Clavileño: Evolution of an Autonomous Car

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***Abstract*—Cars capable of driving in urban environments autonomously are today one of the most challenging topics in the intelligent transportation systems (ITS) field. This paper deals with the evolution of Clavileño -a gas propelled vehicle- in its automation process searching new steps toward a fully autonomous car driving in a real word. So, the required modifications for a mass-produced car in order to equip it with automatic driving capabilities; the on-board sensor systems to analyze the environment; the autonomous guidance system as well as the cooperative maneuvers implemented and the local evaluation system are presented. The system has been tested in a controlled area with other vehicles in several trials with good results.**

I. INTRODUCTION

Almost 40,000 people died because road fatalities during 2008 in European Union [1]. In spite of death rate dropping over 30% from 2001, the European Transport Commission is working towards a new transport white paper in this year in order to revise and update the goals proposed in 2001 [2]. The aim is to attempt to reduce the number of collisions, or at least to mitigate their consequences.

From the automotive sector, several advances have been achieved in the last years. The cruise control (CC) that allows to the driver to set a speed driving or its extension to the adaptive cruise control (ACC) where the vehicle is capable of following a leading car in highways are two of the most popular advanced driving assistance system (ADAS) developed by the car manufacturers to make easier the driving task.

To the best of our knowledge, the trend for the future is for there to be a step up from simple driving aids to automatic driving controls. Of the different solutions to these problems that have been proposed, the development of autonomous vehicles is today a particularly open field of research. Research on developing automated vehicles to improve the safety and efficiency of highways or freeways is indeed one of the most extensively studied topics in the field of intelligent transportation systems (ITS).

To undertake a vehicle automation, the management of the actuators involved in the driving task -steering wheel, throttle and brake- is to be controlled. In the late 1950s, primitive speed controllers with proportional feedback based on the action over the throttle were developed. A review about the evolution in speed control systems can be found in [3]. The automated brake incorporation appeared with the ACC systems where reductions in the speed is to be needed. Mitsubishi was the first automotive manufacturer to introduce ACC systems for highways in its cars in 1995.

Steering wheel automation is less common in the market but several workers have carried out significant advances in this topic. One of the pioneers in the development of autonomous systems applied on commercial cars was Professor Tsugawa as part of the Comprehensive Automobile Traffic Control System (CACS) project where a steering wheel was automatically managed using a motor attached to the steering wheel [4]. In the late 1990s, Professor Broggi´s team developed a vehicle instrumented with artificial-vision cameras and a PC-based computer. This real car was capable of driving for hours at a time, while a human driver performed the longitudinal control, and the lateral control was carried out by an autonomous system [5].

During the last decade, different European projects have been carried out in the ITS field, focusing in the implementation and cooperation among autonomous vehicles. IAI-CSIC AUTOPIA´s group participated in Cybercars-2 project whose main objective was to enhance and enrich the Cybernetic Transport System (CTS) concept already dealt with in the FP5 project CyberMove. Vehicle-to-vehicle and vehicle-to-infrastructure communications were used to perform cooperative maneuvering at close range, and cooperative traffic management from remote control centers. The final demonstration took place in La Rochelle in September 2008, with cars from different manufacturers -Citroën, Mercedes, Fiat- and different groups -CRF, IAI-CSIC, TNO, INRIA- cooperating.

The major advances today in the development of autonomous vehicles can be found in DARPA (Defense Advanced Research Projects Agency) Urban Challenge. It is a competition for automatic vehicles that operate with effectiveness and security close to other vehicles around urban areas. The rules of this test are a good example what it is expected from an automatic car. The vehicles must be prepared for unexpected circumstances, plan alternative routes and avoid static and dynamic obstacles. In the route all the situations common in urban environments, for example, bad pavements, bend zones can be presented, bifurcations, barriers, weeds, constructions, rails, etc. The vehicles have to respect the traffic rules. The Carnegie Mellon University Tartan Racing Team's Boss [6] won the last edition with a run-time of just over 4 h of driving, autonomously covering 85 km.

The goal of AUTOPIA group consists on the development of an open architecture to carry out an automatic driving system able to manage a set of car maneuvers in the same way human drivers do [7]. For that purpose, it deals with some sensorial information and wireless communication as main sensorial inputs and manages the three fundamental actuators in a vehicle: throttle, brake and steering wheel. In this paper, we present the evolution in the automation process of one of our vehicles as well as different cooperative maneuvers implemented to achieve a car capable of driving autonomously in any traffic circumstance.

