A Universal Control System for Self-Driving Car Towards Urban Challenges

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***Abstract*—This paper focuses on the design of an efficient hierarchical control system for a self-driving car in order to navigate safely in the urban environment. The proposed technique is composed of motion planning, local path planner, and control. Firstly, the decision making is designed by applying two-stages finite state machine (FSM) which manipulates the mission planning and control states on the road. Then, the local path planner is conducted to generate a safe and comfortable trajectory. Moreover, an optimization problem with nonlinear constraints is defined and solved to optimize the jerk. Besides, we perform a real-time hybrid A* algorithm based on a probabilistic occupancy grid map to avoid obstacles. Finally, controllers are designed by using the adaptive-purse pursuit controller for lateral control and the scheduled feed-forward PID controller for longitudinal direction. The experimental results show that our algorithms can work efficiently in a practical scenario.**

***Index Terms*—autonomous vehicle, motion planning, local path planning, control system**

I. Introduction

Self Driving Cars (SDCs) are an outstanding solution for transportation to prevent collisions, frustrating circumstances, and reduce energy consumption. Although SDRs have breakthroughs in their trial stages, the administration still hesitant to bring them to society due to the safety concerned and robustness operating in public traffic. By 2002, the Defense Advanced Research Projects Agency (DARPA) announced the opening of its grand challenge [1]. The challenge can be considered as the first well-known self-driving challenge, and it had been enlarged to the imagination of humans about what the autonomous robots can achieved. From that time onwards, many successful frameworks of autonomous driving in urban environments have been developed. Autoware [2], Apollo [3], NVIDIA DriveWorks [4] and openpilot [5] are the most famous open-source frameworks that can be utilized in real world application. Roughly speaking, the SDC system can be generally classified into three principal categories [6], including perception, environment mapping, motion planning and control. This paper individually focuses on handling complete parts of motion planning including decision making and local path planner. The main contributions of this paper are highlighted as follows:

1) We developed a successful hierarchical control system for a SDC platform that performs efficiently in the urban environment.
2) The decision making using two-stage FSM to deal with the tasks and control states is proposed. We define and solve an optimization problem with non-linear constraints to generate a smooth change-lanes path. Besides, a real-time Hybrid A* algorithm with an occupancy grid map is manipulated to avoid obstacles.
3) The adaptive-pure pursuit controller and the scheduled feed-forward-PI controller are implemented and performed well in the urban environment.

The remainder of this paper presents the methodology, implementation, and performance of the control system for an autonomous vehicle called Clothoids. Section II describes the study on motion planning with decision making using two-stages FSM, the local path planning, and the control strategy. Experimental results in the K-city proving ground is described in section III. Finally, part IV concludes this work.

II. Hierarchical Control System

The hierarchical control system exploits the global path planning(GPP), decision making, local path planner, and control [7]. We neglect the GPP in this section and only focuses on how to design the decision making, the local path planning, and the control.

A. Behavior planning based on two-stages FSM

The decision-making mechanism(DMM) [8] of our SDC uses finite state machines (FSM) to evaluate mission planning and control behavior on the road. The first DMM manages the missions called mission finite state machine (M-FSM) that the vehicle should complete on the road. The second DMM called the controlling finite state machine(C-FSM) that mimic the behaviors of the robot as a driver on the road. M-FSM is categorized into five classes: ready, stop-and-go (SAG), change-lane(CL), e-stop, avoid obstacle missions. In particular, M-FSM consists of a C-FSM which is used to manipulate the control states of the robot. When driving on the road, human needs to control the vehicle stop, start and reduce

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or increase speed whenever the car needs to start or stop to avoid damaging to the vehicle's engine. So, the SAG mode is designed to cover all robot's behaviors that mimic the above actions of a human. The e-stop mode is activated when the emergent situations appear. The CL mode with two control states: lane-keeping and lane-changing are called when M-FSM is demanded. The obstacle avoiding mode is operated when the obstacles have been detected lying on the path. To prevent concurrent access to the same resources, we use the priority and flags of each state to control the accession.

