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An Approach to Driverless Vehicles in Highways

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Abstract— **This paper presents AUTOPIA program results towards autonomous vehicles in highways. Based on our previous experience in automatic driving systems, a high-speed controller has been developed to perform vehicle's guidance autonomously. The map is generated in real time by the leading vehicle via vehicle-to-vehicle communications, permitting the vehicle equipped with the automatic system driving in any real circumstance in highways as can be lane-change maneuver. The system has been integrated in one of the AUTOPIA program vehicles and tested in a private circuit at high speeds with good results.**

I. INTRODUCTION

Autonomous vehicles is today a hot topic research in the transportation field. One of the most representative advances in this research area is the last competition organized by the Defense Advanced Research Project Agency (DARPA) called Urban Challenge [1] where autonomous vehicles developed by several research centers have to cover a route autonomously. Most recently, the Vislab Intercontinental Autonomous Challenge (VIAC) [2] where a electric vehicle was capable of driving from Italy to China covering most of the route autonomously. Although these results are encouraging, there are still a long way to go from semi-autonomous driving systems presently in the market to fully-autonomous vehicles in real roads.

Communications among vehicles and with the infrastructure will play a key role to find driverless vehicle in real scenarios. As a matter of fact, several automotive manufactures have joined their efforts in the car-to-car (C2C) Communication Consortium where, using an exclusive frequency band for automotive applications, automotive manufactures are trying to show communication system technical and commercial feasibility [3].

Reliable positioning-based systems capable of locating vehicles around the world with enough accuracy is one of the main problems to obtain a high-precision map to carry out an autonomous guidance. Some solutions based on combining several sensors as inertial measurement unit (IMU) [4], lidar [5] or cameras [6] have been developed but there are still some improvements to do so as to achieve robust positioning systems. Taking this into account, one of the solutions is linked to the use of dedicated lanes for fully-autonomous vehicles. Our approach is based on a leading vehicle with a high-precision positioning system that is capable of generating a real-time digital map for the trailing vehicle equipped with an automatic lateral control.

Of all of traffic scenarios, urban environments constitute the most complex area considering all the singularities a vehicle can find when it is driving in a city –intersections, roundabouts, merging areas, U-turns and so on. In spite of several systems have been developed as semi-autonomous aid driving –i.e. the city safety system from Volvo– the huge number of scenarios that have to be contemplated convert the autonomous driving in urban environment, at the present, in a impossible mission.

Bearing this in mind, automotive manufactures focused their first efforts in highways where systems as the cruise control (CC) or the adaptive CC (ACC) have aided the driver making the driving more comfortable. One of the reasons for this choice is because no singularities are found in highways, that is, vehicle only has to follow its route in the lane and to perform a lane-change maneuver in case of an overtaking was carried out. However, whilst longitudinal control has been solved by automotive manufactures, lateral control in highways remains as an open research problem.

This paper presents AUTOPIA program approach toward an automated lateral control in production vehicles for highways. The system is based on a high-precision dynamically-generated digital map that is in charge of generating the route to follow via a leading vehicle. Using this map, the trailing vehicle is capable of following this route. So this can be considered as a dedicated lane. The system has been tested both to maintain the vehicle in the lane and to perform a lane-change maneuver. To this end, one of the vehicles from the AUTOPIA program –a convertible Citroën C3 Pluriel– has been equipped with the proposed system and several tests at high speeds were performed with good results.

Section II describes the previous results achieved by the AUTOPIA program in the context of fully-autonomous vehicles and cooperative maneuvers among them. The problem to be solved to carry out automatic lateral control in highways is presented in Sec. III. The trajectory generation is explained in Sec. IV. The control system based on fuzzy logic is described in Sec. V. Section VI presents the experimental results and, finally, some conclusions to this work are outlined.

