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Controller Design for Autonomous Vehicle

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Abstract: — **Control system is a vital part of an autonomous vehicle. It is responsible for passenger's safety and better navigation on roads. In this paper, a control system design is discussed, along with lateral and longitudinal control for the autonomous vehicle. A speed profile generator is used for calculating the speed for better stability of the vehicle. Through the paper, implementation of a PID controller with Stanley control is discussed. Mathematical modeling is performed for the controller to analyze the effect of external factors on the vehicle and the proposed system is later coded in python language and later tested through simulation on CARLA simulator and results are discussed**

Keywords: Autonomous Vehicle, Simulation, PID Controller, Stanley Controller, Modeling and Simulation

I. Introduction

Autonomous vehicles are considered as the future of the automobile sector because of their increasing demands due to increasing vehicle density on roads. The infrastructure is lagging in accommodating increasing vehicles on roads; thus, vehicles are more prone to accidents. According to government data, about 94% of all crashes happen due to driver's behavior and autonomous vehicles can help in eliminating these behavior errors of drivers. In comparison with traditional vehicles, autonomous vehicles are much safer and risk-free. Many innovations and developments have been made in the last few decades to improve the design and systems of vehicles.

Autonomous vehicles integrate planning modules with external environment perceptions [1], [2]. According to the requirements of the planning module, the driving module of automatic vehicles manipulates the actuators, and parameters like speed and trajectory of vehicles are monitored. The control system of autonomous vehicles is responsible for the safe and stable movement of vehicles. This control system includes both lateral and longitudinal controllers. A longitudinal controller regulates velocity and a lateral controller manipulates the steering angle of the wheel.

Over a while, many changes have been done in control system design. In beginning, both lateral and longitudinal controllers were designed independently and implemented by zero-pole placement [3]. Hedrick [4] used Linear Quadratic control for implementing lateral control system, sliding mode in the implementation of the longitudinal controller. Similarly, Hingwe [5] used it for implementing lateral control. Later, in the autopia program, a control system was implemented using fuzzy-logic [6]. Similarly, a coupled lateral and longitudinal controller was implemented for better stability of vehicles [7] by Rachid and Rodolfo. During, VisLab Autonomous Challenge [8], a path planner was designed and tested by Broggi and Medici. Katriniok[9], the proposed implementation of a model-based control system for lateral and longitudinal guidance.

Through this paper, a representation of the design for the controller system by integrating both lateral and longitudinal controllers is carried out. The longitudinal control module is responsible for maintaining the speed profile of the vehicle; the lateral control module combines Stanley control and feedback proportional control to improve the path tracking efficiency of vehicles at different speeds and different terrains. For designing trajectory control, a bicycle module is implemented, concept similar to Gillespie [10], who implemented a bicycle model for tracking controller for pneumatic tires with linear states. Similarly, Byrne [11], used a PID controller for GMC Jimmy using a linear system. In the paper, longitudinal control is implemented using a PID controller. Khaled [12] presented a PID controller using feed-forward control and explained the mathematical modeling of the system. It is one of the important and simple control techniques for system design. For the lateral control module, the Stanley controller is implemented. Through their paper, Rajamani [13] discussed the lateral dynamics of an autonomous vehicle. J. Yang [14] implemented a lateral controller using fuzzy logic, similarly sliding mode control is implemented for the lateral system [15], [16]. The aim is to implement Stanley control for a lateral controller. The designed model is implemented using the python language and simulated on CARLA [15] simulator by connecting using socket.io file. The results are included in the paper as well.

The paper discusses is organized as follows: implementation of the bicycle model for system modeling is discussed in section II followed by an explanation of vehicle modeling, where section *A.* discusses about longitudinal control system and section *B.* explains lateral control system. System design and implementation are discussed in section III, sections IV explains the results and VII discusses the conclusion.

