Fuzzy Logic Based Lateral Control for GPS Map Tracking

José E. Naranjo, Carlos González, *Member, IEEE*, Ricardo García, Teresa de Pedro, Javier Revuelto, and Jesús Reviejo

Abstract—**The automatic control of the speed and the steering of a vehicle are two of the main steps in order to develop autonomous intelligent vehicles. In this paper, a development of steering control for automated cars based on fuzzy logic and its related field tests are presented. Artificial intelligence techniques are used for controlling a broad range of systems, trying to emulate the human behaviour when classical control models are too much complex and require a lot of design time. Particularly, fuzzy logic control techniques are well proved success methods for managing systems where there appear to be limitations for classical control. Our control system has been installed in two Citroën Berlingo testbed vans whose steering wheel has been automated and can be controlled from a computer. The main sensorial input is a RTK DGPS that gives us positioning with one-centimeter precision. The results of the realized experiments show a human like system performance with adaption capability to any kind of track.**

I. Introduction

Classical control techniques are the usual way to manage complex systems such as the steering wheel of a car. A characteristic of these techniques is the necessity of a model of the system and the set of equations that describes its behavior. Occasionally, this may be a limitation, when the system to manage is very complex and a linear model does not exist. There are some techniques for dealing with these cases. Linearization of the non-linear systems is classical [1]; depending on the complexity of the resulting model, system performance will be more or less realistic but with a performance loss [2]. The compromise between performance and complexity is the main factor on design time of this kind of systems. Other way for resolving control problems of non-linear applications is the use of artificial intelligence techniques. These methods are specially indicated when we try to emulate human behavior and control actions, such as human car driving. Particularly, fuzzy logic is a well-known methodology for these tasks [3] since the Sugeno´s works [4], [5] about vehicle control in early 1990's.

A number of solutions based in classical control have been proposed for solving the problem of controlling the steering wheel of a car. Particularly the works of Cybercars and Carsense European research projects use multiple sensing techniques for performing lateral control of a vehicle [6] with proved results. During the PROMETHEUS Project, Parma University used vision based sensorial perception for controlling a car in the ARGO project, and its prototypes have traveled more than 2000 kilometers in automatic mode [7]. The University of Munich prototypes use also artificial vision as main sensorial input in order to get robust control of the steering of a car [8]. In Japan Super Smart Vehicle System research is centered in GPS positioning and sensorial fusion for developing automatic guidance [9].

Artificial Intelligence techniques are also used in order to get lateral control of vehicles. The NavLab ALVIN research project is based in the integration of artificial vision and neural networks for driving a car [10] and in the Griffith University of Australia AI based controllers have been developed, with the capability to perform automatic driving [11]. In Spain, AUTOPIA program, to which this work belongs, tries to apply successfully developed techniques in mobile robot intelligent control [12] to managing real vehicles [13]. Particularly our systems are based on the position information acquired by a high precision GPS and fuzzy controllers for performing human-like lateral and longitudinal control and have been installed in real testbed cars. These controllers permit the control of any kind of vehicles without extensive knowledge of the mathematical models of the system emulating the reasoning used by human drivers for managing a car.

This paper will describe the developed lateral control of Autopia, based on fuzzy logic techniques and tested in real cars and real roads.

Manuscript received November 21, 2003. This work was supported in part by the Spanish Ministry of Fomento under Grant COPOS BOE 280 de 11-22-2002 res. 22778, Spanish Ministry of Science and Technology under grant ISAAC CICYT DPI2002-04064-C05-02, Citroën Spain S.A. under project AUTOPIA.

José E. Naranjo, Carlos González, Ricardo García, Teresa de Pedro, Javiar Revuelto and Jesús Reviejo are with the Instituto de Automática Industrial (IAI) of the Consejo Superior de Investigaciones Científicas (CSIC), Ctra. Campo Real, Km, 0,200, La Poveda-Arganda del Rey, 28500, Madrid, Spain (phone: +34 918711900; fax: +34 918717050; e-mail: jnaranjo@iai.csic.es, gonzalez@iai.csic.es, ricardo@iai.csic.es, tere@iai.csic.es, revuelto@iai.csic.es, jesus@iai.csic.es).

II. FUZZY LOGIC FOR STEERING CONTROL

AUTOPIA program consists on a set of ITS research projects whose final goal is the development of unmanned vehicles, using techniques successfully developed in the mobile robot field. In the projects, some partial controllers have been developed and some human maneuvers and behaviors have been emulated in order to automate the human driving in an incremental way.

