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Dynamic Trajectory Generation Using Continuous-Curvature Algorithms for Door to Door Assistance Vehicles

Joshue Pérez Rastelli[1] and Ray Lattarulo[1] and Fawzi Nashashibi[1]

Abstract— **In this paper, an algorithm for dynamic path generation in urban environments is presented, taking into account structural and sudden changes in straight and bend segments (e.g. roundabouts and intersections). The results present some improvements in path generation (previously hand plotted) considering parametric equations and continuous-curvature algorithms, which guarantees a comfortable lateral acceleration. This work is focused on smooth and safe path generation using road and obstacle detection information. Finally, some simulation results show a good performance of the algorithm using different ranges of urban curves. The main contribution is an Intelligent Trajectory Generator, which considers infrastructure and vehicle information. This method is recently used in the framework of the project CityMobil2 [1], for urban autonomous guidance of Cybercars.**

I. INTRODUCTION

In recent years, new techniques and algorithms, previously used in mobile robots, have been used in autonomous vehicles considering some constrains in real roads. Several research groups have increased their investments in areas as planning and control to reduce the time-out on the arrival of totally autonomous transportation systems. Over fifteen years ago, the first Advanced Driver Assistance Systems (ADAS) were introduced on a massive scale in the market [1]. One of the most known is the Adaptive Cruise Control (ACC), which can automatically adjust a vehicle's speed to maintain a safe following distance. The main aim of the ADAS is to ensure safety for the passengers in the vehicles.

The concept of helping humans in the driving process was attached to the ADAS systems from their origins. In this sense, [2] established that ninety to ninety five percent of traffic accidents (great majority) involve human errors; and that seventy percent of these could be avoided with the use of ADAS systems. Additionally based on [3], forty percent of the vehicle crashes are related to unintentional lane departure and seventy percent of these ended up with road fatalities.

In this sense, institutions, organizations and laboratories are looking for a complete autonomy of the vehicles, incorporating some tools, such as: blind spot detection, traffic sign detection, lane detection systems, among others [4] [5]. More recently, sustainability concepts such as energy efficiency have been incorporated (EDAS -Ecological Driver Assistance Systems-) to face the challenges of the new millennium [6], [7]; using as basis electric vehicles which are increasing their acceptance all around the world.

[1]The authors are with the INRIA / Imara team, National Institute for Research in Computer Science and Control (INRIA), Domaine de Voluceau, BP 105, 78153 Le Chesnay, France

[1]http://www.citymobil2.eu/en/

Cybernetic Transportation Systems (CTS) are an example of fully automated vehicles dedicated to urban scenarios, whose goal is to reduce traffic problems, increase comfort and be environmentally friendly. The end of the twentieth century has seen some European projects develop in this area: Cybercars, Cybermove and CityMobil [8]. Some of the researches developed within these projects are: motion planning and safety maneuvers [9]; Inevitable Collision States (ICS) [10], Geographical Information System (GIS) based on GPS, autonomous navigation with cameras and lasers [11], among others.

Recently, research on smooth planning is gaining importance within the CTS; this is because the most important part in the passenger's comfort in a vehicle is related with the route tracked and the speed in each segment. Following these ideas, some authors describe the intersections with parametric curves such as Spline and Clothoids [12]. The problem related to the Splines approach is that it is complicated to estimate what will be the route drawn by these curves. Clothoids are widely used, however the integral definition makes the computational calculation complex and expensive.

Therefore, some works use the parametric curves of Bezier, which allow to define curves in an easy-way and efficient mode. [13] describes a method to generate a smooth path generator using static reference (hand adjusted) by locating control points (figure 2). This method has not considered environment characteristics, like the angle of junction, road width, among others; which are necessary to build correctly a safe and smooth path. For this reason, a new method for setting automatically the control points of Bezier is proposed in this work. Our aim is to have a safe, continue and comfortable path generation.

The rest of the paper is organized as follow: a review of the proposed control architecture which is based on our previous works is described in section 2. Section 3 explain the automatic algorithm proposed, which takes in consideration most of the relevant characteristics of urban roads. The experiments and results are described in section 4 and 5. Finally, conclusions and discussion are presented in section 6.

II. CONTROL ARCHITECTURE

Figure 1 shows the control architecture for cybernetic cars used in this work. This scheme is based on previous modules developed in the IMARA group [14] and [13]. The main contributions have been developed in the decision block (especially in the local planning), and they will be explained in the next section.