B. Local path planning

In general, the local path planning(LPP) is activated when the mission planning demands, as presented in the DMM subsection II-A. This section presents the trajectory generation and control system for the SDC.

1) The trajectory generation on the local Frenet coordinate: This work hypotheses a general problem in which the vehicle needs to move from the selected start position to endpoint point. Effortlessly, in real circumstances, we can consider the car needs to change the lane whenever motion planning requires. The jerk, which is derivative of acceleration, is the best way to present the comfort of the moving vehicle. Different from previous work [9], [10], we define and solve an optimization problem with nonlinear constraints to minimize the sum of the square-jerk over the whole temporary trajectory for both s and d direction. The optimization problem which needs to solve T, ξ_3, ξ_4 and ξ_5 is defined as

$$\begin{aligned} &\xi_s^*, \xi_d^*, T^* = \underset{\xi_s, \xi_d, T}{\arg\min}\,(J_z(\xi, T)) \\ &= \underset{\xi_s, \xi_d, T}{\arg\min}\left(J_s(\xi_{0:5}^s, T) + J_d(\xi_{0:5}^d, T)\right), \\ &s.t. \\ &F(.) = 0 \end{aligned} \tag{1}$$

where $F(.)$ is nonlinear constraint equations, T is travel time and $\xi_{3,4,5}$ are coefficients of jerk equations. The final step is to establish the quintic function of s and d, and regenerate the trajectory to the control. In order to reduce the computational cost, the most effective way is to use a lookup table determined by the offline optimization solving process.

2) Obstacle avoidance based on hybrid A algorithm:* In the proposed framework, an A-star based path planning algorithm is implemented that largely follows the implementation of [11]. The algorithm upon getting activated, is provided with local occupancy grid map, goal pose, and existing pose as an input. The goal pose is decided based on global path, whereas the occupancy grid map is updated by the perception module through a sliding window approach. Unlike previous implementations, where a large static occupancy grid map is provided with a fixed goal pose at the initialization stage, a smaller region about the obstacle is used for planning. This increases the path generation rate and enables to deal with the possibility of dynamic obstacles or the false positives of perception module.

C. Vehicle control strategy

The local path planning and the decision making generate the local trajectory and the target speed, respectively. The principal strategy of our work is that it includes longitudinal and lateral control. The longitudinal controller is used to ask the vehicle follow the desired speed by acting throttle and braking while the lateral controller handles the vehicle's lane tracking by maneuvering the steering angle. The speed profile generation (SPP) is performed according to the curve-level of the trajectory. If the speed after the SPP is less than the target speed of DMM, which be used to feed into the longitude controller, otherwise decision-making speed is applied.

1) The longitudinal controller: This work uses two scheduled feed-forward PI controllers (SFF-PI) for the longitudinal control. The SFF-PI controller is need to discrete with time period T. The output of the controller at time $t = kT$ given by:

$$\begin{aligned} &\psi_{SPI}^k = \tfrac{K_{FF}}{v_0} v_{ref}^k + \tfrac{K_P(v_k)}{v_0} e_{ref}^k + \\ &\left(\tfrac{K_I(v_k)}{v_0} + K_{AW} e_{se}^k\right) T \sum_{i=0}^{k} e_{ref}^k. \end{aligned} \tag{2}$$

The authors of [12] and [13] designed unique SFF-PI controller for both acceleration and brake. Alternatively, we design two controllers which are applied for both acceleration and brake. In summary, to design the longitude controller based on the SFF-PI controller, we use the following steps
Step 1 - identifying the vehicle model.
Step 2 - designing the SFF-PI controller.
Step 3 - evaluating.

2) The lateral control based on adaptive-pure pursuit controller: The role of a lateral controller is to follow a trajectory that is generated from the local path planner. Although the pure pursuit controller (PPC) is not much precise as the state-of-the-art methods, we select the PPC due to its stabilization against disturbances [6]. The pure pursuit algorithm (PPC) [14] is widely used in self-driving cars for path tracking because of its uncomplicated implementation. In this paper, an adaptive-PCC has been implemented for path tracking control.