II. VEHICLE MODELLING

Longitudinal controller

The work of a longitudinal control system is to track the desired speed predicted by the system of planning while taking care of the safe movement of the vehicle. Input is required for longitudinal control systems are position and speed. The position required for maintaining a safe distance from other vehicles at the same time keeping a check on the current speed. The desired speed is mentioned by a system of planning. The output from a longitudinal control system manages two of the actuators i.e., brake and throttle. They regulate the vehicle's speed and maintain a safe distance from other vehicles.

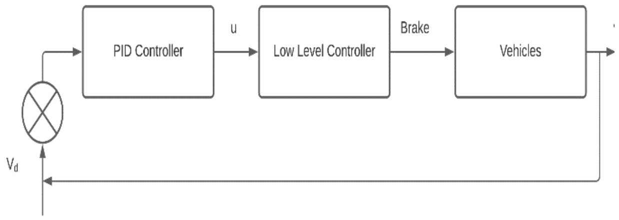

Fig. 1. Block Diagram of Longitudinal Control System

Fig.1 describes the proposed structure and components of the longitudinal control system. The output from the system is the throttle and brake commands. The longitudinal control system is a combination of an upper-level controller and a low-level controller. The upper-level controller builds a feedback controller for the speed tracking problem. In this paper, the PID controller is implemented for the upper-level controller to generate acceleration commands. These acceleration commands act as input for the low-level controller to define brake and throttle inputs for improvement of tracking of the vehicle. One signal from the system manipulates both throttle and brake. For the project, the low-level controller is excluded, as the desired speeds are low and steady. The control system follows an override controller system and combines separate space and speed sub-controllers. Speed sub-controller is mainly used and space sub-controller is deployed when change in trajectory is needed due to obstacle on a planned trajectory. In this paper, the speed sub-controller is discussed. Vehicle control systems have complicated non-linear relations and functions that include speed, throttle and other factors. Proportional Integral Derivative (PID) controller is implemented for control system. In time *to* domain, the PID controller can be expressed as

$$u(t) = K_P\, e(t) + K_I \int_0^t e(t)dt + K_D \frac{e(t)}{dt} \qquad (1)$$

where k_P, k_I and k_D are representations of proportional, integral and derivatives gain in time domain *t*. PID controller *u*(*t*), acts as an input to the plant model. The upper-level controller determines the desired acceleration from the vehicle based on its position, reference and actual velocity. Desired acceleration x_{des} in PID controller can be expressed as,

$$\ddot{x}_{des} = K_P\left(\dot{x}_{ref} - x\right) + K_I \int_0^t \left(\dot{x}_{ref} - x\right)dt + K_D \frac{d\left(\dot{x}_{ref} - x\right)}{dt} \qquad (2)$$

The plant system can be linear or non-linear depending on functionalities. It deals with state space and transfer functions. Linear time variant systems can be expressed by transfer function. Transfer function *(G)* is a relation between input *U* and output *Y*.

$$Y(s) = G(s)U(s) \qquad (3)$$

$$s = \sigma + j\omega \qquad (4)$$

Transfer function, is expressed in Laplace domain, as a function of *S*, a complex variable. Main reason to use Laplace transform is that, it makes it easier to determine transform function of plant system. Laplace transform provides a better and useful insight in understanding control performance. Applying Laplace transform of PID control generates:

$$U(s) = G_C\,(s)E(s)$$

$$= \frac{(K_D\, s^2 + K_p\, s + K_I\,)}{s} E(s) \qquad (5)$$

It helps in generating a single transfer function for PID controller. Interaction of these effects with adjustment is needed to get right closed loop performance. By trial-and-error method, values of k_P, k_I and k_D as 0.2, 0.05 and 0.01 are found to provide better result than other values tested.

Lateral Controller

Planning system generates the desired trajectory by using lateral controller. Orientation errors, cross track errors and their derivatives (calculated by pose and position of vehicles from planning module and perception module), are used by lateral controller as inputs. Output generated by lateral controller controls the steering actuators. For better analysis of vehicle dynamic, lateral characteristics of vehicles are analyzed by implementing it using a bicycle model.