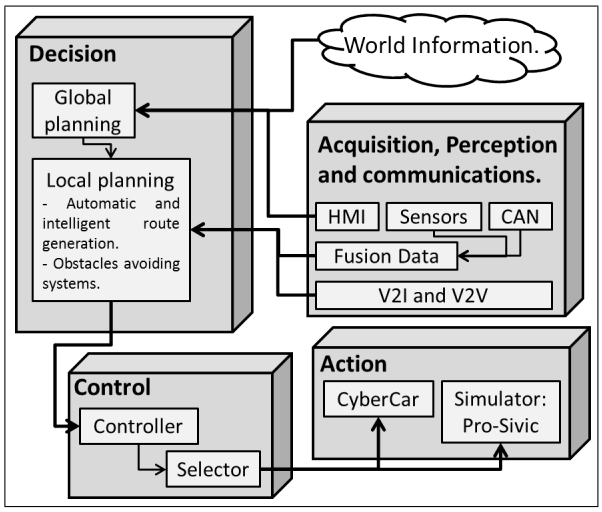


Fig. 1. Control architecture for Cybercars.

Figure 1 illustrates the acquisition, perception and communications in the same module. However, these parts are well separated in our implementation. The decision module receives this real time information. Finally control and action are expressed in two modules in the lower part of the figure.

The software used for the implementation of these modules is RTMaps [2]. It is a real-time prototyping system, performing real-time multisensor data logging and replay, and providing development abilities, libraries, and hardware and software interfaces.

A. Acquisition, Perception and Communications

Acquisition is performed basically for all of the onboard sensors used in the vehicles. These give a real time description of the car and the obstacles; some of them are a differential GPS, inertial measurement unit (IMU), laser scanners, among others. All this information passes through a data fusion process, which also considers CAN information (with kalman filter as [15]), and it is sent to the ego-vehicle module of the vehicle [16].

The perception part uses the laser scanners to calculate the position of the obstacles. Different scenarios can be tested with SLAM, as in [17], and obstacle avoiding detection system.

The vehicles are linked through a mesh-network over WIFI with OLSR Ad-Hoc protocol as described in [18]. Therefore, the acceleration, speed and position information could be transferred by vehicle-to-vehicle (V2V) and/or vehicle-to-infrastructure (V2I) communications, giving the possibilities to make cooperative and emergency maneuvers.

B. Decision

The decision module obtains, analyzes and processes the information coming from the world (route map, destination address, real time variables information, among others). For this reason, it is considered as the core module in the control architecture.

[2]http://www.intempora.com/

It is capable of building a continuous and smooth trajectory, which is going to be followed by an autonomous vehicle. Additionally, it reacts to unexpected conditions and situations, e.g.: obstacle presence, pedestrian crossing, etc. This is divided in two sub-modules with specific properties and characteristics, which will be explained next:

1) Global planning: This module is the first step of the planning generation process. It describes the itinerary in terms of waypoints which define each intersection and a set of points that pattern the route on the roundabout. The information used comes from the world information module (upper right part of figure 1), stored as xml files ([13]). A reference of single points for each intersection and, the center and radius to describe the roundabout are used; additionally the angle of entrance and exit of the roundabout could be provided (or calculated).

2) Local planning: This section describes the main contributions of this work. Improvements incorporating new intelligent methods over hand adjusted methods used in previous works [14], [13] were done. New trajectories adapted to each intersection, considering the kinematic model of the vehicle, environment structure and comfortable driving, have been achieved.

In previous works, the way to build a path in an intersection was standardized; in such a way that the specific characteristics of the road such as width, angle of junction, among other were not taken into account. These characteristics produce some unexpected situations in the planning because the system is not scalable and it is just limited to a specific type of road, without dynamic changes or emergency situations. The goal is to have different kinds of routes and situations, with a special focus on moving obstacles, to adapt the path in real time.

Some characteristics of the intersections were considered in this new algorithm. Additionally, continuous and soft Bézier curves were used to build a smooth path. This module processes the control points set of Bézier automatically; it adapts the generation of the curve to the shape of the intersection to obtain a safe and smooth path that is always inside the lane (e.g.: not going over sidewalks).

This module keeps a communication with the control part via a data buffer; but basically this is used to send the data of the new route generated from the local planning to the next segment. It is important for sudden actions when an unexpected event (obstacles, pedestrian,etc) occurs.

