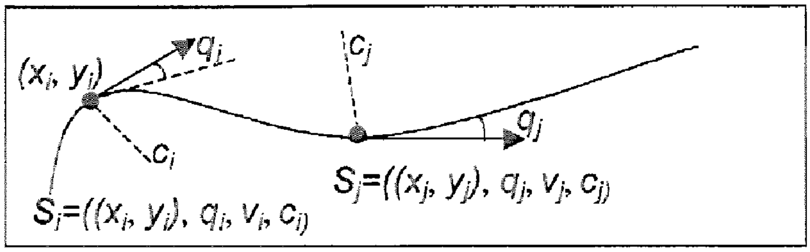
Formal operators can be defined in this state space that change the values of the current parameters and take the vehicle from one state to another. However, the important point about the control model is that, in practice, these operators are equivalent to the actions of the guidance system, which can be either a person or an automatic control system.

The main advantage of a qualitative model is its closeness to the user than the parameters of the classic control form:

$$S = \left((x, y), q, v, c\right)$$

where (x, y), q, v and c stand for the current vehicle position[1], orientation, module of the velocity and trajectory curvature, respectively (Figure 2). It is clear that all drivers find these parameters to be intuitive concepts, which cannot be said of the parameters of the classic expression. A positive value for orientation means that the angle between the vehicle axle and the tangent to the trajectory is clockwise and a negative value that it is anticlockwise. Similarly, a positive value for curvature means that the turn is clockwise and a negative value that the turn is anticlockwise. Finally, velocity is positive if the direction is forward and negative if it is backwards.

Figure 2 Position, orientation and curvature radius of two vehicle states. (x_i, y_i) are the coordinates of a point rigidly joined to the vehicle



In a preliminary kinematic approach, the operators of the state space can be defined according to the intrinsic movement equations of a point rigidly linked to the vehicle, for instance, the centre of the rear axle. These intrinsic equations are:

$$v = \frac{1}{c} \times \frac{dq}{dt}$$

$$\vec{v} = v \times \vec{u}$$

$$\vec{a} = \vec{u} \times \frac{dv}{dt} + c \times v^2 \times \vec{n}$$

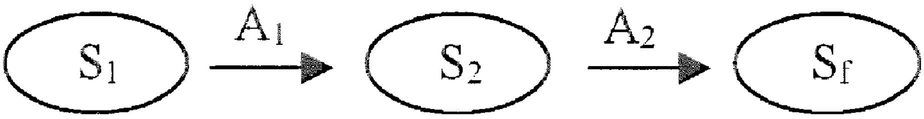
where $\vec{u}$ and $\vec{n}$ are unitary vectors tangent and normal to the trajectory, respectively. Therefore, the operators can be represented by an array of actions:

$$A_i = (\Delta q_i, \Delta v_i)$$

where Δq_i and Δv_i are the increments of the steering wheel angle and the velocity in each control cycle, respectively.

In this model, the route can be represented by a sequence of states, from an initial S_1 to a final S_f, each state S_i being the state of the vehicle at the beginning of each control cycle. Likewise, the controller can be represented by a sequence of actions $A_1 \ldots A_i$, each action A_j being the control action computed in the current control cycle. Finally, the model shows that the controller works as an uncoupled system, that is, the direction and the velocity can be controlled separately. In fact, there are two sets of rules: one set controls acceleration and a second set controls direction (Figure 3).

Figure 3 Abstract model of route and controller



5 Perception of the kinematic variables

For the above-mentioned first step, traffic is confined to one car moving alone unhindered by obstacles. The only control action needed to track the road trajectory, irrespective of speed, affects the steering wheel. The perceptions needed of the environment are the relative position and orientation of the car with respect to the trajectory. All of these data can be obtained by a GNSS, in particular a DGPS. A map of the testbed circuit has to be acquired previously and a GPS receptor onboard the car provides each control cycle with the current car position (x, y) and orientation q.

To manage the vehicle speed, this needs to be adapted to the shape of the road. In our case, a reference speed has been defined for each segment of the circuit, like the speed limits on public roads. The throttle and brake pedal will be managed to keep to this reference speed.