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II. AUTOPIA PROGRAM BACKGROUND

AUTOPIA program is a research group from the Center for Automation and Robotics (CAR) of the Spanish National Research Council (CSIC). It has been working in the development of intelligent driving aid systems, fully-autonomous vehicles and cooperative maneuvers using wireless communications. These systems are based on a modular architecture that permit including or removing new components easily [7]. As a matter of fact, AUTOPIA control architecture has cooperatively worked with automatic vehicles from other institutions in a public demonstration at La Rochelle (France) [8].

Vehicle's location is obtained through a Differential Global Positioning System (DGPS) combined with an Inertial Measurement Unit (IMU) [9] to provide an accurate position of the vehicle with respect to the road. With these premises, several intelligent systems have been recently developed. Among them, an steering wheel controller [10] and a high-precision longitudinal control [11] for urban environments, an intelligent intersection controller based on C2C communications [12] or an automated on-ramp merging system based on vehicle-to-infrastructure (V2I) communications [13].

All these systems have been tested in urban environments in the private driving circuit at CAR's facilities and their adaptations to highways it not a trivial problem. In this communication, the modification in the steering wheel controller based on C2C communications to attack the lateral control in automated vehicles is described.

III. IDENTIFYING THE PROBLEM

In previous results based on steering wheel controller for urban environments, a digital cartography was previously defined to determine check-points for the vehicle guidance [14]. This system is adequate when the route is known and a digital map is defined with high accuracy. Nowadays, there are multitude of roads in which the map precision is not enough or has been modified because public works. Once a high-precision digital map is obtained, a controller capable of maintaining the vehicle in the road has to be developed. Both problems can be summarized as trajectory generation and navigation controller.

For the first problem –to obtain a map with high precision– several solutions have been proposed. Among them, the most renowned is the adopted by the Partners for Advanced Transportation TecHnology (PATH) program based on magnetic markers located in the lane to obtain a good positioning system for each vehicle [15]. This system was tested in several public demonstration showing its good behavior. Its main problem arises from the fact that the infrastructure has to be modified to install the magnetic marks. Taking this into account, our solution is based on the generation of a digital map on the part of the leading vehicle –equipped with a positioning system that is described in [9]– and a C2C communication system to allow information exchange between them. In this way, a trailing vehicle can follow a leading one not only using commercial ACC systems and manually managing the steering wheel but also leaving the lateral control to the automated vehicle. Using this method, a vehicle can follow a leading one for any road layout, performing lane-change maneuvers, highway entrances and exits ramps or maintaining the lane.

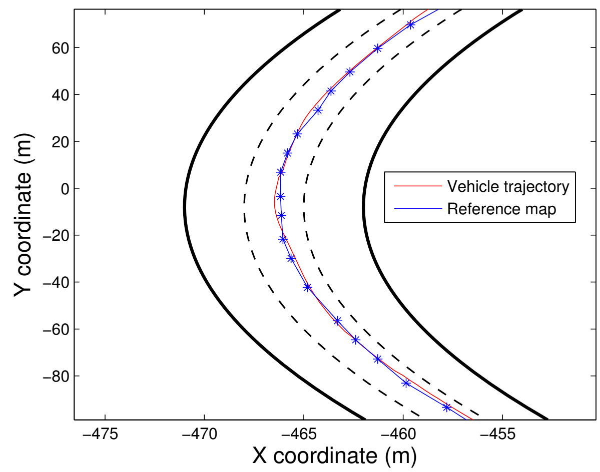

Fig. 1. Dynamically-generated map and trajectory cover by the vehicle equipped with the automatic steering control system

With respect to the longitudinal control, time gap via cooperative ACC (CACC) systems are approximately 0.5 seconds [16] but the lateral control at high speeds has not been yet faced. In this connection, AUTOPIA program has used its background in autonomous guidance to adapt its fuzzy-logic controller (FLC) for urban environments to highways.

Therefore, two problems have to be solved. On one hand, to generate a digital map for the automatic lateral control –described in Sec. IV– and, on the other hand, to design a control system capable of following this map –presented in Sec. V.

