DL-AMP and DBTO: An Automatic Merge Planning and Trajectory Optimization and its Application in Autonomous Driving

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Abstract— **This paper presents an automatic merge algorithm for autonomous driving vehicle, which decouples the specific motion planning problem into a Dual-Layer Automatic Merge Planning (DL-AMP) and a Descent-Based Trajectory Optimization (DBTO). This work leads to great improvements in finding the best merge opportunity, lateral and longitudinal merge control, trajectory postprocessing and driving comfort. Our algorithm's efficiency, adaptiveness and robustness have been tested and validated both in simulations and on-road tests.**

I. INTRODUCTION

In the past several decades, autonomous driving has made a great process extending the ability of autonomous vehicle from Adaptive Cruise Control (ACC) and Lane Keeping Assistance (LKA) to more complex functions such as automatic lane changing, off-road navigation, stopping at traffic light, etc. [1][2]. In merge scenarios, human can predict other vehicles' intentions and react intelligently to make the best merge choice. To deal with such scenario, prediction and planning should be well designed considering driving efficiency, safety, and comfort. Therefore, a robust and intelligent algorithm that can interact with human-operated traffic on freeways is still under research and development. There are mainly two approaches in dealing with automatic merge problem:

One category is prediction and planning coupled method which convert the prediction and planning problem into a convex optimization form, and prediction information is transferred into inequality constraints [3]. Mixed Logical Dynamics (DML) [4][5] is also applied in solving this optimization problem. [6] uses quintic polynomials in merge planning, while polynomial parameters are chosen as optimization targets. This approach usually lacks computational efficiency, and its robustness is not well guaranteed. The other category is prediction and planning decoupled method which first find the best merge opportunity, and then plan a merge maneuver. [7] uses Prediction and Cost Function Based (PCB) method to find the best merge opportunity, while this planner must run continuously throughout the whole merge process, and its acceleration and velocity outputs are discontinuous. [8] uses a rule-based planner to decide when to merge based on its fixed definition of environment safety, but it may fail when faced with complex traffic scenarios.

In terms of motion planning, there are also two major approaches: path/speed decoupled method and path/speed coupled method. In decoupled method, polynomial curvature spiral is generated, and spatial trajectory is solved by using Lagragian method [9][10][11]. Cubic polynomial is also used to generate spatial trajectory [12][13]. In the two methods, piece -wise velocity profile is then generated satisfying some road and trajectory constraints. In merge problem, path/speed decoupled methods do not work well since merge maneuver require that the vehicle reaches some position at some specific time stamp (position/time strictly coupled). In coupled method, quintic polynomials are generated longitudinally and laterally, and they are combined to generate spatial and temporal trajectories [14][15]. Such method, however, does not consider comfort and merge opportunity when deal with merge problem. Therefore, it may lead to uncomfortable lateral acceleration in lane changing, and even lead to danger if unreasonable merge opportunity is selected.

In trajectory postprocessing, gradient descent method is used in [16] to optimize trajectory curvature, but it fails to do collision checking after smoothing. A Dual-Loop Iterative Anchoring Path Smoothing (DL-IAPS) is used to smooth trajectory generated by hybrid A* algorithm, by converting the smoothing problem into a convex optimization problem. The algorithm has an average running time about 0.18s- 0.21s [17]. However, in merge problem, where vehicles usually move at high speed, optimization-based algorithm may degrade system instantaneity.

In this paper, we propose a novel path/speed coupled method for automatic merge planning. More specifically, we decoupled the method into two hierarchical steps, including, Dual-Layer Automatic Merge Planning (DL-AMP) and a Descent-Based Trajectory Optimization (DBTO). Our method addresses above mentioned issues with the following advantages:

1) **The Best Merge Opportunity**: In our DL-AMP, the first layer is a prediction and cost function-based algorithm which can find the best merge opportunity. The difference between our method and that in [18] are: 1) our method is only used in find the best merge opportunity, when the autonomous vehicle begins to merge, the second layer algorithm will be trigger. Therefore, the output continuity is guaranteed by the second layer algorithm. Meanwhile, since the task is much easier for the first layer algorithm, it has less cost function parameters to tune. In our method, candidate ego vehicle acceleration and time are sampled in some ranges. Based on the sampled acceleration and time, constant acceleration prediction model is used to predict the relative distance and velocity between ego vehicle and other traffics. Cost function that emphasis driving efficiency and comfort is designed, and the maneuver that satisfies safety hard constraints with the minimum cost is chosen.

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2) **Efficient optimization- and sampling- based method**: although quintic polynomial sampling method has been used in [14], it does not well deal with merge scenario motion planning. EM planner [23] generate optimal trajectory by solve iteratively dynamic and quadratic programming problems (DP & QP) with an average of 259*ms*. In our DL-AMP, the second layer algorithm is an optimization- and sampling- based path/speed quintic polynomial trajectory generation method. We only sample on time, and under each fixed time, we convert the trajectory generation into a constrained quadratic programming (QP) problem and solve it efficiently. After suboptimal trajectory is generated under each sampling time, another cost function is formulated that considers sampling time. The optimal trajectory is the one with the lowest cost function. Our optimization- and sampling-based method does not have DP process and piece-wise polynomial trajectory is simplified into a single trajectory, thus greatly reducing computation effect. Time *t* is selected as a sampling variable to keep the objective function in quadratic form which can be efficiently solved by robust QP solver.

The longitudinal planning is divided into distance planning and velocity planning to adapt to difference merge scenarios. In lateral planning, we divide the scenarios into four categories, and different desired distance constraints are selected under different scenarios. To improve efficiency, the constraints of sampling time, desired lateral offset in lateral planning and desired distance and velocity in longitudinal planning are well selected (Sec-II-B) based on road geometry, vehicle dynamic constraints and human driver statistics.

3) **Driving Comfort and Control Feasibility**: To improve driving comfort and control feasibility. We do trajectory smoothing after optimal trajectory is generated. A gradient based method that considers trajectory smoothness and curvature is us ed to reduce trajectory discontinuity and turning radius which results in reduced lateral acceleration and wheel turning angles in control. Since we use DL-AMP to find the best merge opportunity, free space is ensured at the very beginning, and collision checking is not necessary after smoothing. Unlike [19], we also modify our gradient based method to deal with exploding and vanishing gradient problems.

This paper is organized as follows: DL-AMP and DBTO are illustrated in Section II and III, respectively. The simulation and on-road tests results are shown in Section IV.