The rest of the paper is structured as follows. Sec. II introduces the hardware modifications to allow acting over the steering wheel and throttle and brake pedals. The on-board sensor systems to obtain information about the environment are described in sec. III. The automatic maneuvers implemented in the car, autonomous guidance, ACC+Stop&Go, overtaking, intersection management and pedestrian recognition are described in sec. IV. The priority levels among each one of these maneuver as well as an experiment about the behavior of the system are presented in sec. V and VI respectively. Finally, some concluding remarks are given.

II. HARDWARE MODIFICATIONS

To develop a vehicle with automatic driving capabilities, the first step is to modify the actuators to permit their automatic control. In this section, the hardware modifications applied over the steering wheel, the throttle and the brake are presented. Figure 1 shows the implementation of each one of the devices and the commutation system between the original system and the automatic one.

A. Steering wheel

The vehicle is a gasoline car whose steering assistance is electric, what is used to aid its automation. The CAN bus of the car provides the control computer with readings of the speed and steering wheel angle.

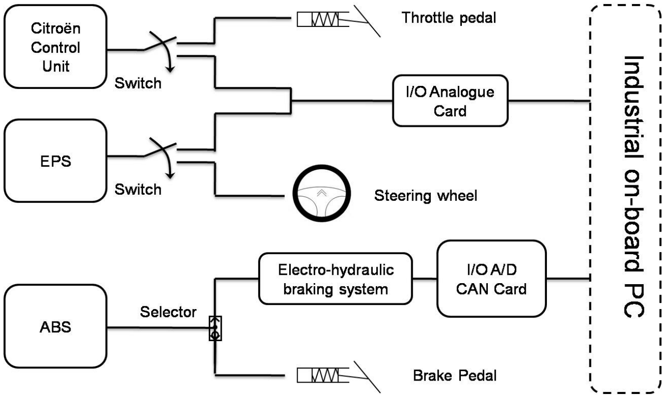

Figure 1. Automation of the vehicle´s actuators.

In order to use the assistance electric motor for the automatic steering this motor is to be controlled by the computer. So the lines leading to the assistance electric motor have been cut and replaced by a line taken directly from the battery, width pulse modulated according to an analog signal controlled by the computer. Actually a relay card has been developed to commute the original lines leading to the motor with the computer controlled ones. A switch in the board activates these relays and the car changes from being manually controlled to be computer controlled.

B. Throttle

The throttle is controlled with an analog signal that represents the pressure on the pedal, generated with an analog card. The action over the throttle pedal is transformed into two analogue values -one of them twice the other- between zero and five volts. These values are obtained from the same I/O digital-analog card used to manage the steering wheel.

C. Brake

Since the brake action is the more critical to permit stopping the car in case of a failure on the part of the autonomous systems, an electro-hydraulic braking system was mounted in parallel with the original one [8]. Two shuttle valves are installed connected to the input of the anti-lock braking system (ABS) in order to keep the two circuits independent. Each valve permits flow from either of two inlet ports to a common outlet by means of a free-floating metal ball that shuttles back-and-forth according to the relative pressures at the two inlets. One of the inlets is connected to the electro-hydraulic braking system and the other to the original one. These valves permit the two braking systems to coexist, but independently of each other.

A pressure limiter tube set at 120 bars is installed in the system to avoid damage to the circuits. Two more valves were installed to control the system: a voltage-controlled electro-proportional pilot to regulate the applied pressure, and a spool directional valve to control the activation of the electro-hydraulic system by means of a digital signal. These two valves are controlled via an I/O digital-analogue CAN card.

III. ON-BOARD SENSOR SYSTEMS

To analyze the environment and take the best control actions, different sensors has been mounted in the vehicle. A brief explanation about the behavior and target of each one of them is presented in this section. The vehicle is equipped with an industrial PC to connect any peripheral. Figure 2 shows the on-board sensors systems and its location in the vehicle.

A. Wireless LAN

A PCMCIA Proxim Wireless ComboCard is installed in the PC of the car. The goal of the communication system is to receive the information coming from either the infrastructure or the vehicles to take the control actions. To avoid an excessive number of communication channels open, an interest zone -up to 80m- is defined into the surrounding area.

Figure 2. Citroën C3 Pluriel on-board sensors.

B. RTK-DGPS

The main sensor used for acquiring driving information is an RTK-DGPS that gives us a 1- centimeter precision. With this data and a precise map of the test circuit we can perform automatic driving in a way similar to human drivers.