IV. TRAJECTORY GENERATION

A dynamically-generated map using straight sections has been used to define the trajectory of the trailing vehicle using the information –position in Universal Transverse Mercator (UTM) coordinates– coming from the leading vehicle.

For the choice of each straight segment, some parameters have to be defined:

- A minimum distance –d_{min}– obtained via the addition of the maximum errors allowed for the positioning system of both vehicles. Considering maximum DGPS errors in two consecutive measurements in both vehicles at the same time as maximum deviations, distance under one meter are neglected.
- A maximum distance –d_{max}– equal to 10 meters to avoid vehicle's check-points out of the lane.
- A minimum speed –v_{min}– in our case equal to zero.
- A maximum speed –v_{max}– whose value is $110 km/h$ for highways, following Spanish Circulation Code.

Considering d the actual separation between points in the digital map and v the actual velocity of the vehicle, the

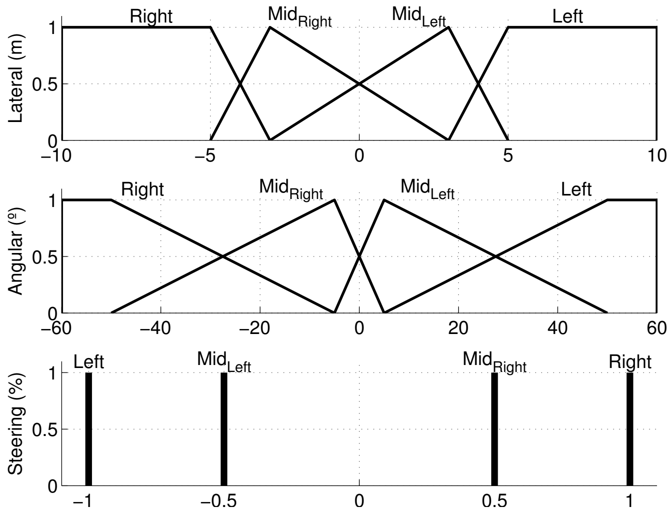

Fig. 2. Membership functions used to codify the input/output variables.

distance between two check-points can be determined as:

$$\begin{cases} d = d_{min} \text{ if } v = v_{min} \\ d = d_{min} + \frac{d_{max}-d_{min}}{v_{max}-v_{min}}(v - v_{min}) \text{ if } v_{min} > v > v_{max} \\ d = d_{max} \text{ if } v \geqslant v_{max} \end{cases} \quad (1)$$

Figure 1 presents an example of how the map is generated. One can appreciate the checkpoints created by the leading vehicle –blue line– and the trajectory followed by the vehicle equipped with the automatic steering wheel control. The speed during this test was $70km/h$. Note that when the Y-coordinate is close to zero and the vehicle is in the minimum of the bend that is tracing, four check-points are combined as a unique straight stretch. The vehicle is capable of following adequately this real-time-generated map.

For low speeds –as occurs in urban environments– where significant bends can be found, the separation between check-points is closer to perform this section with better precision.

V. High-speed control system

The trade-off between performance and complexity is a main factor in steering control systems design. The use of artificial intelligence techniques is especially indicated when the aim is to emulate human control actions, and the driving of a car is a task than humans can easily do without any knowledge about complex equations and dynamics which govern the behavior of the vehicle.

Since authors consider than the control of a vehicle can be easily described by a set of rules of the kind: *if the vehicle is deviated through the left, then move the steering through the right*, a fuzzy logic approach is designed to accomplish the task exposed in this work.

Fuzzy logic [17] expands the theory of fuzzy sets stated by L. Zadeh [18], which establish than an element can belong to a determined set with a real value in the interval [0,1], instead

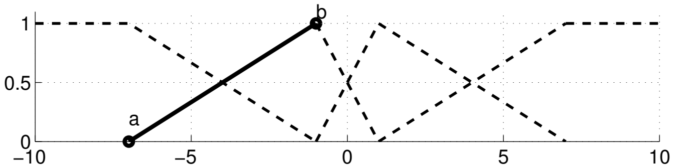

Fig. 3. Graphic representation for the fuzzy adjustment.

of with one of the two values {0,1}. With this basic concepts, rule based decision or control systems can be defined by means of establishing a suitable set of membership functions, defining the AND/OR operations and the inference method.