The second step of automation is the same as the first, except that, as there may be obstacles, their positions have to be known to control the steering wheel and speed accordingly. In this research, these data are acquired by a visual system.

Although the visual system was designed to detect obstacles, it actually perceives more information about the environment, namely the road edges, which can be used for the guidance system. One important feature of the visual system is that it detects the real edges even without the help of marked lines. This can dynamically complement the map of the road built by the GNSS. Indeed, the GNSS provides a line of reference of the road layout, assuming, however, that width is constant, whereas the visual system can detect any kind of narrowing, due to an obstacle, a pothole or roadworks.

In the third step, several vehicles can move simultaneously around the circuit. Therefore, each vehicle's controller has to know the positions of the others. A WLAN has been used to communicate these positions among vehicles. Additionally, as each vehicle has a GNSS receptor on board, which needs to receive correction data from a base station, the aerial network substitutes the communication via radio between each vehicle and the GNSS base station. Finally, this network can be used to send data, programs and any other information, not only between vehicles and the GNSS base station but also with a central control station, if necessary.

From the functional point of view, the performance of the guidance system for the third and the fourth steps are the same. The differences between the two steps are that performance for the fourth step has to be absolutely safe. This will be achieved eventually.

6 Qualitative guidance model

The guidance system has been modelled in terms of fuzzy variables and rules. Basically, we can divide the management of a vehicle into two controllers: one for the steering and the other for the speed. These controllers are independent but work cooperatively.

Then, we defined fuzzy contexts that will be selected depending on the manoeuvre. Accordingly, we define three fuzzy contexts for steering control: driving on bends, driving on straight roads and overtaking. Similarly, we also define two contexts for speed control: Cruise Control (CC) and ACC.

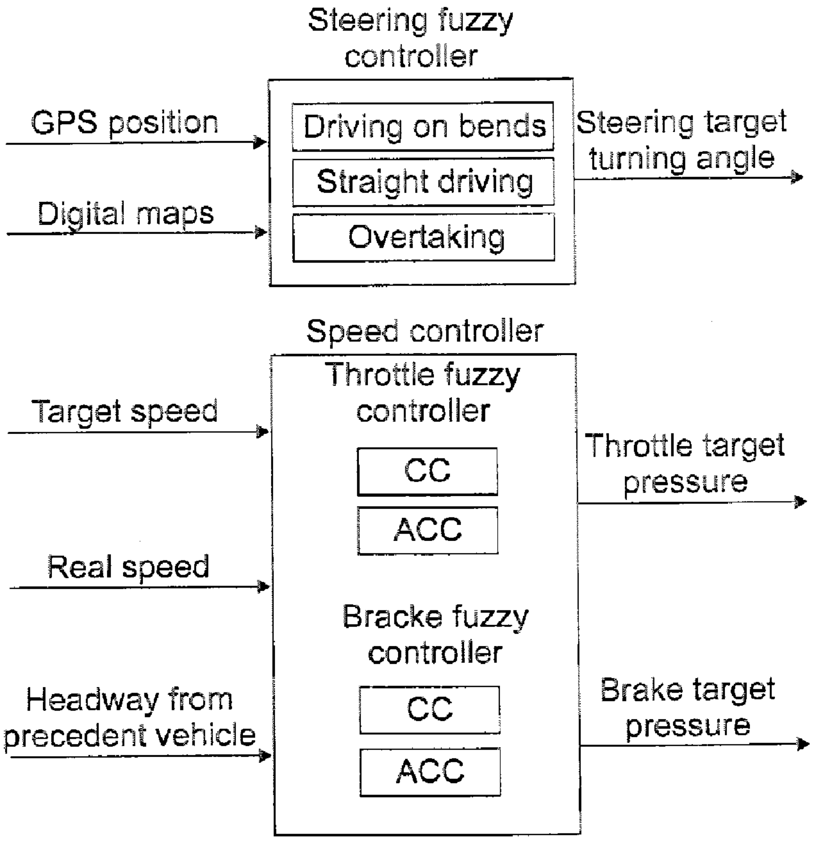
Figure 4 shows a diagram of the control system, including the five fuzzy contexts, as well as the input and output variables, which will be explained in detail in the following sections.