In this sense a brief explanation of the Bézier curves and the kinematic model used in the algorithm will be presented in this section; and the complete explanation of the intelligent algorithm will be shown in section III.

a) Parametric Curves Of Bézier: Bézier curves are used in the local planning because of their simplicity and versatility [19] in urban scenarios. Their goal is to build a continuous, smooth and safe path that will be tracked by a vehicle. They are defined by:

$$B(t) = \sum_{i=0}^{n} P_i b_{i,n}(t); \quad t \in [0,1] \tag{1}$$

where n is the degree of the polynomial equation, P_i are the control points that define the curve, and $b_{i,n}$ is the Bernstein basis polynomial [20] given by:

$$b_{i,n}(t) = \binom{n}{i}(1-t)^{n-i}t^i \tag{2}$$

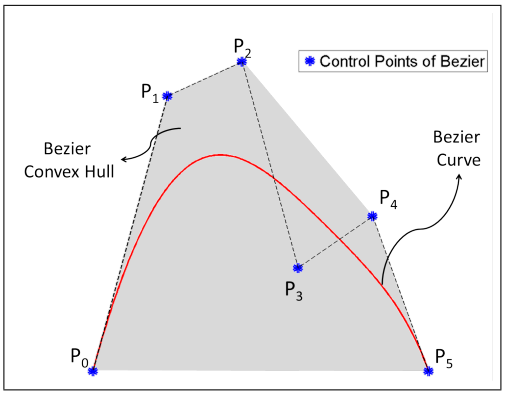


Fig. 2. Convex Hull formed by control points of Bézier

Some of the properties of the Bézier curves are mentioned in [19]. The most relevant are explained as follow:

- The curve starts on the position of the control point P_0 and it ends at P_n.
- The tangent line in P_0 will be equivalent to the one formed by the connection between $\overrightarrow{P_0P_1}$ and the tangent line in P_n is going to be equivalent to $\overrightarrow{P_{n-1}P_n}$.
- All their control points will lie within the convex hull formed by them. Figure 2 shows the convex hull formed around the curve.

b) Kinematic Model: The kinematics models are a good approach for prediction the behavior of the vehicle at low speed [21]. The kinematic modeling is an easy way to improve the process of building the trajectory using as a reference the vehicle's characteristics. These can be vehicle width, the wheelbase, steering angle, among others. Hence, the Ackerman model, also known as the bicycle model, represents a good method for the odometry of the car.

In [22] and [21], they consider as a motion model of the vehicle a non-lineal system of equations where the main contribution to this work is the possibility to obtain an equation with graphical methods which defined the curvature all the time.

This equation is:

$$k(t) = \frac{1}{r(t)} = \frac{\tan(\phi(t))}{l} \tag{3}$$

Where $k(t)$ is the curvature of the path. We are assuming that the maximum curvature feasible is when the angle of the wheel is maximum. It is valid using the bicycle model for low speed, and more dynamic restrictions will be considered in future works.

C. Control

The control system is based on classic control variables for autonomous vehicles; such as lateral error and angular error [23], [24]. The curvature variable adapts the vehicle behavior to the trajectory generated for intersection situations.

The control law for the steering of the car is defined in equation 4:

$$U(t) = \alpha_1 k(t) + \alpha_2 L_{error} + \alpha_3 A_{error} \tag{4}$$

where $k(t)$ is the curvature, L_{error} is the lateral error and A_{error} is the angular error. And α_1, α_2 and α_3 are the controller gains.

D. Action

The action stage is related to the platforms (or simulator) where the control architecture will be implemented. In this work, a 3D simulator (ProSivic[3]) was used to validate our proposed approach. This simulator is connected through diagram blocks with RTMaps, consequently the modules can be easily relinked with the real platforms (Cybercars). Additionally, the system is capable of simulating urban scenarios and most of the characteristics over different weather conditions (figure 3). Several properties of the vehicle were used, as follows: inertia, acceleration, speed, odometer sensors, among others.