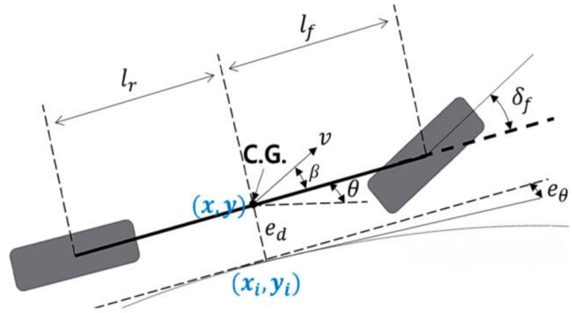

Fig. 2. Bicycle Model of Vehicle

Bicycle model is implemented with certain assumptions. These assumptions are:

- The vehicle is a rigid body and suspension dynamics are ignored.
- Dynamics between front and steering wheels are neglected and steering system is considered as fixed gain.
- Wheels of each axle are assumed as one in centerline of the vehicle.
- Movement of vehicle is considered to be on a flat road and force analysis in vertical direction is neglected.
- The vehicle uses the center of front axle as reference point.
- The model considers both error in heading and error in position relative to closest point on the path.

For the lateral control system, a geometric controller, Stanley is implemented. It is a simple and effective steering control law used by Stanford University's DARPA grand challenge team. It is represented as:

$$\delta(t) = e_2(t) + \tan^{-1}\frac{\mathrm{K}e_1(t)}{\mathrm{v_f}(t)}, \delta(t)\epsilon[\delta_{min}, \delta_{max}] \quad (6)$$

In the law, $e_1(t)$ represents cross-track error, $e_2(t)$ represents orientation error, and k represents gain parameter. Grain parameter determines convergence rate. Cross-track error is distance from center of front axle to closest point on path. For large positive change in cross-track, it is represented by:

$$\frac{\mathrm{K}e(t)}{\mathrm{V_f}(t)} \approx \frac{\pi}{2} \rightarrow \delta(t) \approx \omega(t) + \frac{\pi}{2} \quad (7)$$

Heading error is component of velocity which is perpendicular to trajectory divided by ICR radius (fig. 2). Desired heading error is zero. In Stanley control law, for large heading error, the steering wheel is moved in opposite direction. Larger the heading error, larger would be the steering angle. Since, the it is a non-linear feedback control law, it generates good results for low speeds (< $10\mathrm{ms}^{-1}$).

The error dynamics for vehicles are taken into the consideration. Error dynamics for model, when it is not at maximum steering angle is represented by (9) and for small cross-track errors, it can lead to exponential decay characteristics. It is represented by (10).

$$\dot{e}(t) = -\mathrm{v_f}(t)\sin(\omega(t) - \delta(t)) \quad (8)$$

$$e(t) \approx -ke(t) \quad (9)$$

The Stanley control law neglects dynamics like noisy measurements, tire force effects, mass etc. For adjusting these dynamics, certain adjustments are made in the control system. During low-speed operation, inverse speed causes numerical instability. To overcome it, softening constant K_s is added to the controller (11).

$$\delta(t) = e_2(t) + \tan^{-1}\frac{ke_1(t)}{k_s + \mathrm{v_f}(t)} \quad (10)$$

To cope up with dynamics in high speed, dynamic controllers like sliding mode control or MPC control can be used.

III. System Design And Implementation

The autonomous vehicle consists of three modules, environment perception, planning, and autonomous driving vehicle. Radar, Lidar, cameras, and GPS are major sensors presumed to be employed in the vehicle. Environment perception processes input from different sensors and generates traffic environment symbols for other modules, i.e., planning and autonomous driving vehicle. The planning module is responsible for path planning, predicting trajectory, and behavior decisions. The autonomous driving vehicle module controls the vehicles by following the commands generated by the planning module. The driving module converts the predicted trajectory into the lateral and longitudinal controller and operates the actuators like the throttle, steering, brake etc.

