Overtaking maneuver for automated driving using virtual enviroments

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Abstract. Among the driving possible scenarios in highways, the overtaking maneuver is one of the most challenging. Its high complexity along with the interest in automated cooperative vehicles make this maneuver one of the most studied topics on the field on last years. It involves a great interaction between both longitudinal (throttle and brake) and lateral (steering) actuators. This work presents a three phases overtaking path planning using Bézier curves, with special interest in the continuity of the curvature. Communication among the vehicles is also considered. Finally, the maneuver will be validated using *Dynacar*, a dynamic model vehicle simulator.

1 Introduction

With the evolution of the Intelligent Transportation Systems (ITS) in the last decade, a great variety of ADAS systems have been tested with successful deployment in commercial vehicles; some examples of these are: lane departure warning and assistance, automatic parking, blind spot monitoring, among others. Most of them are based on on-board sensors such as radars, LiDAR, cameras, ultrasonic sensors and communication V2X.

Great variety of tests related with automated driving have been performed on highways. However, planning constrains and control techniques have not been implemented in an extensive way [1]. One of the biggest and most interesting scenario on highways is the overtaking maneuver. This is defined by a series of constrains and conditions given by the perception systems (detection of the environment and obstacles), and the control stage (speed considerations and communication with nearby vehicles).

The control architecture used in this work was based on [2], with special approach in the behavioral planner, as part of the decision block, which is going to take responsability for the lane change maneuver on highways. We are considering the information obtained from the sensors as frontal LiDAR and cameras to detect obstacles on the road, and communication with other vehicles in a cooperative way.

Three possible stages were established to validate the maneuver. The first is the generation of a parametric (continuous) curve to change the lane, considering the possibilities that a vehicle could come on the opposite way, and the total time to recreate the maneuver. The second stage is to overtake the other vehicle in the opposite lane (adding a secure distance in front of the overtaken vehicle) and the third stage is the return of the vehicle to the lane.

The implementation of these algorithms and the control architecture was performed on MATLAB/Simulink, along with *Dynacar*, a dynamic model vehicle simulator [4].

2 Control architecture and decision module

The architecture used in this work is based on [4]. It is a 6-block generalization to define an automated vehicle control structure; it has been firstly presented in [5]. To accomplish the goals of the current work, two critical blocks are considered: decision and communication.

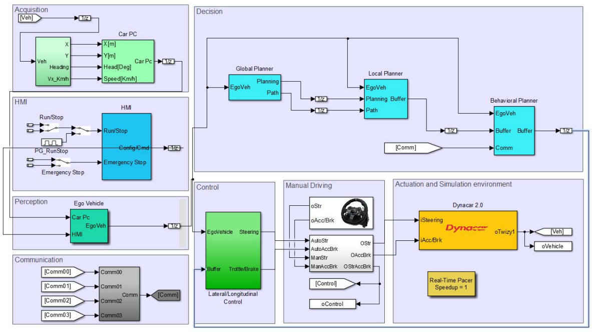

Fig. 1. Control architecture in detail with obstacle avoidance.

The acquisition module gather information from the different on-board sensors on the real platform and on the simulator, as well as, the information from the low level CAN (Ego-vehicle information).

The perception stage considers all the information collected from the acquisition block, and, with the use of different techniques and algorithms, it defines the environment surrounding the vehicle.

Communication stage is relevant for the purposes of this work, because it collects the information coming from other vehicles involved in the maneuver (V2X capabilities). Without this module, the difficulty to accomplish the lane-change maneuver safely, increases.

The control refers to the steering or lateral control and the throttle/brake or longitudinal control. It allows the vehicle to correctly track the trajectory and keep the desire speed.

Actuation is conformed by the actuators of the real and simulated platform; those are: throttle, brake and steering wheel. This block considers the low level control of the actuators.