ORBEX [19] is a fuzzy co-processor developed by the CAR, specially designed for the execution of real time-based fuzzy controllers. Input variables are codified by trapezoids, which are represented by four values. The degree of membership of an input value to a certain trapezoid (a,b,c,d) is calculated as follows.

$$\mu(x) = 0, if\ x \in [-\infty, a]\ or\ x \in [d, \infty]$$
$$\mu(x) = 1, if\ x \in [b, c]$$
$$\mu(x) = \frac{x-a}{b-a}, if\ x \in [a, b]$$
$$\mu(x) = -\frac{x-c}{d-c}, if\ x \in [c, d]$$

Output variables are codified by singletons, that represent discrete values. This kind of fuzzy systems allow both fast calculations and simplicity during the design process [20]. The AND/OR operator is implemented by the maximum and minimum functions. Finally, once the degree of truth of the rules are calculated, the final output value returned by the system is obtained by the center of mass method:

$$y = \frac{\sum w_i \cdot y_i}{\sum w_i} \quad (2)$$

where w_i and y_i represent, respectively the degree of truth and the position of the output singleton of the i-th rule.

Input variables used as inputs for the fuzzy system are named *Lateral* and *Angular*, referring respectively to the both lateral (in meters) and angular (in degrees) deviation of vehicle's nose with respect to the trajectory generated according to Sec. IV. The output variable represents the desired steering angle to be sent to the module in charge of moving the steering. The codification of the input/output variables is done by means of trapezoids and singletons presented in Fig. 2.

The rule base is conformed by eight rules:

1) IF *Lateral* is $right$, THEN *Steering* $left$
2) IF *Lateral* is Mid_{right}, THEN *Steering* Mid_{left}
3) IF *Lateral* is Mid_{left}, THEN *Steering* Mid_{right}
4) IF *Lateral* is $left$, THEN *Steering* $right$
5) IF *Angular* is $right$, THEN *Steering* $left$
6) IF *Angular* is Mid_{right}, THEN *Steering* Mid_{left}
7) IF *Angular* is Mid_{left}, THEN *Steering* Mid_{right}
8) IF *Angular* is $left$, THEN *Steering* $right$