The guidance system with the RTK-DGPS is modeled using fuzzy variables and rules to correct the trajectory errors computed with the on-board GPS receiver and the high-precision digital cartography that defines the target route.

C. IMU

RTK– DGPS information is optimal to reference the car from the digital cartography that defines the target route. However, it is necessary to add a secondary positioning system that complements the GPS when its accuracy is not enough to allow safe driving. In our case we added an inertial unit to the odometry signal in the test-bed car. With this information, we obtain the car's true position (North, East) either a short-time faults where GPS signals are lost for less than one second, for example, in a city, where buildings may occlude satellite signals or a long-time fault, e.g., in a tunnel or circulating through a tree canopy.

To overcome these failures, a Crossbow IMU300CC was placed close to the center of gravity of the vehicle and a positions system in case of GPS faults was developed [9].

D. Cameras

Two cameras located in the rear-view mirror are used to perform pedestrian detection. The camera characteristics are images resolution of 320x240 pixels, a baseline of 30cm and a cameras focal length of 8mm. Their inclusion in the control algorithm is to increase the environment perception. Specifically, they are in charge of detecting pedestrians.

IV. IMPLEMENTED MANEUVERS

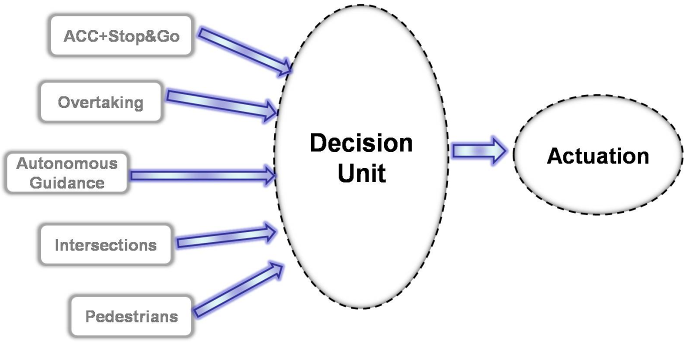

Figure 3. Block diagram implemented maneuvers.

We here describe chronologically the different maneuvers that the prototype vehicle is capable of performing. They are based on real traffic circumstances and deal with real traffic problems. The controllers for each one of the maneuvers are based on an experimental fuzzy coprocessor (ORBEX, acronym of Experimental Fuzzy Processor in Spanish), which is an inference motor with a natural-language-based input language [10]. ORBEX functions with Mamdani's inference method, with singleton-type membership functions to codify the output variables, and allows control decisions to be very rapidly and very precisely made.

A. Autonomous guidance

The first maneuver consisted on providing autonomous driving capabilities without taking into account the environment, that is, the interaction with other cars. The autonomous guidance was achieved through three controllers: straight stretches and bend stretches for the steering control and another controller to perform the longitudinal control.

For the lateral control two variables were used: the lateral error and the angular error. The former is the deviation -in meters- of the front of the car from the reference trajectory, measured perpendicularly from it. The latter is the angular deviation -in degrees- of the vehicle from the reference trajectory and is represented by a director vector.

For the longitudinal control we use the speed error -in kilometers per hour- defined as

$$Speed_{error} = Speed_{current} - Speed_{target} \qquad (1)$$

where $Speed_{target}$ is obtained through a pre-defined digital cartography route [11] where the vehicle´s speed is up to the urban limit in straight stretches and is reduced in bend stretches. To increase the comfort in the speed´s target changes, the car´s acceleration is combined with the speed error as inputs for the longitudinal fuzzy controller.

B. ACC+Stop&Go

The first cooperative implemented maneuver was the ACC with Stop&Go capability [12]. This maneuver is an extension of the CC maneuver and permits to follow a leading vehicle in a safe distance.The fuzzy controller developed uses two inputs: the time-gap (TG) error defined as

$$TG_{error} = TG_{current} - TG_{target} \quad (2)$$

and its derivative error. Through the Wireless LAN previously presented, the unmanned car received the information about the leading vehicle in order to determine the TG.

C. Overtaking

As first consideration, we assume than an overtaking follows an ACC. From a functional point of view, an overtaking in a two-way road can be considered as a double lane-change maneuver. First change from the right lane to the left one is needed to overtake the leading vehicle. Second lane change is performed in order to come back to the right lane. For this controller the same variables that were considered for the lateral control are to be taken into account. Designed controller [13] is softer than the bend stretches one and harder than the straight stretches one in its action upon the steering wheel.

