Mechanical Systems and Signal Processing 105 (2018) 183–199

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Coordinated path-following and direct yaw-moment control of autonomous electric vehicles with sideslip angle estimation

Jinghua Guo [a,*], Yugong Luo [b], Keqiang Li [b], Yifan Dai [b]

[a] School of Mechanical Engineering, Beijing Institute of Technology, China
[b] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, China

ARTICLE INFO

Article history:
Received 18 July 2017
Received in revised form 5 November 2017
Accepted 10 December 2017

Keywords:
Autonomous electric vehicles
Vehicle dynamics
Time-varying
Path-following control
Direct yaw moment control

ABSTRACT

This paper presents a novel coordinated path following system (PFS) and direct yaw-moment control (DYC) of autonomous electric vehicles via hierarchical control technique. In the high-level control law design, a new fuzzy factor is introduced based on the magnitude of longitudinal velocity of vehicle, a linear time varying (LTV)-based model predictive controller (MPC) is proposed to acquire the wheel steering angle and external yaw moment. Then, a pseudo inverse (PI) low-level control allocation law is designed to realize the tracking of desired external moment torque and management of the redundant tire actuators. Furthermore, the vehicle sideslip angle is estimated by the data fusion of low-cost GPS and INS, which can be obtained by the integral of modified INS signals with GPS signals as initial value. Finally, the effectiveness of the proposed control system is validated by the simulation and experimental tests.

1. Introduction

Autonomous vehicles have excited a great research interest as an effective way to improve the traffic safety and alleviate the environment pollution of intelligent transportation systems (ITS). Furthermore, they can be used for conducting military missions and executing routine tasks for industry. With each wheel actuated by electric motors, four-wheel independently drive autonomous electric vehicles have exhibited superior maneuverability, control flexibility, and actuation redundancy [1–3].

As one of the basic and key technologies of autonomous electric vehicles, lateral motion control has been attracting wide research attentions, such as, active front-wheel steering (AFS), path-following system (PFS) and direct yaw moment control (DYC). Owing to the fact that autonomous electric vehicles have the features of parametric uncertainties, time-varying and strong nonlinearities [1], how to design the lateral motion control strategy has a profound research significance.

The mission of PFS is to accurately track the desired lane while ensuring the safety, ride comfort, and stability of autonomous electric vehicles. In recent years, there are many PFS control method proposed for autonomous vehicles. In [4], a novel Type-2 fuzzy neural network controller is designed for path following control of autonomous vehicles, and the proposed control system can learns the system dynamics in real-time. In [5], in order to track the planned path for collision avoidance maneuvers, a model predictive control (MPC) system is designed for calculating the front steering angle to prevent the vehicle from colliding with a moving obstacle. In [6], an optimal genetic-based fuzzy controller is constructed to imitate the

* Corresponding author.
E-mail address: guojing_0701@live.cn (J. Guo).

https://doi.org/10.1016/j.ymssp.2017.12.018
0888-3270/

humanlike driving behavior, the results demonstrate this path following controller can provide the dynamic tracking performance and maintains good maneuverability. In [7], a vehicle steering assistance is presented, in which a switching strategy is built to govern the driver-assistance interaction, and the resulting hybrid system is formalized as an input/output hybrid automation, the proposed steering assistance control system can track the desired path in real-time. In [8], to deal with the parametric uncertainties and external disturbances, a robust H_∞ static output-feedback controller based on the mixed genetic algorithms (GA) and linear matrix inequality (LMI) approach is proposed to realize the path following without the information of the lateral velocity. In [9], an adaptive fuzzy sliding mode control approach used for lateral path following of vision-based automated vehicles is presented, and the asymptotic stability of the closed-loop path-following control system is proven by the Lyapunov theory.

The task of DYC system is to stabilize the vehicle lateral motion by the external yaw moment generated as a result of the difference in tire driving or braking forces between the right and left sides of the vehicle. In [10], a novel sliding mode-based direct yaw moment control method is proposed for electric and hybrid vehicles equipped with independent motors, and this method employs a novel switching function to simultaneously track the desired yaw rate and vehicle side-slip. In [11], a stabilizing observer-based control algorithm for an in-wheel-motored vehicle is proposed, which generates the direct yaw moment to compensate for the state deviations. In [12], a hierarchical direct yaw moment control architecture is adopted, in which a driver model and a vehicle model are used to obtain the driver's intention and the vehicle states, respectively. In [13], a novel fault-tolerant yaw moment control for a vehicle with steer-by-wire (SBW) and brake-by-wire (BBW) devices, and in order to deal with the actuator failure, a novel control allocation with variable weights is proposed in this direct yaw moment control procedure.

With regard to the lateral motion control of vehicles, the application of DYC can provide rapid torque response and flexible actuation. But, the study of coordinated PFS and DYC control of autonomous electric vehicle is rather limited [14]. The main contributions of this paper are given as follows

(I) A coordinated PFS and DYC control system consisting of two-levels for autonomous electric vehicles is proposed to strengthen the lateral stability and improve the path tracking performance.
(II) A linear time varying (LTV)-based MPC high-level control law is presented to produce the desired front steering angle and external moment torque, which could effectively deal with the features of time-varying and external disturbances.
(III) A pseudo inverse (PI) low-level control allocation law is designed to realize the tracking of desired external moment torque and management of the redundant tire actuators.
(IV) The vehicle sideslip angle is estimated by the data fusion of low-cost GPS and INS, and the covariance matrix of measurement noise can be adaptively adjusted to improve the estimation accuracy.

The rest of this paper is organized as follows. System description and modeling of autonomous electric vehicle are developed in Section 2. A novel coordinated PFS and DYC control system consisting of a LTV-MPC high-level control low and a PI low-level control allocation law is presented in Section 3. The vehicle sideslip angle is estimated via the integration of low-cost GPS and INS in Section 4. Simulation and experimental tests of proposed coordinated PFS and DYC control system are carried out in Section 5. Finally, conclusions are drawn in Section 6.

2. System description and modeling

2.1. Vehicle lateral dynamic model

Autonomous electric vehicles equip with vision system and GPS/INS sensors. As shown in Fig. 1, the motion of vehicles can be described in the three sets of frames: the body frame (X_b, Y_b) for the INS, the east north up frame (X_e, Y_e) for the GPS,

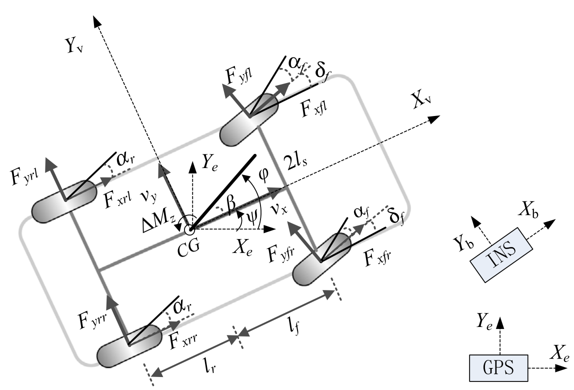

Fig. 1. Autonomous electric vehicle model.