The hardware and software requirement for implementation of vehicle can be done with the help of simulation software. For implementation of the proposed control system of the vehicle, the vehicle is trained and tested on CARLA simulator. CARLA is an open-source simulator built on UE4 gaming engine, with added features including LIDAR, depth map, semantic data segmentation and options to run without display. CARLA works in the left-handed system. The simulator is easy to use and implement.

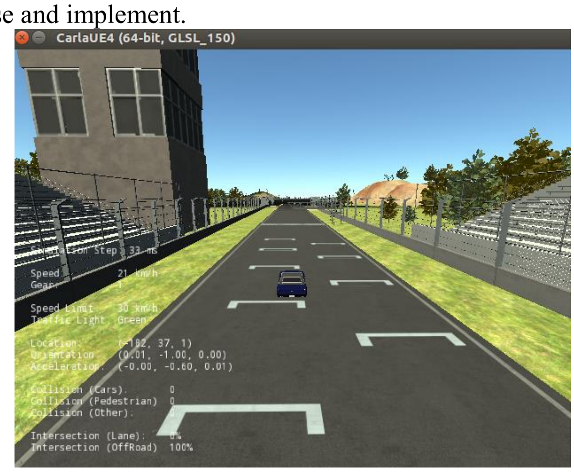

Fig. 3. Simulator Image captured during vehicle testing

For implementation of above discussed control system, the input provided by simulator includes:

- Current position in two dimensional co-ordinates
- Current velocity
- Current yaw pose angle
- List of waypoints to track accuracy of vehicle movement

The waypoints are interpolated subset of a set of waypoints provided in a text file (.txt) in simulator software, i.e., waypoints variable is an enhanced portion of entire set of waypoints that is near vehicle, and this reduces computation time and performance of controller. The desired speed is computed to be waypoint speed at closest waypoint to vehicle. All measurements from simulator were recorded with respect to the center position of vehicle. The output provided by the system in simulator includes:

- The engine throttle (decimal value between 0 & 1)
- Steering angle (-1.22 radian to 1.22 radian)
- Brake (decimal value between 0 and 1)

IV. Results

This section discusses about the results to discuss about the effectiveness of the controller system. To show the performance of the system, simulation results from race track simulation test has been carried out and the results of system are fast as well as efficient in tracking trajectories. The test of the control system was carried on an empty race track simulation. The track was empty and a loop of roads with differing angle of turns. During testing, with speed profile between 0 and 80 kmph, the vehicle was able to cover most of waypoints. The generated mapping of vehicle movement on waypoints is demonstrated by the graph in Fig4.

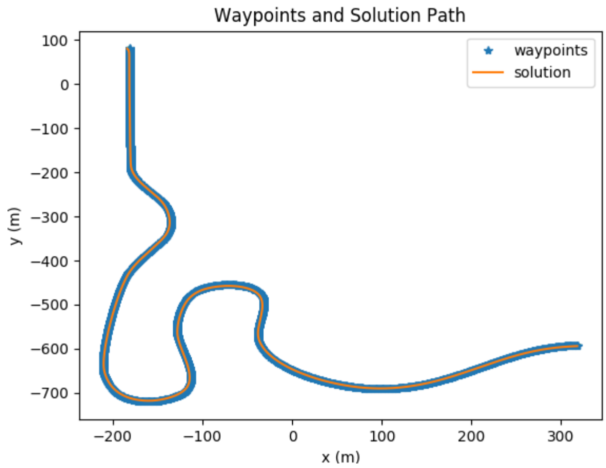

Fig. 4. Vehicle movement mapping

The controller was able to track reference speed with very little deviations. The generated speed profile graph is demonstrated in fig5. This shows the accuracy of the vehicle's control system. The vehicle was able to cover most of the waypoints without losing its accuracy on speed profile.