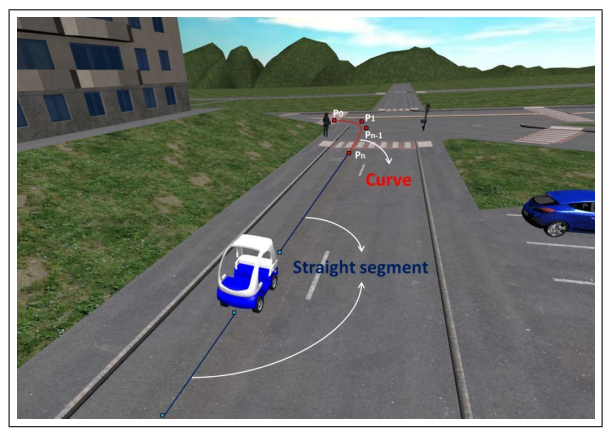


Fig. 3. ProSivic simulator

III. THE INTELLIGENT PLANNING ALGORITHM

The main aim of this work is to propose an algorithm which sets the position of Bézier control points in a dynamic and intelligent way, giving a safety path tracking for autonomous vehicles. The dimensions of the vehicle, speed limit and comfort acceleration are also considered as design parameters.

In [25] and [13] are presented two ways to set Bézier control points on typical urban road structures (roundabouts and intersections) using some analytical equations to fix them. But, both methods were adjusted manually. In this sense, an algorithm that is able to do this automatically represents an evolution of the previous works.

[3]www.civitec.com

The algorithm is described as follows:

1: **Start**
2: **Read** algorithm properties
3: **Obtain** geometrical data of the route
4: **while** it is not complete the segmentation process **do**
5: **Make** Bézier control points segmentation
6: **if** Maximum k is $\leq$ maximum vehicle k **then**
7: **Assign** weight to max. k
8: **Assign** weight to $max\,\{k_{start}, k_{end}\}$
9: **Save** control points and weight of curvatures
10: **end if**
11: **end while**
12: **Select** best option
13: **End**

Where k is curvature of the path, and the weight is the position of the Bezier control points. In the second line, the algorithm obtains the properties used in the segmentation process (line 4 - 11) of the pseudocode, some of them are: the width of the road (in our case is $3.7m$), maximum distance for the points P_0 and P_n in referenced to middle of the intersection (in our case $15m$) and number of divisions for the segmentation. Line 3 treats the geometrical problem for the coming intersection (the roundabout is a particular case). This work was carried out with the aim of obtaining the interest points which are going to be used in the segmentation process (next sections).

A. Segmentation process in intersections

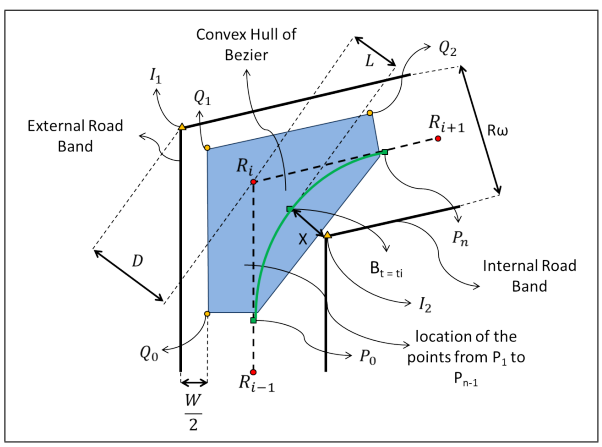


Fig. 4. Solution for the intersections

Based on figure 4, using three points and the road width a description of the intersection can be performed. In this sense, a geometrical approach considering the joining of straight and curved segments was carried out. Moreover, it is necessary to set some conditions to keep the vehicle on the road while it is tracking the path. The algorithm proposed will set these conditions in the generation of the Bezier control points as follow:

- If the points Q_0, Q_1 and Q_2 describe the separation against the external band of the road and the Bezier control points are limited by the polygon built with them, then the Cybercar will not exceed the external band.
- If distance x, which form the Bézier point over the I_1I_2 axis and the point I_2, is bigger than the half of the vehicle width, then they are possible control points; otherwise they are discarded.
- The maximum curvature in all Bézier curve must be less than the maximum curvature, defined in equation 3.

The algorithm sets the points P_1 to P_{n-1} into the dark area (Convex Hull) shown in figure 4 and the points P_0 and P_n are going to be set over the last and first straight before and after the intersection, respectively (based on the first property of Bézier's curves). W is the Width of vehicle.

The locations of these points are described by the equations:

$$P_0 = R_i + L_0 \frac{R_{i-1} - R_i}{\|R_{i-1} - R_i\|} \tag{5}$$

$$P_n = R_i + L_n \frac{R_{i+1} - R_i}{\|R_{i+1} - R_i\|} \tag{6}$$

where L_0 and L_n are the separation distance between P_0 and R_i and between P_n and R_i respectively.