6.1 Steering fuzzy control

Steering management, as performed by human drivers, can be divided into three behaviours. When we are driving a vehicle round a bend in a road, the steering movements are wide and, logically, slow to prevent accidents. When driving along a straight road, the steering movements must be short and very fast to correct slight trajectory deviations. In other words, control must be very reactive in this case. Overtaking is a combination of the two behaviours, moderately wide turnings being permitted to make the respective lane changes.

All of these characteristics are considered in the definitions of the control system variables membership functions given later.

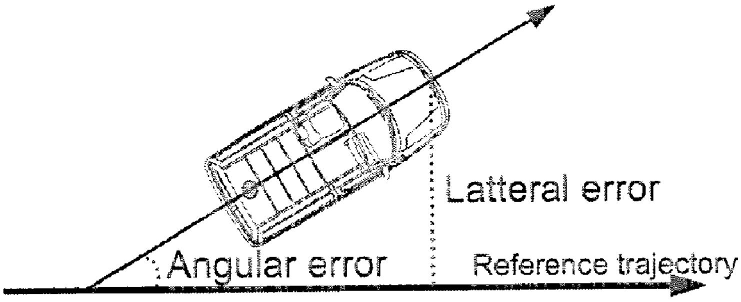
Figure 4 Automatic driving control system: general schema



6.1.1 Steering input/output variables

Two input and one output variable is used in this controller. The input variables are the angular and lateral errors. Angular error is defined as the angular trajectory deviation of a vehicle from the reference route. In the same way, lateral error is the distance from the front of the car to this reference route (Figure 5). The output variable of the system is the target steering turning, which is the degree that the steering wheel must be turned to correct the input error in this control iteration.

Figure 5 Steering control input variables



Depending on which of the three possible situations the vehicle is in, the membership functions definition for these variables will change (Figure 6). Accordingly, in bend driving mode, the gentle slope of the triangular part of the trapezoidal definitions of angular error and lateral error permits gradual steering actuation as these two variables grow, thus leading to the control behaving correctly on bends. These membership functions are asymmetric to allow for different behaviours when turning to the left or to the right, as is usual when circulating in the right-hand lane. The definition of the output variable membership function allows the steering wheel to be moved across its entire mechanical range.

Figure 6 Membership function definition for the input variables (a, b, c, d, e, f) and output variables (g, h) of the steering fuzzy controller

(a) Bend driving. Angular_Error

(b) Bend driving. Lateral_Error

(c) Straight driving. Angular_Error

(d) Straight driving. Lateral_Error

(e) Lane change. Angular_Error

(f) Lane change. Lateral_Error

(g) Curve/Lane change: Steering

(h) Straight driving change: Steering

For circulating along straight stretches, the membership function definition of the variables discussed earlier is changed. The reason for this steeper slope is that it allows the system to be more reactive to slight deviations, which is essential when driving on a straight road. Furthermore, the output membership function definition limits the steering turning to 2.5% of the total.

Finally, the lane change steering control for overtaking is a combination of both of these controllers. This control allows a moderately large steering turning on straight sections for lane changes.

6.1.2 Steering rules

Only four rules are needed to control a vehicle's steering wheel. The meaning of these rules is very intuitive, as driving should be spontaneous.

R1: IF **Angular_Error** *Left* THEN **Steering** *Right*

R2: IF **Angular_Error** *Right* THEN **Steering** *Left*

R3: IF **Lateral_Error** *Left* THEN **Steering** *Right*

R4: IF **Lateral_Error** *Right* THEN **Steering** *Left*,

where the words in bold are fuzzy variables, the words in plain script are language key words and the words in italics are linguistic values of the variables. The variables to the left of the term THEN are input variables and the variables to the right are output variables.

The working of these rules is simple: if there is a trajectory deviation to the left or to the right, the controller tries to correct it by turning the steering wheel in the opposite direction.

6.2 Speed fuzzy control

Two actuators are used to manage a vehicle's speed control: the throttle and the brake pedal. These actuators are independent, but must work cooperatively. In our case, we have set up two fuzzy controllers that are capable of operating these pedals autonomously and also assure they work together correctly.

