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Trajectory planning and tracking control for autonomous lane change maneuver based on the cooperative vehicle infrastructure system

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ABSTRACT

Lane change maneuver is one of the most conventional behaviors in driving. Unsafe lane change maneuvers are key factor for traffic accidents and traffic congestion. For drivers' safety, comfort and convenience, advanced driver assistance systems (ADAS) are presented. The main problem discussed in this paper is the development of an autonomous lane change system. The system can be extended applied in intelligent vehicles in future. It solves two crucial issues – trajectory planning and trajectory tracking. Polynomial method was adopted for describing the trajectory planning issue. Movement of a host vehicle was abstracted into time functions. Moreover, collision detection was mapped into a parameter space by adopting infinite dynamic circles. The second issue was described by backstepping principle. According to the Lyapunov function, a tracking controller with global convergence property was verified. Both the simulations and the experimental results demonstrate the feasibility and effectiveness of the designed method for autonomous lane change.

1. Introduction

1.1. Problem and motivation

Lane change maneuvers are one of the most conventional behaviors in driving. It is defined transfer of a host vehicle from the current lane to the next adjacent lane. To perform a lane change, drivers have to collect a large amount of information, such as velocity and distance between the host vehicle and vehicles in the target lane, traffic flow and road traffic environment information related to facilities. The decision of lane change is made on condition that the safe gap between vehicles is satisfied according to human driver experience. Actually, the process of a lane change involves environmental information collection and analysis, opportunity judgment, trajectory generation, collision detection, conflict processing and etc. According to past research, lane change and lane merge maneuvers account for approximately 5% of total crashes and as high as 7% of total crash fatalities (Habel & Schreckenberg, 2014; Rodemerk, Habenicht, Weitzel, Winner, & Schmitt, 2012). At present, traffic accidents related to lane change on highway account for a considerable proportion. From the Netherlands's transportation statistics, 12.6% of all traffic accident are caused by lane change (Bax, Leroy, & Hagenzieker, 2014). In Canada, 9.8% of crash fatalities result from lane change (Amin, Zareie, & Amador-Jiménez, 2014). In the United States, from 1994 to 2005, there were 13,939 traffic accidents caused by lane change and 24,565 killed (Kretschmer, Neubeck, & Wiedemann, 2005).

In developing countries such as India, Brazil and China, the problem gets worse. In China, traffic accidents caused by lane change are on the rise. Depending on the report from the China's Highway Traffic Safety Administration, massive traffic accidents caused by lane change are outstanding. Especially, more than 60% of the traffic accidents on the freeway are related to lane change (Li, Wu, Xu, & Lin, 2014). It is obvious that traffic accidents caused by lane change occur frequently. Thereby, how to improve safety for lane change has become an urgent issue to be dealt with.

Recently, traffic safety administration agencies and automobile companies focus more on reducing the number of lane change crashes. Traffic safety administration agencies are actively finding a solution to the issue that can regulate driving behavior by encouraging safer driving actions. For instance, through public advertisement or publicity board, the serious consequences in lane change crashes are emphasized. Also, notes on lane change safety

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are repeated. Some agencies in China use large variable message board (VMB) for freeways to remind drivers to reduce the number of lane change in accident high-risk or heavy-traffic areas.

On the other hand, the automobile companies have an urgent interest in utilizing high technology to provide lane change assistance for drivers. With the increase in the wide application of sensor technology in automobiles, advanced driver assistance systems (ADAS) have been implemented in recent years. The development of ADAS to aid in driving-related tasks has a crucial role to play in the automotive field. For more lane change safety, the lane change assistance system will become one of the most significant parts of the ADAS.

1.2. Related works

As discussed above, ADAS are developed to assist human drivers. One of the main objectives of the technology has been to increases driver awareness by providing useful information. Over the last years, ADAS have obtained a large number of research achievements. There are some examples of lane detection and lane keeping assistance (LKA) (He, McCarley, & Kramer, 2013; Lefevre et al., 2014; Son, Yoo, Kim, & Sohn, 2015), and obstacles detection and avoidance in the vehicle's path such as either vehicles (Hassannejad, Medici, Cardarelli, & Cerri, 2015) or pedestrians detection (Alahi, Bierlaire, & Vandergheynst, 2014; Sermanet, Kavukcuoglu, Chintala, & LeCun, 2013), adaptive cruise control (ACC), stop&go, autonomous parking or other elements, like traffic lights on roads (Diaz-Cabrera, Cerri, & Medici, 2015). ADAS are onboard vehicle systems which concentrate on the driving process. Of all examples, LKA and ACC are becoming the highest potential technologies in ADAS. The former was regarded as an extension of cruise control (CC). Drivers can set a specified driving velocity in advance with CC in which the vehicle is capable of following a leading car on freeways by controlling the throttle and brake pedals, i.e., longitudinal control. On the other hand, in essence, LKA, which remains one of the toughest challenges in the development of ADAS, is lateral control for vehicle. It is designed to alert the driver when the system detects that the vehicle is about to deviate from a lane. Complete lateral vehicle control has still to be addressed by the automotive companies.

