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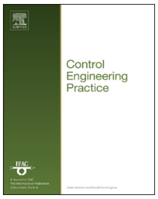

Lateral control of autonomous vehicles based on fuzzy logic☆

Xinyu Wang, Mengyin Fu, Hongbin Ma*, Yi Yang

State Key Laboratory of Intelligent Control and Decision of Complex Systems, Beijing Institution of Technology, Beijing 100081, PR China

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ABSTRACT

Autonomous vehicles have attracted considerable attention in the research community and industry. This paper addresses a problem in designing lateral control law and develops a strategy to determine the given speed of autonomous vehicles. An improved method for calculating the lateral offset and heading angle error is proposed to reduce the impact of reference path data noise. Multiple fuzzy inference engines are used to design the steering controller and determine the given driving speed, including the forward and backward directions. The stability condition is given to guide the design of fuzzy inference engines. Satisfactory simulation and experimental results have been obtained from different reference paths.

1. Introduction

1.1. Background

Autonomous vehicles play an important role in intelligent transportation systems (ITS). It has become popular because of the vehicles' potentially wide applications in transportation, dangerous tasks, driver assistance systems, and others. The lateral control system is one of the foundations of the safety and stability in autonomous vehicle control. Early studies on lateral control were based on classical control theory. In Fenton, Melocik, and Olson (1976), Fenton designed a lateral controller using the root locus design method. In Kosecka, Blasi, Taylor, and Malik (1998), Kosecka presented a model of the dynamics of vehicles and sensing systems, where a single look-ahead distance was used in the sensing system model to estimate the lateral offset and heading angle error. This sensing model was widely used in later studies. Kosecka also compared the performance of a lead lag control law, a full-state linear controller and input–output linearizing control law. In Rajamani, Zhu, and Alexander (2003), Rajamani used a nonlinear kinematic model and a sensing model similar to those presented in Kosecka et al. (1998) with a fixed look-ahead distance. A controller based on input–output linearization with stable internal dynamics was proposed to achieve backward driving control under low speeds. In Sotelo et al. (2003), Tseng et al. (2005), and Guo et al. (2012), time-varying look-ahead distances were used for adapting different driving speeds. The selection method of the look-ahead distance is introduced in detail in Tseng et al. (2005). In Guo et al. (2012), Onieva et al. (2011), Ruan, Fu, and Li (2005), Ting and Chang (2012), Ho, Chan, Rad, Shirazi, and Cina (2012), Hessburg and Tomizuka (1994), and Peandrez, Milaneands, and Onieva (2011), fuzzy control strategies or fuzzy-neural networks were presented to address parametric uncertainties and nonlinear models of autonomous vehicles. In particular, Guo used genetic algorithms (GAs) to search and select the parameters of controllers (Guo et al., 2012). In Yang and Zheng (2007), Yang designed an expert fuzzy controller to adapt different driving speeds and different curvatures for crossing and turning actions, in contrast to changing the look-ahead distance. In Fang et al. (2011), Du, Zhang, and Naghdy (2011), Ohara and Murakami (2008), Solmaz and Baslamsl (2012), and Talvala, Kritayakirana, and Gerdes (2011), unexpected sliding effects were taken into consideration. Robust anti-sliding controllers were designed for the observation and suppression of such sliding effects (Fang et al., 2011). In Talvala et al. (2011), a look-ahead controller coupled with longitudinal control based on the path position and the wheel slip was designed to create an autonomous race car. In Matsushita and Murakami (2008) and de Wit and NDoudi-Likoho (2000), further studies were conducted for the lateral control of tractor-trailer or convoy-like vehicles based on nonlinear models. Independent driving tasks such as parking, overtaking, and changing lanes, were studied in detail as separate tasks (Kochem & Isermann, 2004; Li & Chang, 2003; Shamir, 2004; Zhou & Wang, 2012). In addition, some other types of nonholonomic wheeled mobile robots, such as unicycles, were studied in Aicardi, Casalino, Bicchi, and Balestrino (1995), Rehman

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* Corresponding author.
E-mail addresses: wangxinyu@bit.edu.cn (X. Wang), fumy@bit.edu.cn (M. Fu), mathmhb@bit.edu.cn (H. Ma), yang_yi@bit.edu.cn (Y. Yang).

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and Ahmed (2007), and Mori, Nakano, and Takahashi (2002). Underactuated autonomous vehicles in the presence of possibly large modeling parametric uncertainty were considered in Aguiar and Hespanha (2007).