D. Intersection management

The development of this system naturally divided itself into two parts. The former was a system capable of detecting the position and intention of the other cars in its vicinity. The latter was a fuzzy controller to act on the actuators. The detection system was designed on the basis of a local topological analysis. If a vehicle is close to the intersection and coming from the right-of-way, the intersection fuzzy controller is activated. As inputs, the distance of each car to the cross point and the relative speed between them defined as

$$Speed_{dif} = Speed_{right-of-way} - Speed_{automated-car} \quad (3)$$

are used. The system is capable of not only stopping the vehicle should another vehicle be entering the same intersection point but also crossing the intersection if the speed of the other vehicle is too slow, even if it is approaching with right-of-way [14].

E. Pedestrians

A vision-based system was installed in the car to perform pedestrian protection. Pedestrian detection is carried out using the system described in [15] and [16]. Non-dense 3D maps are computed using a robust correlation process that reduces the number of matching errors. The camera pitch angle is dynamically estimated using the so-called virtual disparity map.

This pedestrian detection system in combination with the information coming from the vehicle's CAN bus is used to estimate the time-to-collision (TTC). This value is used as a trigger in order to perform a pedestrian collision avoidance maneuver avoidance maneuver.

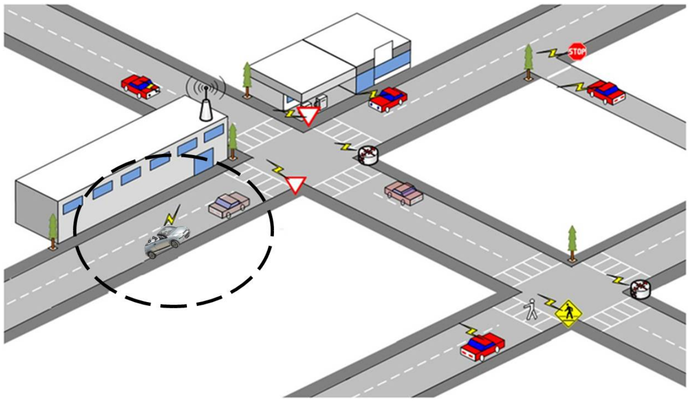

Figure 4. Overview environment evaluation system.

V. ENVIRONMENT EVALUATION SYSTEM

The autonomous car described and its associated maneuvers are selected taking into account an environment evaluation system designed through priority levels. The autonomously driven vehicle continuously checks a circular area of up to 80-m radius. When another vehicle or a pedestrian is detected within this area, its trajectory is analyzed to select among the different controllers in order to perform the safer maneuver.

Figure 4 shows an overview of the environment evaluation system. In this case, the vehicle receives the information about a vehicle driving in front of it and the change from autonomous guidance to ACC+Stop&Go controller is carried out. If a pedestrian is detected during the ACC or an overtaking maneuver can be performed, the fuzzy controller selected is changed.

VI. RELATED EXPERIMENT

We here present an example about the behavior of the autonomous car in a real traffic circumstance. The test consisted on performing a pedestrian avoidance maneuver plus an intersection without right-of-way crossing. Fig. 5 depicts the implemented autonomous route. Solid black will be used to correspond to the autonomous vehicle, and gray symbols to the manually driven one.

The test begins when the autonomous vehicle is started, marked with the time equal to zero. Until the first bend, the vehicle is driving using the autonomous guidance mode. Around second 20, an unexpected pedestrian is detected in the lane and the pedestrians mode is activated. A steering change is done occupying the other lane to avoid the pedestrian collision. One can observed how the maneuver is carried out in advance and the pedestrian is avoided safely. After second 28, the vehicle is coming back to the reference lane and the autonomous guidance mode is activated again.

Around second 32, a vehicle approaching to the crossroad with right-of-way is detected and the intersection management