The decision module has the objective to generate the trajectories that the vehicle has to follow. To accomplish this goal, the global planner reads a basic trajectory file (the assignment of going from point A to point B) that are basic points, for instance, the intersections and roundabouts of the route. After this, a first approach to a single route is done, and then sent to the local planner. It improves the trajectory softness (hard changes in the curvature) using different types of curves, such as Bézier [11]. The behavioral planner is related to the dynamic conditions of the route and how to face them. Some of the maneuvers considered are lane change, obstacle avoidance and overtaking; the latter will be studied in this work.

3 Overtaking maneuver planning

This work presents a three phases overtaking path planning, using two 5th order S-Shaped Bézier curves and one straight line. This curve is of special interest due to its capacity to joint with $G2$ continuity [12] with straight segments, both at the beginning and the end of the curve. The design of the path will be presented and the maneuver will be explained taking into account another vehicle in the opposite way. The necessary conditions to make the route free of collisions will be given.

3.1 The path

In real driving it is common to follow a S-Shaped path in order to make a lane change. Previous works have emulated this behavior using graph search algorithms, as shown in [8]. Other techniques have been presented in [10] where static curves such as sigmoid functions are used to create the S-path. This work use Bézier curves to create a smooth curve to make the transition between lanes.

Parametric Bézier curve: Given $n+1$ points in the space, $P_0, P_1, ..., P_n$, a Bézier curve is defined as a combination of these points with the Bernstein Polynomials. Equation 1 shows the general representation of the degree-n Bézier curve [11]. The $P_i's$ are called the control points of $B(t)$, and the parametric curve will lie within their convex hull.

$$B(t) = \sum_{i=0}^{n} \binom{n}{i} t^i (1-t)^{n-i} P_i \tag{1}$$

In [9] paths for overtaking are designed aiming for $G2$ (curvature) continuity, due to its importance in the reduction of lateral accelerations and improving comfort. With this in mind, the present work shows the design of a S-shaped continuous-curvature path using Bézier curves.

Designing the path: Due to Bézier curves properties [9] it is possible to build a S-shaped route, placing the control points in specific positions: $\overrightarrow{P_0P_1}$ must be parallel to the road and placed in the right lane and $\overrightarrow{P_{n-1}P_n}$ parallel to the road and placed in the left lane. This configuration allows a minimum of four control points. Taking into account the curvature in the search of smoothness, it is important to joint the Bézier curve with $G2$ continuity with a straight line, resulting in curvature 0 at both the beginning and the end of the path. Curvature for parametric curve is defined in Equation 2.

$$k(t) = \frac{\left\| \overrightarrow{B'(t)} \times \overrightarrow{B''(t)} \right\|}{\left\| \overrightarrow{B'(t)} \right\|^3} = \frac{\left\| \overrightarrow{B''(t)} \right\| sin(\alpha(t))}{\left\| \overrightarrow{B'(t)} \right\|^2} \tag{2}$$

Where $t \in \mathcal{R}$ such that $0 \leqslant t \leqslant 1$, and $\alpha(t)$ is the angle between vectors $\overrightarrow{B'(t)}$ and $\overrightarrow{B''(t)}$. The intention is to find the proper conditions where $k(0) = k(1) = 0$. Using equations 1 and 2 the following results are obtained:

$$\overrightarrow{B'(0)} = n(P_1 - P_0) = n\overrightarrow{P_0P_1} \tag{3}$$

$$\overrightarrow{B''(0)} = n(n-1)(P_2 - 2P_1 + P_0) = n(n-1)(\overrightarrow{P_0P_1} - \overrightarrow{P_1P_2}) \tag{4}$$

From 2, 3 and 4, $k(0) = 0 \Leftrightarrow \alpha(0) = 0$ or $\overrightarrow{B''(0)} = 0$. This condition is met when P_0, P_1 and P_2 are collinear. By symmetry $k(1) = 0$ if P_{n-2}, P_{n-1} and P_n are collinear as well. Thus, the minimum number of point to achieve a S-shaped Bézier curve with $G2$ continuity with straight lines is six.

