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Fuzzy logic steering control of autonomous vehicles inside roundabouts

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ABSTRACT

The expansion of roads and the development of new road infrastructures have increased in recent years, linked to the population growing in large cities. In the last two decades, roundabouts have largely replaced traditional intersections in many countries. They have the advantage of allowing drivers continuous flow when traffic is clear, without the usual delay caused by traffic lights. Although roundabouts with and without traffic-signal control have been widely used and considered in the literature, driverless control on roundabouts has not been studied in depth yet. The behavior of autonomous vehicles in roundabouts can be divided into three stages: entrance, inside, and exit. The first and last may be handled as an extension of intersections. However, autonomous driving on the roundabout requires special attention. In this paper, the design and implementation of a fuzzy logic system for the steering control of autonomous vehicles inside the roundabout is proposed. Cascade architecture for lateral control and parametric trajectory generation are used. Fuzzy control has proved to be easy to define using expert knowledge. Experiments with a real prototype have been carried out, taking into account different speed profiles and lane change maneuvers inside the roundabout, with very satisfactory results.

1. Introduction

Recent automatic facilities in the field of Intelligent Transportation Systems (ITS) have improved safety and driving comfort. Different functionalities are already available in commercial vehicles, such as: cruise and adaptive cruise control [1], emergency breaking systems with assistance of active suspension [2], automatic parking systems [3], detection of vehicles to the rear based on vision systems [4], and many others Advanced Driver Assistance Systems (ADAS) [5,6]. The ultimate goal of automotive technology is the realization of self-driving vehicles.

Driving a vehicle is a complex process that requires the expertise of a driver. In that sense, soft computing techniques provide the advantage of representing expert knowledge for controlling complex and nonlinear processes, such as autonomous driving. Specifically, fuzzy logic has been widely used in the field of ITS. The fuzzy controllers, while achieving good results in controlling an autonomous vehicle, provide a smooth and safe driving [7].

The automatic functionalities for driving are mostly dedicated to the longitudinal control (brake and throttle). For instance, [8], or the recent paper by [9], apply fuzzy logic to control the speed and throttle of an autonomous vehicle. However, the lateral control in autonomous vehicles requires special consideration because it can be critical. The small angle of the wheels in urban curves or at high speeds can leave the driver without enough reaction time and, therefore, unable to recover control of the steering wheel.

A small range of automatic maneuvers, and only at low speeds, is available for the steering wheel: semi-autonomous parking [10], and lateral stability assistance [11]. Some new applications considered haptic feedback in the steering wheel and warning signals on dangerous situations [12]. A notable exception is the work presented by Sunwoo et al. [13]. In the distributed architecture they have developed for real autonomous vehicles, longitudinal proportional-integral-derivative (PID) control is applied; lateral control is based on steering angle error tracking. The platform they have implemented has been tested in scenarios with traffic lights, therefore including light detection, obstacles, and overtaking.

On the other hand, roundabouts are a scenario where the steering control is crucial. It has not been studied in depth yet. Some papers address traffic management at signalized roundabouts [14]. In this case, the problem has been considered from the signal's point of view, i.e., using the speed control limits, the geometrical characteristics of the infrastructure, and even monitoring the traffic flow [15–17]. In addition, control of autonomous vehicles is not included in these scenarios, except using predefined trajectories [18]. Cai

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et al. [19] proposed an intelligent fuzzy controller for intersections but, despite the fact that they mention four types of traffic intersections, including roundabouts, they only develop and apply fuzzy control on the traffic lights at the intersection and do not control the vehicle. Onieva et al. [20] apply genetic algorithms to optimize a fuzzy decision system for driving at intersections. In this paper, the fuzzy rule cooperates with a manually driven vehicle. In [21], a double gain controller (equivalent to a proportional-integral regulator) for autonomous driving at roundabouts was proposed. But this conventional controller was tested only using a 3D simulator. Other approaches have applied soft computing techniques for autonomous motion planning in unorganized traffic at intersections, but without considering roundabouts [22].

Driving on a roundabout can be divided into three phases: entry, exit, and circulating lane. The first two phases can be modeled as standard intersections, using parametric equations, and thus are relatively easy to handle. However, the circulation inside a roundabout is one of the most common and difficult scenarios at present. Contributions on this issue are required.