These controllers are capable of performing two kinds of manoeuvres. When there is no obstacle in front of the unmanned vehicle, the system keeps to a pre-set speed, which can be either entered by the user or the speed limit of the road on which the vehicle is circulating. If another vehicle appears in the same lane, the system will reduce speed to keep a safe distance from the lead car and stop if necessary. This behaviour is known as ACC.

Next, we are going to define the fuzzy controllers for both actuators. Four input variables are defined to control a vehicle's speed and safety distance

1. *Speed error*. This is the difference between current speed and the user-preset speed.
2. *Acceleration*. This is the derivative of the speed at time *t*.
3. *Time_gap_error*. This is the difference between the user–pre-set target time gap and the headway to the lead vehicle. The variables *target time_gap* and *current time-gap* are defined below.
    - *Current time_gap* or time headway. This is the time it would take to catch up with the preceding vehicle at the current speed.
    - *Target time_gap*. This is the time-headway that the ACC should maintain between the vehicle and the lead vehicle. It should be between 1 and 2 sec in commercial ACCs. We recommend a distance of 4 sec for urban driving, as in our case.

4 *Time_gap derivative*. This is the variation of the *current time_gap* with time. This variable is included to smoothen the control action, just as *acceleration* smoothens the *speed_error*-induced action.

These variables are used for throttle, as well as for brake control, but with different fuzzy meanings.

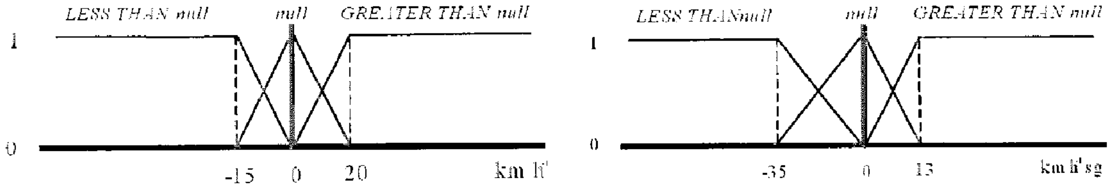
6.2.1 Throttle

The ACC throttle controller can adapt pedal management to maintain or change a vehicle's speed as a human driver would do. This feature is very important when designing these kinds of controllers, because no human will use them if they are not comfortable.

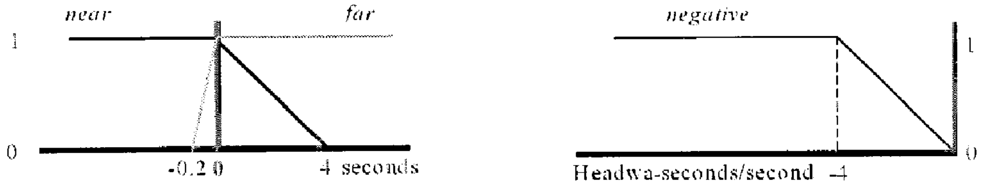
6.2.1.1 Throttle input/output variables

To manage this pedal, the throttle controller uses the four defined input variables and one output variable that indicates an increase or reduction in the pressure to be applied to the pedal. The associated membership functions definition for inputs is illustrated in Figure 7.

Figure 7 Throttle input variables membership function definitions



(a) Speed error (b) Acceleration



(c) Time gap error (d) Time gap derivative

The output variable, named *throttle*, is represented using classic Sugeno singletons, which represent the increased pressure to be applied to the pedal to correct the input variable errors in a human-like way.

6.2.1.2 Throttle rules

Five fuzzy rules are defined to mimic human throttle management behaviour in ACC situations.

R5: IF **speed_error** GREATER THAN *null* THEN **throttle** *up*

R6: IF **speed_error** LESS THAN *null* AND *time_gap_error* GREATER THAN *near* THEN **throttle** *down*

R7: IF **acceleration** GREATER THAN *null* THEN **throttle** up

R8: IF **acceleration** LESS THAN *null* AND **time_gap_error** *far* THEN **throttle** *down*

R9: IF **time_gap_error** *near* AND **d_time_gap** *negative* THEN **throttle** *up*

The function of speed error and acceleration in the rules is to maintain a target speed and time gap error and time gap derivatives are used to keep a safe headway from the lead vehicle.