III. EXPERIMENTAL RESULTS

The results of the path tracking algorithm shows that it works efficiently and performs obstacle avoiding successfully in the proving ground. The lateral controller achieves robustness to deal with the disturbances such as the aerodynamic forces, the rolling resistance, and the up slopes. We visualize the results in the Fig. 1, which is recorded and presented in Rviz. The results of local path planning are illustrated in Fig. 2. In order to change lane, the vehicle should generate a path with minimal jerk described in section II-B1. Fig. 2a illustrated the lane-changing process to the right. The vehicle changes back to the left lane, as shown in Fig. 2b.

Hybrid A* results is demonstrated in Fig. 3, which shows two instances of custom-built visualizer. First instance is when perception module notices obstacle in the global path and initiates path planning module, thus occupancy grid map starts

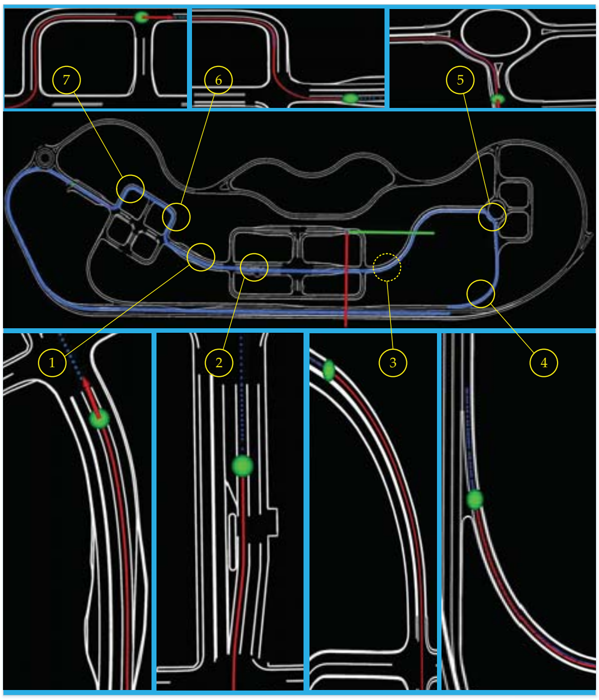

Fig. 1. Path tracking results in various paths.

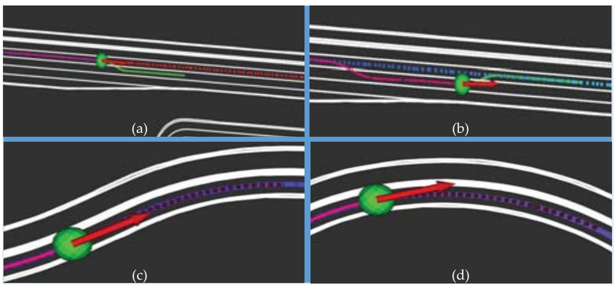

Fig. 2. Minimizing jerk and smoothing path generation in the Rviz.

to populate. Second instant is of detoured path that is being followed by vehicle.

IV. Conclusions

The problem of autonomous driving has achieved significant progress over the last 20 years. This paper addresses the analysis and design of the control system of self-driving car in urban environmental challenges. Besides, this work also presents the turning, implementation, and practicing of the control system in a proving ground. Firstly, the decision making is designed to manage the missions and control states on the path by applying the two-level of the finite state machine. Next, the local path planner implies the decision and utilizes them to produce a local pathway to the controller. In addition, the local path planning is manipulated the online

Fig. 3. (a,b) Clothoid visualizer showing obstacles and generated path; (c) Occupancy grid map with generated path by Path planner

trajectory generation problem with the minimization jerk and the hybrid A* to secure lane changing and obstacles avoiding. The controllers operate the vehicle by commanding throttle and braking to follow the local track efficiently with the longitudinal and lateral controllers. Our on-going work is designing and implementing on the autonomous vehicle for all terrain which perform efficiently and robustly in challenging urban environment.

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