The exit of the roundabout is managed as an entrance, using symmetric conditions. And the middle segment of the roundabout is generated by parametric circle equations as in [26].

To conclude, the algorithm makes a selection process based on weight assignment criteria of the maximum curvature. It considers the whole curve and the differences between the curvature at the start and the end in comparison to the map in these points.

IV. Experiments

This work has been validated in simulation. The modules were programmed in RTMaps, and linked to Pro-Sivic Simulator, which provides urban environments, perception information and vehicle dynamics behavior [27].

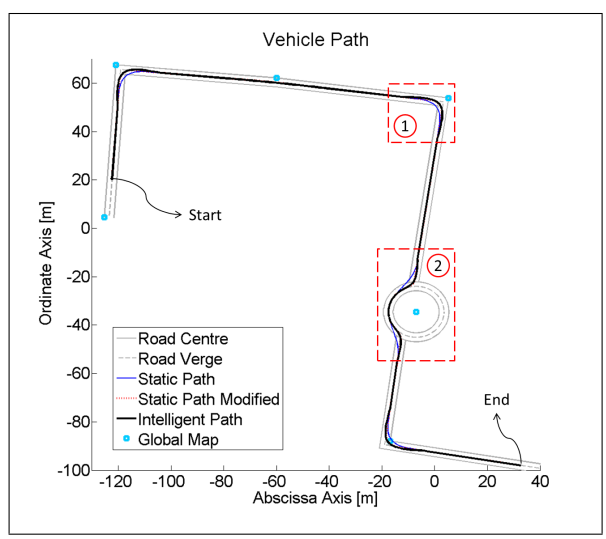


Fig. 5. Generated path

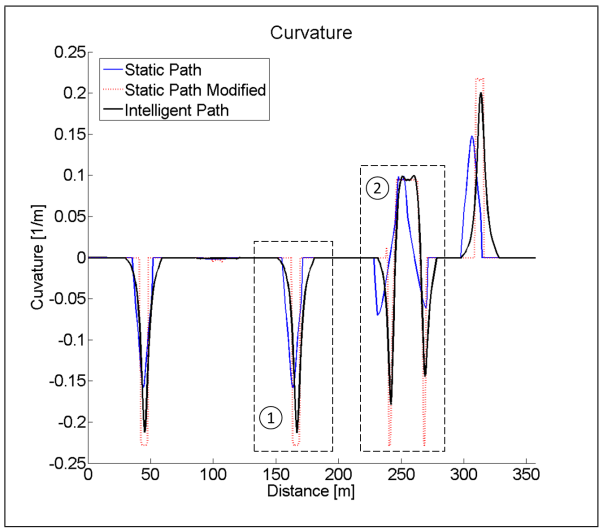


Fig. 6. Route's curvature

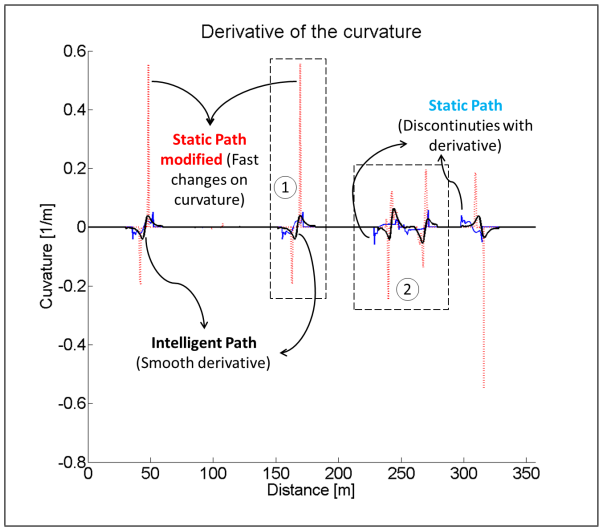
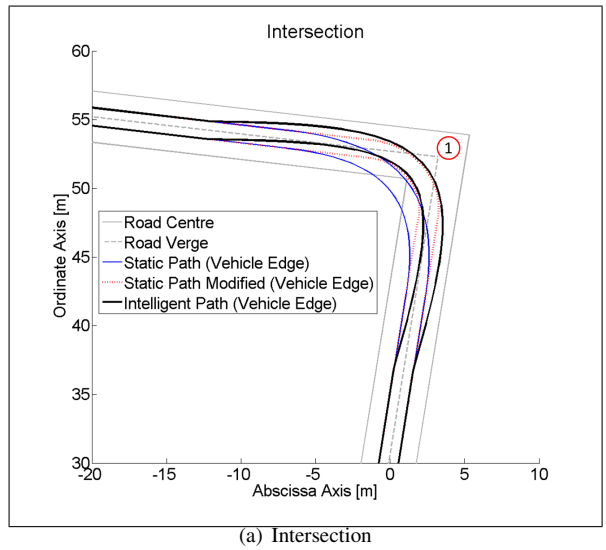
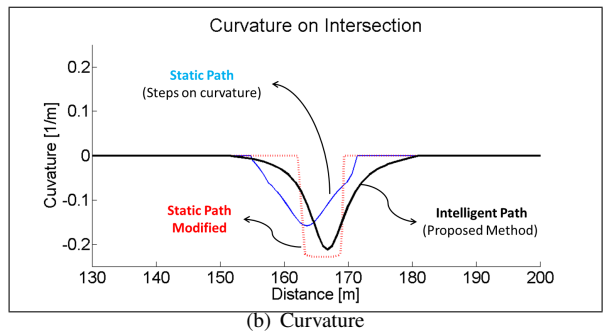