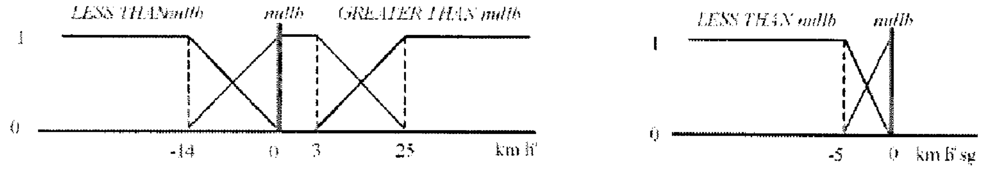
6.2.2 *Brake*

Two main design parameters have been used to set up the brake fuzzy controller: safety and comfort. Safety, to permit adapting the vehicle speed to environment requirements as soon as possible, maintaining the comfort of the system, as far as it does not jam with safety.

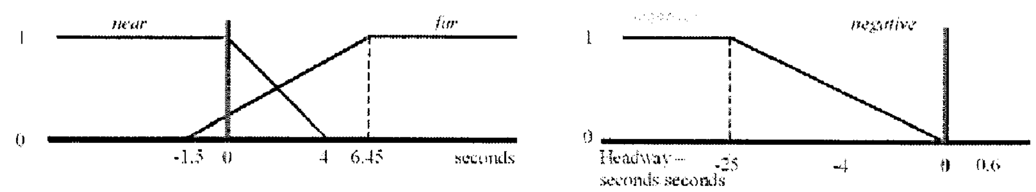
6.2.2.1 *Brake input/output variables.*

The input variables of the brake controller are the same as for the throttle controller. However, the membership function definition will be different for each one to tune them to behave in a human-like way and work together correctly with the other pedal. This definition is shown in Figure 8 for the four input variables.

Figure 8 Brake pedal input variables membership function definition



(a) Speed error (b) Acceleration



(c) Time gap error (d) Time gap derivative

The output variable for the brake pedal controller is named *brake* and represents the increased pressure to be applied to this pedal to achieve the target speed. Singletons have again been used in the fuzzy representation of this variable.

6.2.2.2 *Brake rules*

In this case, we have defined four fuzzy rules to control the brake pedal in ACC, as well as to cooperate with the throttle.

R10: IF **time_gap_error** *near* AND **d_time_gap** *negative* THEN **brake** *down*

R11: IF **speed_error** GREATER THAN *nullb* THEN **brake** *down*

R12: IF **speed_error** LESS THAN *nullb* AND **time_gap_error** GREATER THAN *near* THEN **brake** *up*

R13: IF **acceleration** LESS THAN *nullb* AND **time_gap_error** *far* THEN **brake** *up*

As with the throttle, the speed error and acceleration variables are used to adapt the vehicle speed to a target velocity and the time gap error and its derivative reduces the velocity when there is another vehicle ahead of the controlled vehicle.

6.3 Implementation

The automatic guidance system essentially consists of two fuzzy controllers dealing with the steering wheel and the throttle separately. From a functional point of view, both controllers are implemented in a fuzzy co-processor. The controllers are actually implemented in a conventional processor at two levels. The top level contains the qualitative model of the vehicle control problem, that is, the knowledge base of the specific control problem written in natural language-like sentences. The bottom level contains the internal representation, that is, the standard procedures for implementing the conventional fuzzy operations (fuzzification, inference, defuzzification, etc.) and the intrinsic movement equations.

7 Experiments

Three experiments for testing whether the related controllers perform correctly are shown in this paper. The first is route tracking within the IAI driving zone, the second is an overtaking experiment and the third represents an ACC operation.

7.1 Route tracking

This experiment represents the vehicle response when a reference route has been defined around the driving zone. The x-axis shows the East UTM coordinate of the driving zone and the y-axis is the North UTM coordinate, both measured in meters.

A dotted black line shows the reference trajectory that matches the centre of the road. A grey line represents the trajectory followed by the unmanned vehicle.