In this paper, the application of fuzzy logic to the steering wheel control of an autonomous vehicle inside roundabouts, where lane change maneuvers at different speeds are performed, is proposed. Besides, a new trajectory generation procedure is proposed.

The new fuzzy controller was applied to an electric van of the Autopia project [1]. Experiments have been carried out on a real roundabout, at different speeds, performing lane changes and using different entries and exits. Results prove the effectiveness of our proposal. To our knowledge, this is a novel contribution in the field of ITS.

The paper is organized as follows. Section 2 describes the roundabout scenario and the trajectory generation. In Section 3, the design of the lateral fuzzy control of the autonomous vehicle while it is circulating inside the roundabout is presented. Section 4 shows and discusses the results of the application of the intelligent steering control to the real prototype. Conclusions and future works end the paper.

2. Problem approach: roundabout

In the last two decades, roundabouts have gradually become a very popular alternative to tackling the problem of intersections [23]. But, at the same time, they have become a controversial point for drivers [24]. Some results presented in previous studies (in the United States and China) showed that drivers do not have enough skills circulating in roundabouts, generating traffic jams in the vicinity [24,15].

A roundabout is a type of circular intersection or junction in which road traffic flows almost continuously in one direction around a central island. There are many types of roundabouts. Even more, it needs to be pointed out that roundabouts in different countries differ in their layouts. Circular intersections at highways can have from 2 to 6 lanes around the center. In urban environments, roundabouts are usually small (radius of less than 2 m, called mini roundabouts). They can be unsignalized or may have traffic lights and other traffic signals regulating the flow [25]. Therefore, it is important to describe the scenario in which the control scheme is going to be applied.

2.1. Roundabout description

Fig. 1 shows the actual roundabout used for validation of the proposal. The roundabout is located at the Center of Automatic and Robotic (CAR), in Arganda del Rey (Madrid), Spain, which belongs to the Technical University of Madrid (UPM) and the Spanish National Research Council (CSIC). The characteristics of this roundabout are the following:

Fig. 1. Real test scenario: roundabout

- The smallest radius of a roundabout is conditioned for the turning radius of the autonomous vehicle (6 m) and the lane width (3 m). Accordingly, the minimum radius is 7.5 m. In our case, the radius of the roundabout is 13 m.
- Two lanes on the circulating roadway are considered, 3 m wide each. Therefore, lane change inside the roundabout has been considered.
- The number of entry and exit points is limited to 4. One will be used as an entry and the other three as exits.
- The approaching lanes are also 3 m wide.
- The flow direction is counterclockwise.

2.2. Trajectory generation

The control of autonomous vehicles on the roundabout can be divided into three stages: entrance, circulating lane, and exit. Different controllers are used at each stage once the roundabout is detected. The control on the circulating lane is performed by small control segments. Therefore, it is necessary to define the trajectory along these segments.

The solution to the problem of trajectory generation on the circulating roadway can be solved by setting predefined points [18]. Nevertheless, this approach has the disadvantage of being non-generic, since each roundabout may have different radius, number of lanes, number of entry and exit points, etc. Thus, in this work a more general approach to design the path is proposed.

The geometrical characteristics (origin determined by 2-dimensional Cartesian coordinates, and radius) are used to generate the trajectory. On the one hand, perpendicular roads to the tangent line in the roundabout are determined. Different approach angles at the entrances and exits can be considered. The trajectory to approach the entry and exit points is then estimated based on Bezier curves at the intersections [26]. This polynomial is expressed as:

$$B_{(t)} = P_0 * (1-t)^3 + 3 * P_1 * t * (1-t)^2 + 3 * P_2 * t^2 * (1-t) + P_3 * t^3 \quad (1)$$

where t is a parameter $\in$ [0,1] and $B_{(t)}$ are the trajectory points generated. Since it is a 3rd degree polynomial, P_0, P_1, P_2, and P_3 are the Bezier control points of the curve. In this case, 25 points have been generated increasing parameter t by 1/25 from 0 to 1. Fig. 2 shows the Bezier curves generated at the entry and exit of the roundabout.

But once the vehicle is already inside the roundabout (second stage), the intelligent controller proposed in this work is activated. The parametric generation of the trajectory on the circulating

[1] http://www.car.upm-csic.es/autopia/videos.php