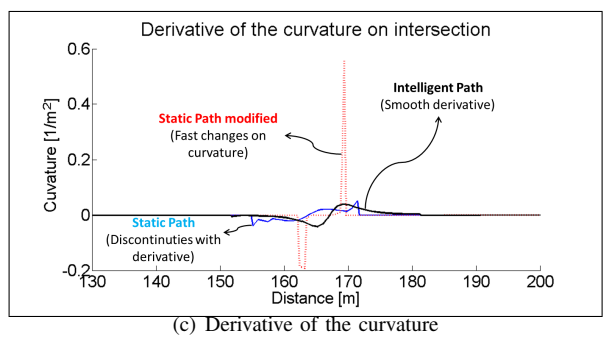
Fig. 7. Derivative of route's curvature



(a) Intersection



(b) Curvature



(c) Derivative of the curvature

Fig. 8. Zoom over the intersection

The experiments present several urban intersections. Figure 5 shows the whole generated path with three intersections and a roundabout, using the global map as was described in [13]. A comparison with three methods was drawn. The first one (thin line) is based on the static method used in [13], which sets the control points by hand. In this case we can see how sometimes the path passes over the sidewalk.

The second experiment (dotted line) is using the same previous method, but modifying the distance used to position the control points, to obtain a path into the road. This consideration makes that curvature increase significantly, as we see in figure 6.

The thick line shows the method proposed in this work. As we can see in the figure, the automatic algorithm sets the control points of Bezier (based on the convex hull property) achieving a smooth path, without going over sidewalks or obstacles.

V. Results validation

Figure 7 shows the derivative of the curvature per each experiment. Although the first experiment (static path) shows fewer changes, these are abrupt. The handmade adaptation of this algorithm shows an overshoot in the curvature (more pronounced in this derivate), this means higher acceleration and discomfort in the driving process. The proposed algorithm shows a better behavior in the changes of the curvature, as we can verify in the intersections (thick line on figure 7).

Figure 8 shows the result over an intersection. This figure shows that the behavior of the proposed method is better than the others, mainly by the following reasons:

- The method achieves an automatic method to obtain a path, which keeps the vehicle into the lane (setting the control points of Bézier).

- The curvature smoother than previous works. Figure 8(c) shows the curvature using the second method, which produces a fast changes on the curvature (slopes of big magnitude in the derivative). Moreover in the first method, the derivative has some discontinuities points, which can be translated into sudden lateral deviation.
- Finally, this method is the only one of the three methods proposed which is capable of keeping the car in the lane, has a smooth curvature and soft changes on its derivative.

VI. Conclusions

In this work, a new control architecture for cybernetic cars was presented in terms of urban scenarios. The main contribution is an Intelligent Trajectory Generator, which achieves a real time path generation engaging to the specific characteristics of the vehicle and of each intersection.

A safety planning algorithm is the first contribution of this work. The second goal was to generate a smoother route, compared to previous methods, with softer changes on the derivative, and improving the comfort of the vehicle's passengers. The longitudinal speed was adapted to keep the comfort acceleration in all the experiments.

This new method can also be employed to resolve optimal path planning in an efficient manner, to avoid dynamic obstacles. In future works, experiments with real platforms (Cybercars) are considered, in order to validate the model including the proposed method in real urban scenarios.

Acknowledgment

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