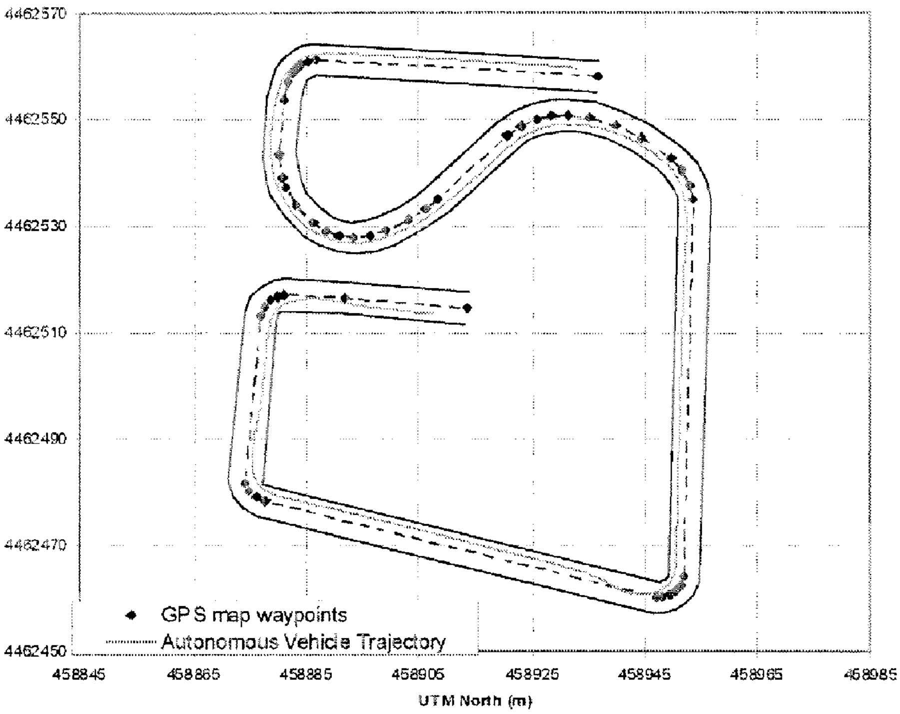
The experiment starts at the top centre of the diagram and the car always circulates in the right-hand lane of the road. The route is composed of six left and right bends, with diverse curvature radii, linked by straight segments.

As we can see from Figure 9, the vehicle adapts its lateral behaviour perfectly to track and complete the reference trajectory without leaving the right-hand lane.

7.2 Overtaking

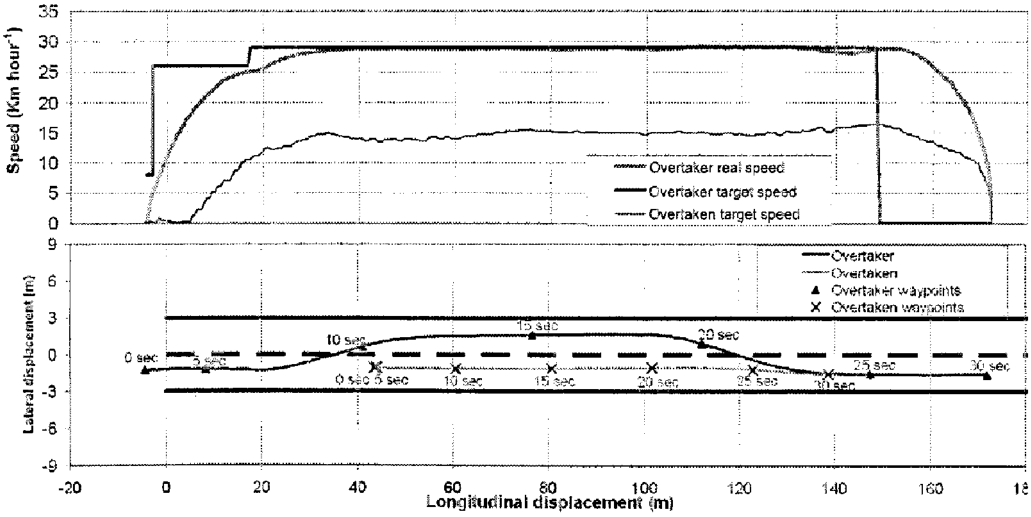
The second experiment represents an automatic overtaking manoeuvre. Two vehicles are involved in this case: the overtaking and the overtaken vehicles. The overtaking vehicle is driven automatically and the overtaken vehicle is manually operated. The reason for the lead vehicle being manually driven is that human driving is more unpredictable than automatic driving and this is, consequently, a more comprehensive test of our automatic system.