The experimental work in automatic driving of the program has been implemented using two Citroën Berlingo vans, whose main actuators (steering wheel, throttle and brake) have been automated so they can be controlled from an onboard computer in which the automatic driving control system based on fuzzy logic resides. The experiments have been developed in a private test circuit located in our institute facilities. The main sensor used for acquiring driving information is a 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.

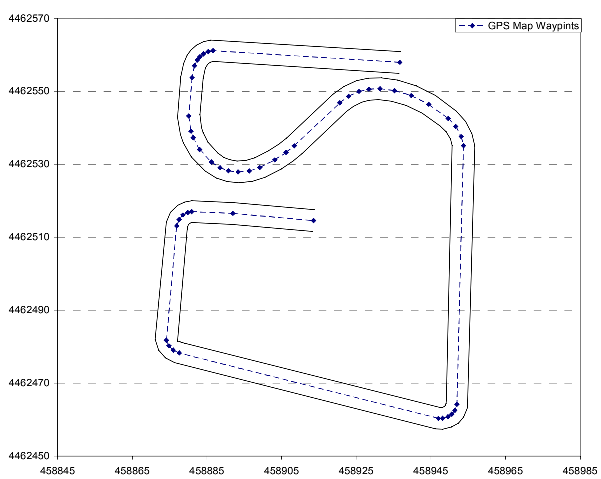

Figure 1. Representation of a GPS map of the IAI driving test circuit.

The GPS maps are built automatically tracking the desired route with a GPS equipped car and, after the end of the run a computer system selects the most significant waypoints that will be used by the autonomous driving system. An example of the resulting GPS map is shown in Figure 1.

We assume that the acquired positions are located at the center of the street and the right and left limits are located at 3 meters of this center, this is the lane width. When it is used for automatic driving, the circulation lane can be selected at left center or right, depending of the selected maneuvers. The default lane is the right one, but it can be changed to the left, for example in an overtaking maneuver. The method used to select the desired reference lane is very simple; only a 1.5 meters (the center of each lane) displacement to the left or the right of the map reference lines is necessary in order to circulate on it.

Once described the equipment and the mapping we are going to illustrate the fuzzy logic based control system for controlling the steering wheel of the testbed cars. Since Sugeno´s already mentioned works [4], [5] fuzzy logic is an accepted technique to deal with vehicle control and it is also a powerful way to represent the human knowledge in control, avoiding to develop extensive mathematical equations and complex world models. In our philosophy, an artificial driver must learn from the experience of other drivers and some basic information. When a human goes to a driving school, he doesn't learn mathematics; he learns how to drive. In a similar way, a fuzzy controller arises from the human expert information and the previous knowledge of the environment. Only four fuzzy rules are necessary for controlling the steering wheel:

IF Lateral_Error left THEN Steering right
IF Angular_Error left THEN Steering right
IF Lateral_Error right THEN Steering left
IF Angular_Error right THEN Steering left

Where angular error and lateral error are the input variables of the system. The angular error represents the angle between the car's direction vector and the segment of the map that is actually running, and the lateral error is the distance from the position of the car to the reference segment.

The fuzzification of each variable is made through two membership functions that are defined in Figure 2. We have also used the minimum for defining the fuzzy *tnorm* (AND) and the maximum for the *tconorm* (OR). The defuzzyfication method we have applied is Sugeno's *singletons*, very useful in control systems. The output also depends of the speed the car is circulating. Then, if this speed is higher than 30 Km/h, the steering wheel will only move the 75% of the fuzzy output. If the speed is between 20 Km/h and 30 Km/h, it is used the 90% and when it is less than 20 Km/h, it can move the 100%.

The aim of this controller is to make both errors tend to zero in order to track accurately the map, but also functionalities must be added such as to open the steering a little more in right curves and to start a little earlier the turning in left curves. It also depends of the curvature radius. The way to add these functionalities to the controller is the definition of the membership function shapes. Note that two shapes have been defined for each label of the input variables membership functions. The reason for this is that, as for humans, it is not the same to drive in a straight lane than in a curve track. This way, the system detects which kind of road is tracking in each moment and uses the black shapes for curve lanes and the gray shapes for straight lanes.