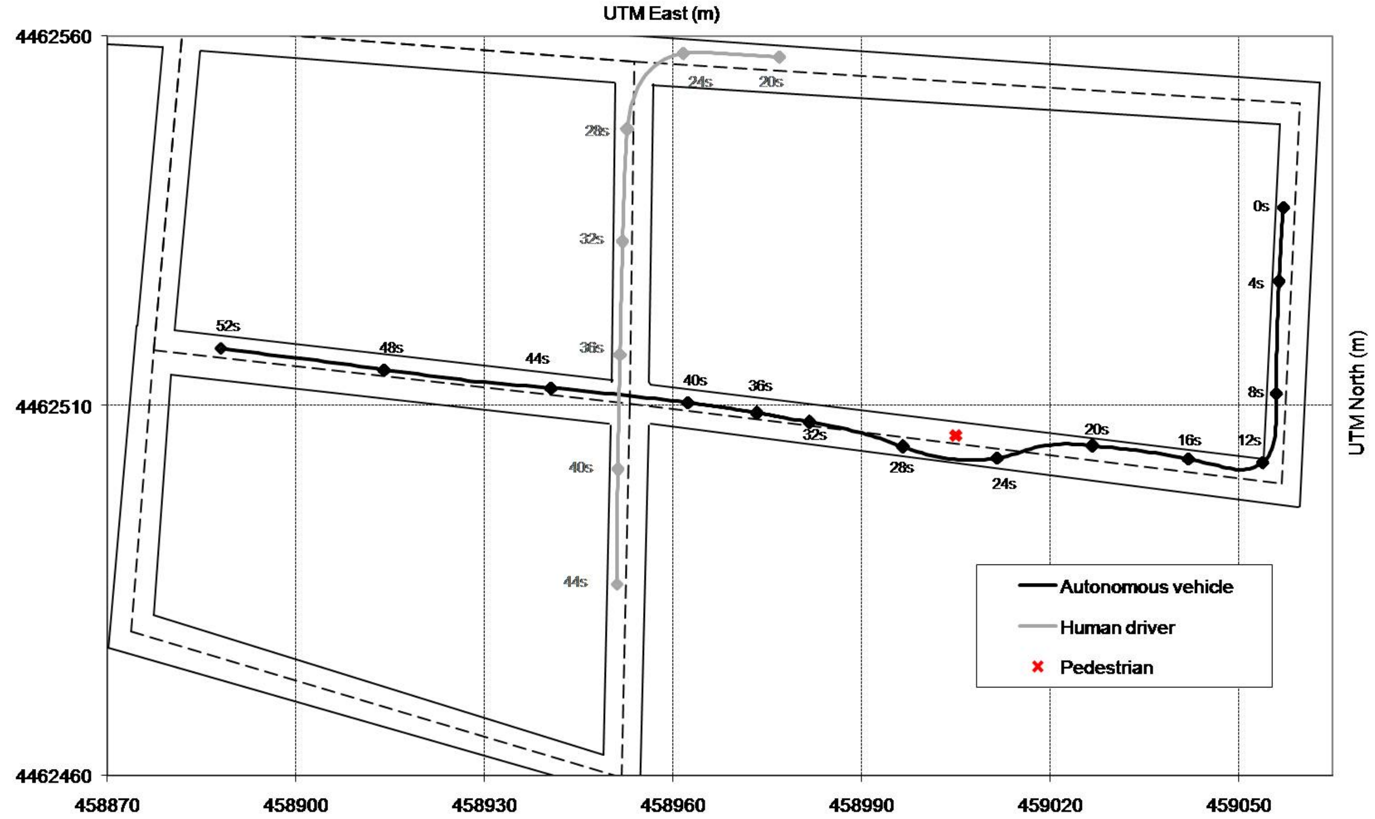

Figure 5. Experiment including a pedestrian avoidance plus intersection management.

mode is activated. The speed of the autonomous vehicle decreases slightly between seconds 32 and 36 to permit the manually driven traversing the intersection. Then, around second 40, the autonomous vehicle detects the intersection is free and is accelerated significantly to ensure traversal of the crossroad. Then, the autonomous guidance mode is in charge of performing the longitudinal as well as the lateral control. Around second 44, the manually driven vehicle position is lost because is out of our interest area.

VII. CONCLUSIONS AND FUTURE WORKS

The evolution of an a unmanned car is shown in this paper. First, the hardware modifications to permit an autonomous driving were explained. Second, the on-board sensors to analyze the environment that permits taking control actions were described. Third, the implemented autonomous maneuvers and the decision unit to select among them were mentioned. Finally, a test with the two last maneuvers added to the vehicle were presented.

Several maneuvers have to be developed in the future. Work in roundabout management as well as in incorporation to highways is now in progress. Indeed, work with more vehicles to study the effects on traffic flow is a mid-term goal. Finally, new pedestrian detection algorithms to detect them in advance has to be obtained.

ACKNOWLEDGMENT

The authors would like to thank the Spanish Ministry of Science and Innovation by means of Research Grant TRANSITO TRA2008-06602-C03 and Spanish Ministry of Development by means of Research Grant GUIADE P9/08 for their support in the development of this work.

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