In most of the studies cited above, only fixed driving direction, forward or backward, was focused on, and the driving speed was just taken as an input value. The generating strategy of the given driving speed was rarely mentioned. In addition, a single look-ahead distance was used in the sensing system model. However, as the autonomous driving tasks become more and more complex, the lateral control system should be adaptive to different kinds of reference trajectories. When the reference trajectory is complex, precise control under low speed with both forward and backward directions is needed, and when the reference trajectory is simple, the controller must be stable under high speeds. Additionally, the lateral control system should have the feature of determining a reasonable reference driving speed to guarantee the stability and safety of autonomous vehicles. In this paper, a new sensing system model and a descriptive model of the reference path are presented. Based on the new model, the estimates of lateral offset and heading angle error are no longer limited to a single look-ahead distance; all the points on the path are considered. In order to adapt different driving directions, multiple fuzzy inference engines are used in designing the steering controller and drawing the given driving speed, including forward and backward directions. In each of the inference engines for steering control, the driving speed is directly used in the fuzzy logic to achieve lateral control under different driving speeds for both complex tasks with sharp corners and simple tasks for high-speed driving. Stability analysis based on the nonlinear dynamic model of autonomous vehicles is presented using the Lyapunov theory to guarantee the stability of the controller and to guide the design of fuzzy inference engines.

1.2. Organization of this paper

The remainder of this paper is organized as follows: Section 2 presents the basic equations used to model the dynamics of autonomous vehicles and provides a method to describe the local reference path, from which some useful parameters are obtained and described in Section 3 with the corresponding mathematical formulas. Section 4 presents the control strategies used in the lateral controller. Section 5 describes the system stability conditions, and Section 6 presents the results of the simulations and experiments carried out with these controllers. Finally, we conclude this paper in Section 7 with some remarks based on the simulations and experiments.

2. Lateral model and problem formulation

2.1. Modeling

In some previous studies, a linear system model, as a simplified model, is adopted to solve the lateral control problem. Linear models were not accurate enough in many cases, such as following a reference path with small turning radius. When the steering angle is large, the modeling error will becomes unacceptable. Nonlinear system models can reflect the actual vehicle dynamics much better than a linear model and are thus used in this paper.

The dynamics of an autonomous vehicle is shown in Fig. 1, where the X-axis positive direction is due east; the Y-axis positive direction is due north; $P_0(X_0, Y_0)$ is the midpoint of the vehicle's rear axle, and $P_1(X_1, Y_1)$ is the midpoint of the vehicle's front axle. L is the length of the wheelbase, φ is the heading angle of the vehicle, and θ is the front wheel steering angle.

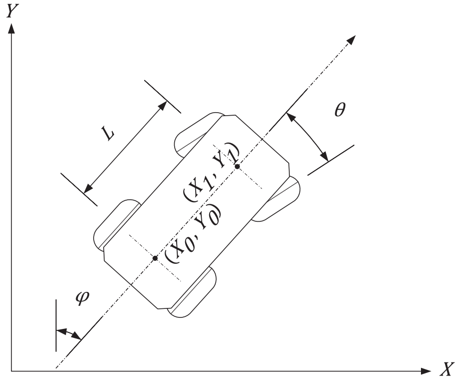

Fig. 1. The dynamics of autonomous vehicle.

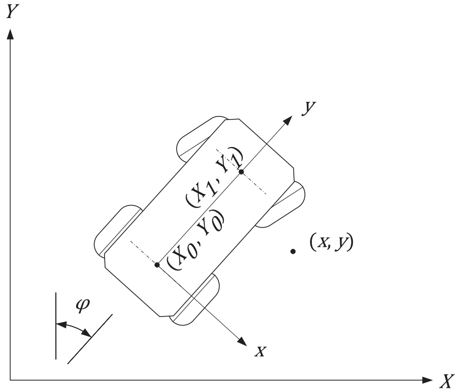

Fig. 2. The transformation between the local coordinate system and the geodetic coordinate system.

The dynamics of the vehicle can be determined by the state variable (X_0, Y_0, φ) or (X_1, Y_1, φ). Thus, the lateral kinematic model of an autonomous vehicle can be written as the following equation (Gillespie, 1992):

$$\begin{bmatrix} \dot{X}_0 \\ \dot{Y}_0 \\ \dot{X}_1 \\ \dot{Y}_1 \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} v \sin\varphi \\ v \cos\varphi \\ v \sin(\varphi+\theta) \\ v \cos(\varphi+\theta) \\ \frac{v \tan\theta}{L} \end{bmatrix}, \tag{1}$$

where v is the longitudinal velocity.

2.2. Description of the local reference path

The *local reference path*, defined by the perception and decision-making system, is the path that the autonomous vehicle is to drive along. The local reference path is described with the vehicle-body local coordinate $x-y$, which are Cartesian coordinates. The midpoint of the vehicle's rear axle is the origin of the coordinates. The y-axis positive direction is the forward direction of the vehicle, as shown in Fig. 2. The coordinate transformation of an arbitrary point between the local coordinate system and the geodetic coordinate system is shown in the following equation:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \mathbf{R} \begin{bmatrix} X \\ Y \end{bmatrix} + \mathbf{T}, \tag{2}$$

where

$$\mathbf{R} = \begin{bmatrix} \cos(-\varphi) & \sin(-\varphi) \\ -\sin(-\varphi) & \cos(-\varphi) \end{bmatrix}$$