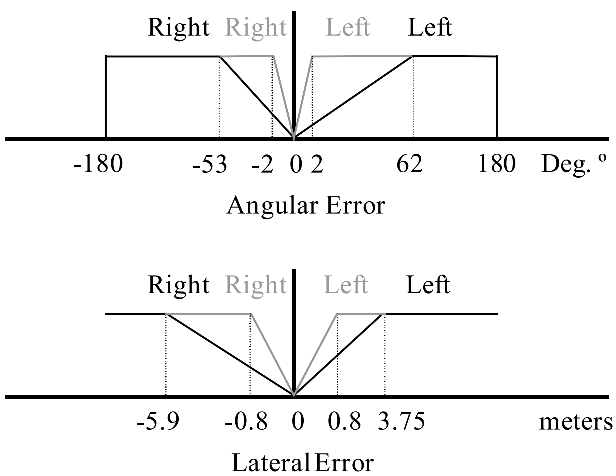

Figure 2. Angular and Lateral error membership functions

When curve mode is selected, the input membership functions definition is different depending on the direction of the curve. The gradient of the function's shape indicates the actuation of this input over the control. When the value is 0, no actuation is derived from the label on this input over the related fuzzy rules and when its value is 1, the incidence over the rules is maximum. Besides, the shape of the gradient increases in a different way to the left than to the right, it means that the behavior of the control is different when the car takes a curve to the left or to the right. In this case, the gradient of the shape of the angular error membership function *right* label is higher than *left* label one and in the lateral error the gradient of the *right* label is lower than *left* label. Thus, when a curve to the right comes, the *left* label of the angular error variable activates, and since its gradient is lower than the gradient of the *right* label, the action is later as in the contrary curve, thus approximating more to the curve before turning. In general terms, the higher the gradient of the lateral error shape definition, the nearer to the center of the turning axis the car will take the curve.

However, the straight tracking input linguistic labels definitions are symmetric; meaning that its objective is to maintain the same orientation without hard steering movements. Furthermore, the output singletons define the maximum steering movements as 2.5%.

III. Related Experiments

Once installed the controller in the testbed cars, some experiments have been performed at the IAI test circuit, in order to demonstrate the system performance.

In this paper, we show the experiment depicted in Figure 3 and consists on the track of the trajectory of a circuit with straight lanes and curve lanes with a small curvature. In this case, the selected circulation lane of the road is the right lane, as a human driver would do.

The X-axis of the graphic represents the East UTM coordinates and the Y-axis is the North UTM coordinate, both expressed in meters. The round starts at the top extreme in a straight road, maintaining the lane center position. 60 meters after starting, the car must turn left a 90º curve with a small curvature. In this case, the angular error is *left* and the lateral error is *right*, and the control actions cancel one another so the car maintains the same direction until the lateral error decreases to 3.75 meters and the higher strength of the angular error makes the steering wheel move to the left.

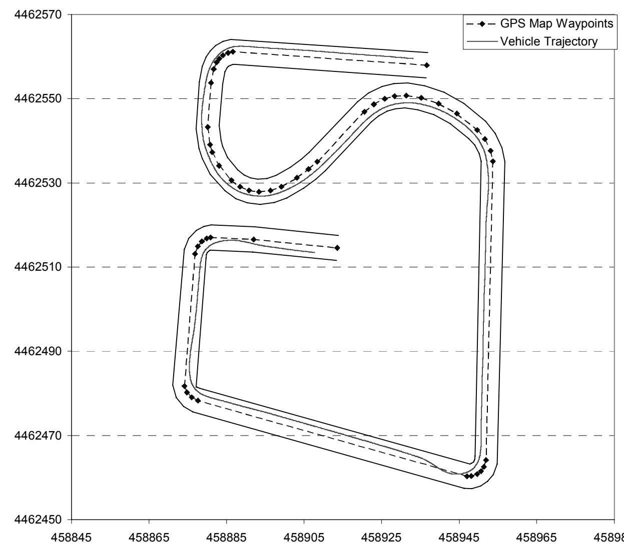

Figure 3. Schematic representation of an automatic road tracking based on fuzzy logic and GPS.

After this turn, a straight segment appears and consecutively to it, a left curve and a right curve, both with a variable curvature radius.

The controller adjusts the car correctly to both curves and exits curve mode in order to travel the next long straight circuit street. At the end of this, about UTM northing position 4462470 m, there is a sharp turn to the right, with a short curvature radius. In this case, the fuzzy controller makes the steering to open a little in the curve, due the relaxed gradient definition for the lateral error right and with this, the car can perform this turning without stepping out of the corner of the road. After that, the car goes back to its active lane and continues its route. The last two turns are made in the same way that this.

In order to demonstrate the correct system performance, the associated control surface for the curve driving fuzzy controller is shown in Figure 4. This output surface for the straight tracking controller is very similar, changing the inflexion points due to the straight membership functions definition.