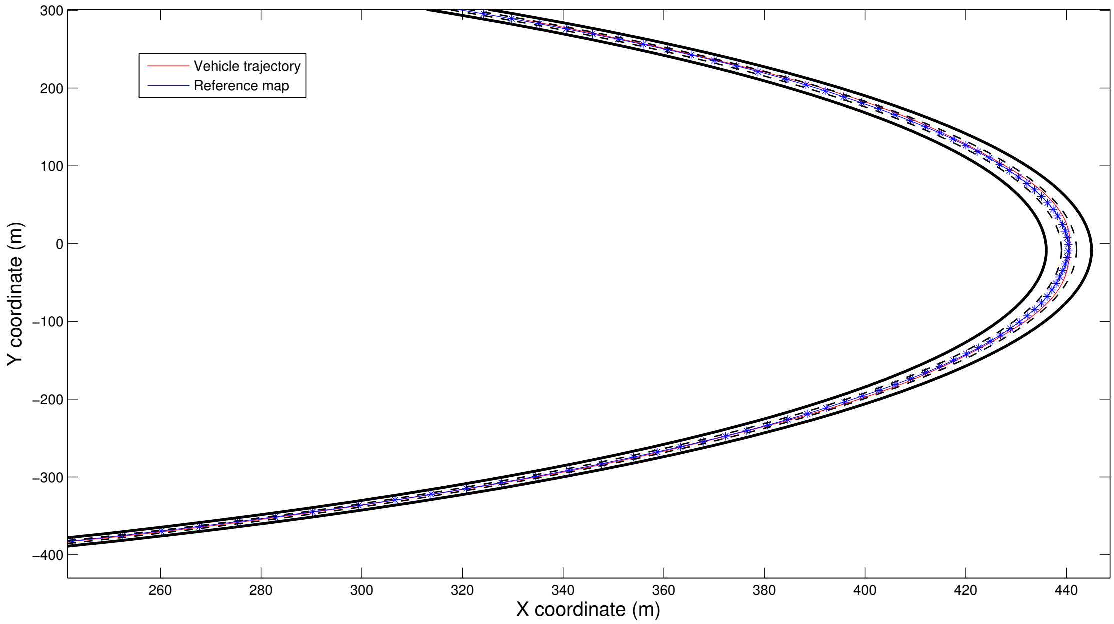

Fig. 4. Automatic steering wheel maneuver at speeds higher than 100 km/h

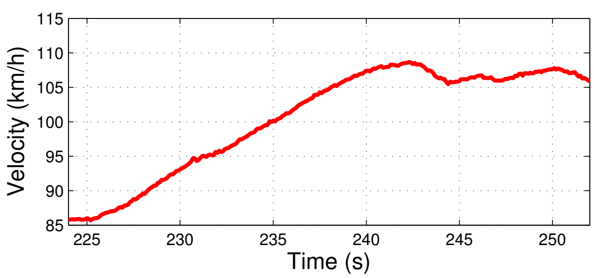

Fig. 5. Trailing vehicle velocity during the automatic steering wheel maneuver at high speed

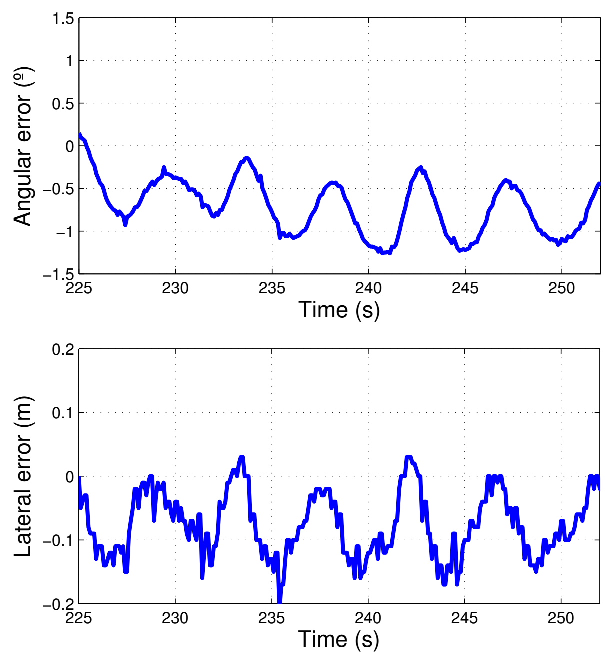

Fig. 6. Lateral and angular errors during the automatic steering wheel maneuver at high speeds

The rule base is quite simple and intuitive but, as is shown in Fig. 2, the membership functions are not that much. The values used to codify the trapezoids are calculated by executing several tests with the vehicle controlled by a human driver. Data about the lateral and angular errors and the position adopted by human to guide the car are recorded. Then, the a and b values of the triangles representing the Mid_{right} (see Figure 3) have been iterated in {-10,-9,-8,...-1} for the $Lateral$ input and in {-90,-80,-70,...-10} for the $Angular$ input, comparing outputs given by the resulting controller with the ones recorded from the human driver. The final values for the controller were the ones which produced less absolute error with the recorded outputs.

VI. Real results

The presented system has been validated using two Citroën C3s. A description about the equipment and automation process of the trailing vehicle can be found in [21]. For the leading vehicle, a brief description about the necessary equipment to carry out these tests is presented in [12]. The tests were carried out in a private circular test track with a radius of 500 meters where speeds up to $120 km/h$ can be achieved.