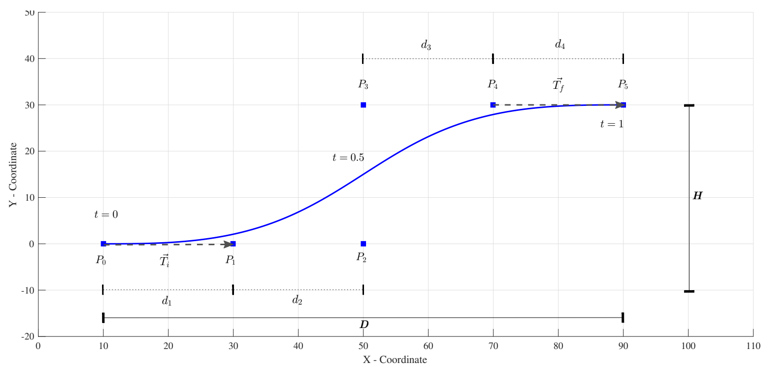

Fig. 2. 5th Order S-Shaped Bezier Curve.

Quintic Bézier Curve: The representation of the 5th order Bézier curve is shown in Figure 2. It is a degree-5 polynomial with a S-shape graph as previously deduced. To find the corresponding control points the following formulas are given:

$$
\begin{aligned}
P_0 &= (x_i, y_i) & P_5 &= P_0 + D\vec{p} + H\vec{q} \\
P_1 &= P_0 + d_1\vec{p} & P_4 &= P_5 - d_4\vec{p} \\
P_2 &= P_1 + d_2\vec{p} & P_3 &= P_4 - d_3\vec{p}
\end{aligned} \tag{5}
$$

Where (x_i, y_i) is the position of the vehicle previous to the overtaking maneuver, $\vec{p}$ is the unit vector in the direction of the road, $\vec{q}$ is the unit vector that is orthogonal to $\vec{p}$, D is the distance between the vehicle and the obstacle, H is the height of the lane change; in general it is equal to the length of the lane. The lengths $d1$, $d2$, $d3$ and $d4$ are design parameters that change features of the curve; specially the curvature is of great interest.

3.2 The Maneuver

This section presents a three phase overtaking maneuver, composed by a lane change, an overtaking and a lane return. This is the normal behavior when avoiding slower cars in highways. The maneuver considers the joint of two Quintic Bézier curves and a straight line. Figure 3 shows the complete scenario with one vehicle as obstacle and a second vehicle in the opposite direction in the left lane.

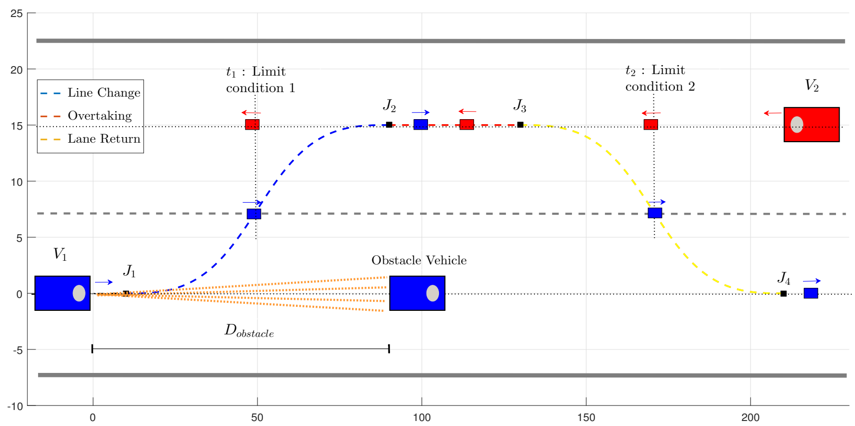

Fig. 3. Overtaking Maneuver

Lane Change: The first phase is to avoid the obstacle in the road by making a lane change. The path to follow will be a Quintic Bézier curve. The design parameters are the width of the lane H and the critical obstacle distance D_{min} that is the minimum distance to the obstacle to make a safe lane change. This distance is directly proportional to the velocity of the vehicle. [7] define an approximate quadratic function to relate D_{min} and the velocity v . In this case, the LiDAR is responsible for detecting the obstacle.