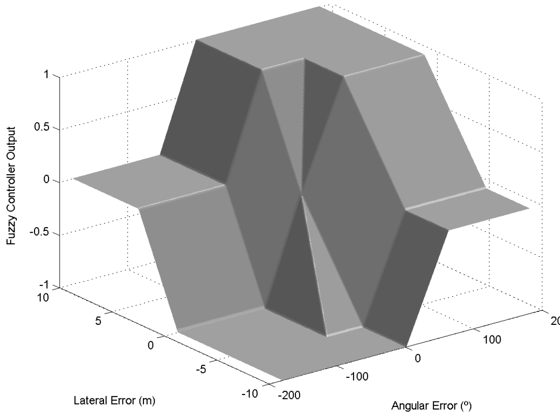

Figure 4. Control surface of the curve driving fuzzy controller.

An analysis of the generated data logs shows that the greatest lateral error in straight driving is about 22 centimetres and the angular error is less than 0.5 degrees. In curve driving, the objective is not to maintain the car in the center of the road but adapting correctly to the shape of the road like human drivers do, as was introduced in the controller definition. In this case, the right performance of the system cannot be quantified, but it is shown graphically in Figure 3.

IV. CONCLUSION

We have developed a fuzzy control based driving system that can manage the steering wheel of a car very close to the way humans do. The performed test shows that with precise GPS maps and positioning it can be possible to maintain a vehicle in its lane of the road in a private circuit very close to real roads.

ACKNOWLEDGMENT

We want to thank Ministerio de Fomento COPOS project and MCYT ISAAC project. We thank specially to Citroën España SA, without its collaboration this work wouldn't be achieved.

REFERENCES

[1] J. Ackermann and W. Sienel, "Robust Control for Automated Steering", Proc. Of the 1990 American Control Conference, ACC90, pp. 795-800, San Diego, CA, 1990.
[2] H. Susssmann et al., "A General Result on the Stabilization of Linear Systems Using Bounded Controls", IEEE Transactions on Automatic Control, 39 (12): 2411-2425, January 1994.
[3] T. Takagi and M. Sugeno, "Fuzzy Identification of Systems and Its Applications to Modeling and Control", IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-15, No. 1, pp. 116-132, January/February, 1985.
[4] M. Sugeno et al., "Fuzzy Algorithmic Control of a Model Car by Oral Instructions", IFSA'87 special issue on fuzzy control, K. Hirota and T. Yamakawa Ed., October 1987.
[5] M. Sugeno, I. Hirano, S. Nakamura and S. Kotsu, "Development of an Intelligent Unmanned Helicopter", IEEE International Conference on Fuzzy Systems, Vol. 5, pp 33-4,1995.
[6] Langheim et al., "CARSENSE – Sensor Fusion for DAS", ITSWC Chicago, Oct. 2002.
[7] A. Broggi et al., Automatic vehicle guidance: the Experience of the ARGO Autonomous Vehicle, World Scientific. 1999
[8] E.D. Dickmanns et al. "A Curvature-Based Scheme for Improving Road Vehicle Guidance by Computer Vision", Proceedings SPIE Conference on Mobile Robots, vol. 727, 1986.
[9] S. Kato, S. Tsugawa, K. Tokuda, T. Matsui, H. Fujiri, "Vehicle Control Algorithms for Cooperative Driving With Automated Vehicles and Intervehicle Communications", IEEE Transactions on Intelligent Transportation Systems, vol. 3, No. 3, September 2002, pp. 155 – 161.
[10] D. A. Pomerleau, "ALVINN: An Autonomous Land Vehicle In a Neural Network", Advances in Neural Information Processing Systems 1, Morgan Kaufmann, 1989.
[11] M. Hitchings et. al., Fuzzy Control, Intelligent Vehicle Technologies, Vlacic, Parent, Harashima eds. pp. 289-327, SAE International, 2001.
[12] MA. Sotelo, S. Alcalde, J Reviejo, JE Naranjo, R. Garcia, T. DePedro and C. Gonzalez "Vehicle Fuzzy Driving based on DGPS and Vision," 9th IFSA World Congress, Canada, July 2001.
[13] JE. Naranjo et. al., "Adaptive Fuzzy Control for Inter.-Vehicle Gap Keeping", IEEE Transactions on Intelligent Transportation Systems, Special Issue on Adaptive Cruise Control, Volume 4: No. 3, September 2003, pp. 132-142.