For the validation of the system, two trials are here presented. The former describes how the system is capable

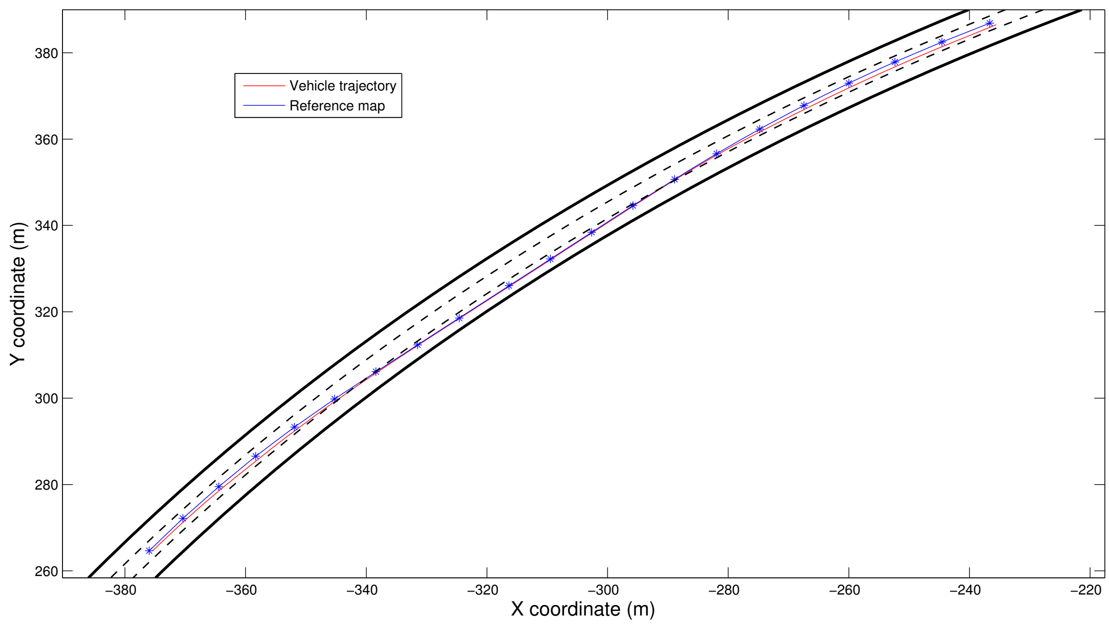

Fig. 7. Automatic lane change maneuver

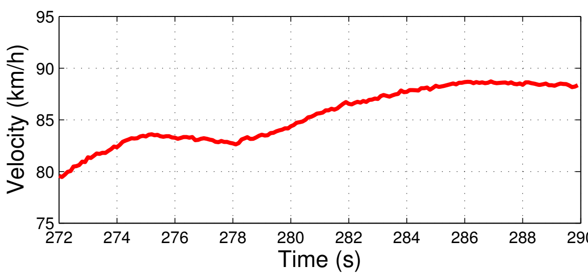

Fig. 8. Trailing vehicle velocity during the automatic lane change maneuver

of generating the map for high speeds –up to $110km/h$– maintaining the vehicle in the lane. The latter illustrates a lane-change maneuver following the leading vehicle. A video in which both maneuvers are shown can be found in http://www.iai.csic.es/users/autopia/Videos/INTA_Tests.wmv.

A. Tracking a leading vehicle

Figure 4 depicts the evolution of the vehicle equipped with the automatic steering control system in the test track with the vehicle driving by the central lane –driving in anticlockwise direction. Vehicle's velocity during the trial is shown in Fig. 5. One can appreciate how the vehicle is accelerated from $85km/h$ up $110km/h$. It is capable of following the leading vehicle maintaining itself in the road.