Figure 9 Diagram of the route taken in an automatic driving experiment



The top graph in Figure 10 shows the speeds of both vehicles and the bottom graph represents the shape of the vehicle trajectory during the manoeuvre. Some waypoints are marked on these trajectories that represent the positions of the vehicles at the same points in time during the overtaking operation.

Figure 10 Graph of the overtaking manoeuvre experiment



In the experiment, the overtaking vehicle circulates at 29 km h^{-1} and the overtaken vehicle at about 15 km h^{-1}. The manoeuvre starts when the overtaking vehicle is near enough to the other to correctly achieve the operation, assuring that there are no obstacles in the route or vehicles circulating in the adjoining lane and that there is enough distance on the road to complete the manoeuvre.

As shown in Figure 10, the overtaking vehicle starts the passing operation about 7 s after starting up, changing the lane it is circulating in using the lane change controller. Once the lane change has been completed, the vehicle continues in the left lane in straight steering control mode until it passes the overtaken vehicle. At this moment, the vehicle again selects the lane change controller and returns to the right-hand lane to continue normal driving.

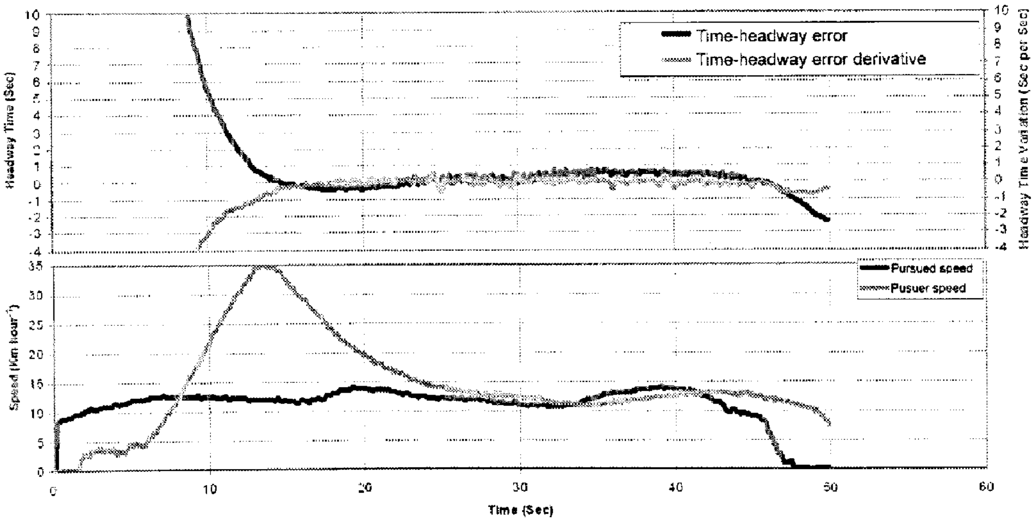
7.3 Adaptive cruise control

The third experiment shows the longitudinal control behaviour of the throttle and brake in an ACC situation. In this case, the experiment is represented by two graphs. The top graph shows the variation of the two system input variables and the bottom graph displays the speeds of both the vehicles involved.

The vehicle that is automated and circulates behind what is, in this case, the manually driven pursued vehicle is called pursuer.

We find from Figure 11 that the pursuer adjusts its speed to reduce both input variables to zero, adapting to and keeping a safe distance from the lead vehicle (in this case 4 sec), despite any change in speed of the vehicle being pursued.

Figure 11 ACC experiment representation



8 Conclusion

We have presented an Intelligent Transport System (ITS), mainly based on DGPS, designed to operate in partially structured environments, such as industrial or residential areas. The system is driven by its steering and velocity fuzzy controllers, according to a global plan. These controllers have been used to execute some automatic driving manoeuvres: route tracking, overtaking and ACC.

Many unmanned transport missions have already been carried out on a private urban-like circuit using two Citroën Berlingo electric vans.

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Note

[1] To simplify, the height of the vehicle is not considered.