Compared with the achievements achieved in ADAS, the research on lane change safety lags behind. In all maneuvers, lane change is one of the most complexes since both lateral and longitudinal control need to be considered. Drivers have to consider several factors affecting safety. These factors include, speed and position of the subject vehicle and vehicles in the target lane, geometric characteristics of the road, vehicle characteristics, and others. Due to the significance of the lane change safety, recent literature has been devoted to four main aspects of lane change, i. e., lane change warning, lane change behavior, lane changing trajectory planning and lane change control.

- Lane change warning

According to the ISO Standard 17387, Lane Change Decision Aid System (LCDAS) consist of three different types of warning systems – Blind Spot Warning (BSW), Vehicle Proximity Warning (VPW), and lane change warning (LCW). In BSW systems, there is a warning message triggered in case that any obstacles intervene into drivers' blind spots or areas. VPW systems are capable of recognizing approaching vehicles from behind in adjacent lanes. LCW systems are considered as a hybrid system, which has the function of both BSW systems and VPW systems. Based on the Standard, some studies have been conducted. For instance, in Shiller, Prasanna, and Salinger (2008), a collision warning approach due to neighboring traffic is presented. Based on the concept of velocity obstacles, it designed to alert the driver of a potential front collision and against attempting a dangerous lane change maneuver. To avoid false alarms in lane changes, prediction of a lane-change maneuver is needed. In Schmidt, Beggiato, Hoffmann, and Krems (2014), obtained early predictors by analyzing 3111 lane changes with regard to speed, secondary task engagement, turn signal usage, and steering wheel angle. Tomar et al. proposed a strategy for warning and intervention to assist the driver in a lane change maneuver (Tomar, Verma, Kushwah, & Tomar, 2013). The strategy consists of a relative motion estimator and supervisor. To assess the threat in a lane change situation, vehicle sensor information and rear-side radar sensor information have been combined in the relative motion estimator. In our work, we have not considered this approach, since our technique, which is not only warning for lane change, focus on how to accomplish autonomous lane change.

- Lane change behavior

Many research works like (Guo, Wan, Zhao, Wang, & Li, 2013; Zheng, Suzuki, & Fujita, 2014) have been conducted in lane change behavior. These studies show that the drivers' decision to change lanes is associated with driver characteristics, driver attitudes (such as aggressive behavior) and depends on many factors. In Gipps (1986) designed a lane changing model that was implemented in a microscopic traffic simulator. In a recent study Hou, Edara, and Sun (2015), have developed a genetic fuzzy model to predict merging behavior of drivers at lane drops. Xiaorui and Hongxu (2013) established a lane change model integrated with the car following behavior. The model considers kinematic behavior of the lane-changing vehicle in the case of acceleration. In Zheng, Ahn, Chen, and Laval (2013) presented a method to explore diverse components of lane changes impacts- anticipation process, relaxation process and change in driver characteristics induced by lane changes. Laval and Daganzo (2006) proposed a model to consider the drop in discharge rate at bottlenecks due to lane-change maneuvers. It provides simulations that appear to replicate empirical results observed from fixed-point detectors in their studies. These models stated above have been proposed to acquire the accurate way to describe a lane change maneuver. However, none of them were designed for use in a real-time lane changing assistance system that advises drivers of when it is safe or unsafe to merge.

- Lane changing trajectory planning

A predefined trajectory must be presented to track during the lane change maneuver. Accordingly, trajectory planning is an extremely significant issue in the topic of autonomous lane change maneuver. Its main aim is to generate a trajectory from current lane to goal lane that satisfies some limitations or objectives, like acceleration, joint jerk, minimization of time interval, vibration, collision avoidance criteria or other dynamic constraints.

There are numerous experiences in lane changing trajectory planning. Classical trajectory planning strategies, such as road map, cell decomposition and potential field methods are frequently mentioned in robot field. Nevertheless, they have the possibility of getting stuck in local minima. Furthermore, it takes an extremely long time to reach global minima in the case of too many parameters. Actually, trajectory planning for a lane change is always simple. The existing methods are on various types of curves – circular (Kim, Oh, Suk, & Tsourdos, 2014), harmonic (Zhang, Chen, & Shen, 2013), polynomial (Rossi & Savino, 2013) and line segments (Vale, Fonte, Valente, & Ribeiro, 2014). In Ioannou (2013), lane change patterns of each driver are modeled with a hidden Markov model (HMM). From the HMM, vehicle trajectories are selected in a maximum likelihood criterion at random lane-changing time and state