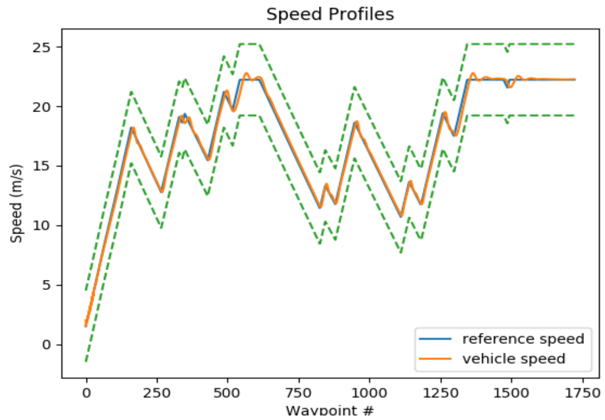

Fig. 5. Reference speed and vehicle's speed during Simulation

In addition to simulation results, the output for steering angle and throttle were recorded during testing of the vehicle on the tracks. The graphs are demonstrated in Fig.6a and Fig.6b:

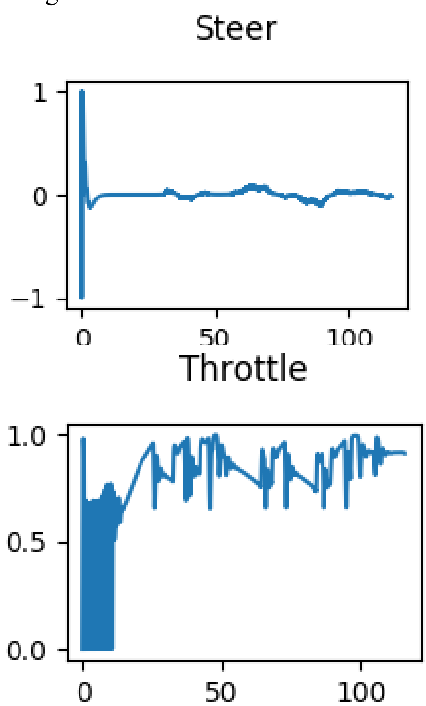

Fig. 6(a). Steering output generated from controller, (b) Throttle output generated from controller.

V. Conclusion

Through this paper, a system design for control system was proposed for autonomous vehicles. For control system, longitudinal control system was based on PID controller and for lateral control, Stanley controller was implemented. Longitudinal controller is responsible for regulating cruise velocity and lateral controllers responsible for trajectory tracking. The proposed system was implemented on CARLA simulator for autonomous vehicles.

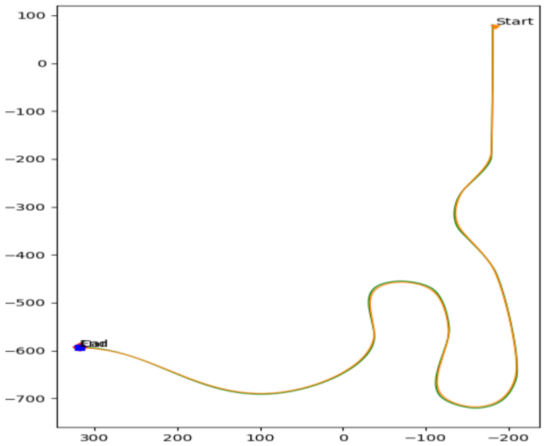

Fig. 7. Mapping of vehicle movement and prescribed path

The performance of system on the simulator was tested and performance was discussed in the paper. The mapping of movement of vehicle on track and prescribed path is shown in fig7. The overlapping of both path shows the accurate movement of the vehicle. The system is accurate and covered most of the waypoints on the track with a low speed. The system requires less computational power, simpler as compared to other control systems discussed in the paper.

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