Overtaking: The overtaking takes place after the lane change, passing the obstacle by the other lane. This phase is specially useful when the obstacle is moving at a constant speed.

Lane Change (Return): When the obstacle has been left behind the vehicle can return to the right lane to continue with the original trajectory. This is done with other Quintic Bézier curve. In order to perform the maneuver without collide with vehicles driving in the opposite direction, it is assumed that exists $V2V$ (Vehicle to Vehicle) communication and its positions are well known. In this case, according to Figure 3 two critic conditions must be evaluated in $t = t_1$ and $t = t_2$. If after a prediction in time both conditions are hold then the overtaking can take place. In the other case the autonomated vehicle needs to stop until the vehicle in manual mode is no longer a threat.

4 Results and validation

The simulated scenario was made on Dynacar Simulator and it is composed by one obstacle and two vehicles driving in parallel lanes in opposite direction. The first vehicle $V1$ is driving in automated mode and is able to change the trajectory and take decisions, while $V2$ runs in manual driving. The maneuver consists of $V1$ overtaking an obstacle considering two possible cases:

4.1 Case 1: Overtake without stop

This case presents the scenario where the vehicle avoids the obstacle via the overtaking maneuver without stop, after predicting no collision in future states with the overcoming vehicle in the other lane. Figures 4 shows the sequence of the maneuver in the simulator.

4.2 Case 2: Overtake with stop

Other scenario is presented, where the conditions does not allow an overtaking without collision. In this case, the vehicle in automated mode must be in charge of delaying the overtaking until the vehicle in manual mode is no longer a threat.

Figure 5 illustrate this scenario. It can be noticed that after 7 seconds the automated vehicle starts decreasing the velocity until it stops. It waits for the

Fig. 4. Overtaking without stop

other vehicle to pass and when the path is safe it activate the overtaking maneuver following the two Quintic Bézier curves previously designed. It can be noticed that $t_1 \neq t_2$, showing that both X and Y coordinate does not coincide at the same time, demonstrating a non-collision maneuver.

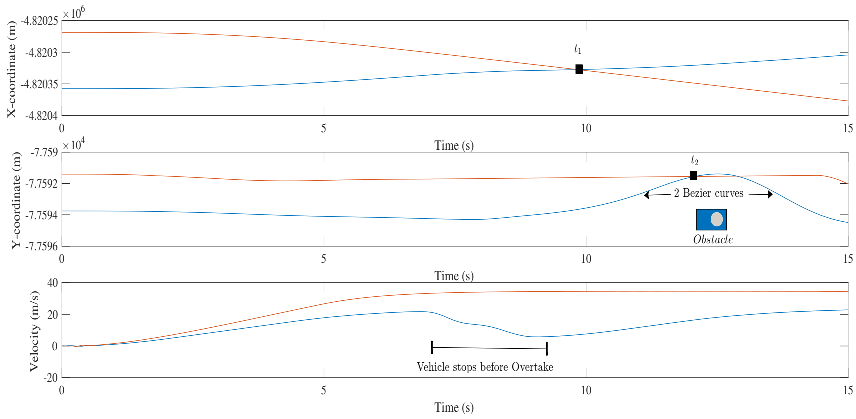

Fig. 5. Overtaking Simulation with Stop

5 Conclusions and Future Works

In this work, a three phases overtaking maneuver was presented. The path was designed with two S-shaped curves and one straight line, following the common behavior of drivers when overtaking vehicles in highways. The S-shape part was designed with a Quintic Bézier curve, because of its low computational cost and its property of zero curvature at the beggining and end of the curve.

The overtaking was implemented in simulation showing successful results after running two different scenarios without collision. The automated vehicle is capable of both overtaking with and without stop.

As future work, the proposed curve will be designed with additional parameters, such as the time to collision and the kinematics of the vehicle. Non-static obstacles such as vehicles with constant speed will be considered in the near future.

Speed profiles will be taken into account along with a deeper curvature analysis in order to look for comfort when performing an overtaking with higher velocities.

In addition, simulation implementation needs to be tested in a real vehicle, on highways and urban scenarios.

6 Acknowledgment

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