The angular and lateral error of the vehicle during this test are shonw in Fig. 6. Since the vehicle is driving in anticlockwise direction, the values of both variables remain lower than zero during the most of the time. This is because when the deviation generated by the next check-point is corrected, a new check-point is read so a new deviation is

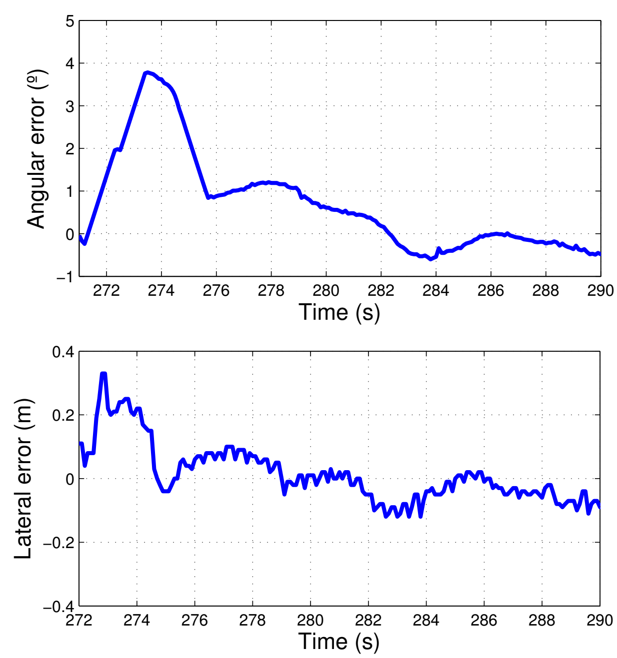

Fig. 9. Lateral and angular errors during the automatic lane change maneuver

generated. In this connection, some fluctuation can be noted in both variables.

B. Lane-change maneuver

The second experiment tries to reproduce one of the risk maneuver that can be performed in highways: a lane-change. Taking into account the vehicle is driving on the central lane, a lane-change to the left lane with respect to its position is performed –considering the vehicle is driving in anticlockwise direction. Since the goal is to mimic a real traffic driving as can be an overtaking in highways, a double lane-change is performed as occurs in real traffic.

Figure 7 shows the evolution of the digital map, that is, the trajectory followed by the leading vehicle and the trajectory of the automated vehicle. At the beginning of the maneuver, the vehicle is trying to correct its trajectory since it is slightly deviated to the left. Later, the first lane-change maneuver is carried out by the leading vehicle and the trailing vehicle follows rapidly the generated route to the left lane. The vehicle only remains a few seconds in the new lane and the leading vehicle performs a new lane-change –as occurs in real traffic circumstances when an object is overtaken– returning to the central lane. One can appreciate how the vehicle follow this route returning to the central lane with a minimum error but within the lane. The speed during this maneuver can be appreciate in Fig. 8.

Figure 9 depicts the angular and lateral error during this double lane-change maneuver. In this trial, both variables reach positive values when the lane-change is performed from the central lane to the left lane during the first seconds. The lane-change from the left lane to the central lane is similar to maintain the steering in the central position when a lane-change is performed in a bend. As can be appreciated, values of both variables are close to zero during the rest of the trial.

VII. Conclusions and Future Works

AUTOPIA program has been working in driving aid systems during more than 10 years. During this time, several intelligent systems to aid the driver in managing both the longitudinal and the lateral control of the vehicle working toward fully-automated vehicle driving in dedicated roads in urban environments. In this line, several cooperative maneuvers have been developed based on C2C and V2I communications to permit the interaction between different automated vehicles. In this paper, we present our first contribution to the automated lateral control in highways at high speeds.

The proposed system is based on a leading vehicle equipped with a communication system to permit information exchange between both vehicles. This information is used by the trailing vehicle to dynamically generate a digital cartography that is followed using a fuzzy logic controller. The developed system is capable of not only of following the route maintaining the vehicle in the lane but also performing lane-change maneuver emulating an overtaking in highways.

The system was tested with different passengers in the vehicle. As strong point, they highlight the smoothness in the ride-quality. As weak point, the minimum oscillation because the change in the reference segment or positioning errors.

As future work, an experiment will be carried out in real roads with real traffic to evaluate how the system works with more vehicle in its vicinity. In this sense, the test will be used to evaluate which additional sensors are necessary to improve its feasibility.

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