Advances in Engineering Software 121 (2018) 188–196

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Analyzing the influence of automatic steering system on the trajectory tracking accuracy of intelligent vehicle

Ruochen Wang*, Qing Ye, Yingfeng Cai, Yong Wang, Xing Xu, Xiangpeng Meng, Chen Long

School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China

ARTICLE INFO

Keywords:
Automatic steering system
Intelligent vehicle
Trajectory tracking control system
Nonlinear analysis
Nonlinear dynamic model

ABSTRACT

In this paper, the influence of interference torques, time delay and noise of automatic steering system (ASS) on trajectory tracking accuracy of intelligent vehicle (IV) is analyzed to further study the coupling mechanism between automatic steering control system and IV trajectory tracking control system. The system architecture of ASS and IV trajectory tracking control system is briefly introduced at first. The correlation controller models are then established based on nonlinear ASS and IV dynamic models. The influence of ASS on the trajectory tracking of IV is validated through simulations with various forms of ASS nonlinear factors. And the results show clearly that the interference torques of ASS have great influence on the accuracy of IV trajectory tracking system, especially in the lateral deviation of IV trajectory tracking system, the noise and time delay of ASS have almost no influence on lateral deviation and azimuth deviation of IV trajectory tracking.

1. Introduction

As one of the important parts of intelligent transportation system (ITS) [1,2], intelligent vehicle (IV) can improve road traffic efficiency based on vehicle intelligent behaviors, such as environmental perception [3], route planning [4] and vehicle motion control. Among them, the trajectory tracking motion control is a core part of IV motion control which has attracted much attention.

Earlier papers study on trajectory tracking control system of IV has verified the accuracy and robustness of IV trajectory tracking controller. Tai [5] investigated the trajectory tracking accuracy of IV under the conditions of vehicle steering and obstacle avoidance motion, and designed the trajectory tracking controller based on fuzzy control algorithm to improve the IV trajectory tracking accuracy. Hatipoglu and Ozguner [6] did research on lateral control algorithm of IV to track desired yaw velocity, and designed the controller based on robust switching control method. Netto and Chaib [7] applied the self-tuning regulator into the concerned vehicle lateral model to deal with the vehicle lateral control problem. Lee and Yoo [8] proposed a new predictive control algorithm based on tracking deviation function, and the center-of-mass velocity and slip angle were considered as controlled objects. Chen and Luan [9] used adaptive model predictive control with linear time-variant prediction model in lane keeping system, and a cost function which consists of the errors between the target trajectory and predicted trajectory was considered in the control system. M. Chadli [10–11] studied the vehicle path-following control problem considering time delay and tire force saturation, and designed composite nonlinear feedback strategy to improve the robustness of the path tracking controller. Wang [12] presents a fast and accurate robust path-following control approach for a fully actuated marine surface vessel in the presence of external disturbances. Several simulation analysis and test results [13–15] also indicated the effectiveness of trajectory tracking control of autonomous robots and vehicle under parametric modeling uncertainty. However, most studies simplified the IV into Car-like model or bicycle model, and did not take the automatic steering system (ASS) into consideration.

To solve the problem, some researchers focus on the coupling mechanism between ASS and IV trajectory tracking motion system. M. Chadli [16] studied the stability condition of nonlinear EPS system with constraint and saturation control. Mammar and Koenig [17] investigated the influence of vehicle speed, pavement coefficient and the steering angle on vehicle yaw-rate under phase-plane condition, and used the feedback H_∞ controller for active front steering system to improve vehicle handling stability. Ghani and Sam [18] used sliding mode control strategy to overcome different road friction coefficients and various disturbances on active steering vehicle system. Cerone and Milanese [19] addressed the problem of combining automatic lane-keeping and driver's steering for either obstacle avoidance or lane-change maneuvers for passing purposes and other desired maneuvers, through a closed-loop control strategy. Guo and Hu [20] designed the automatic steering controller for trajectory tracking of unmanned vehicles using genetic algorithms, and different control algorithms were

---

* Corresponding author.
E-mail address: wrc@ujs.edu.cn (R. Wang).

https://doi.org/10.1016/j.advengsoft.2018.04.011
Received 28 December 2017; Received in revised form 11 March 2018; Accepted 29 April 2018

compared to verify the effectiveness of designed control algorithm.

Those studies on coupling mechanism of ASS and IV trajectory tracking system have been successfully verified in applications, and each applied control strategy can partly improve the vehicle handling stability or trajectory tracking accuracy. However, few studies have drawn attention to the nonlinear interference analysis of IV trajectory tracking system, especially analyzed the influence of nonlinear factors of ASS on the accuracy and stability of IV trajectory tracking control system. In this paper, we propose a novel vision guided IV trajectory tracking control system which includes the nonlinear ASS, and the influence of interference torques and time delay of ASS on IV trajectory tracking is analyzed. This paper is arranged as follow:

In Section 2, the architecture of vision guided IV trajectory tracking control system based on expected yaw velocity is introduced. In Section 3, the ASS and IV dynamic models are established, and the nonlinear factors of ASS are considered. In Section 4, the IV trajectory tracking control algorithm and automatic steering control algorithm are built, which include the formula of designed virtual driving path, expected yaw velocity generator, back-stepping sliding mode controller and proportional-integral and derivative (PID) controller. In Section 5, the simulations of IV trajectory tracking controller with and without ASS are compared to verify the influence of nonlinear factors of ASS on the accuracy of IV trajectory tracking control system. Conclusions are drawn in Section 6.

2. Architecture of IV trajectory tracking control system

The architecture of IV trajectory tracking control system is shown in Fig. 1.

In Fig. 1, IV trajectory tracking control system includes sensors, trajectory tracking controller, ASS and vehicle system. The trajectory tracking controller is composed of two parts: expected yaw velocity generator and back-stepping sliding mode controller. The working principle of IV trajectory tracking control system is shown as follow:

When IV trajectory tracking control system starts, the vehicle sensors output the corresponding signals (target path, vehicle location and vehicle velocity) into trajectory tracking controller through signal processing, and a virtual path model between current vehicle position and preview point is established based on the sensors signals. The expected yaw velocity generator obtains the target yaw velocity through virtual path model and sends it to back-stepping sliding mode controller. The back-steeping sliding mode controller calculates the tire steering angle signal based on vehicle kinematics model and inputs it to ASS. Then ASS outputs the actual tire steering angle through automatic steering controller. Finally, the signal of actual tire steering angle is transmitted to vehicle system, and the correlative signal of vehicle dynamics performance is sent back to IV vehicle sensors.

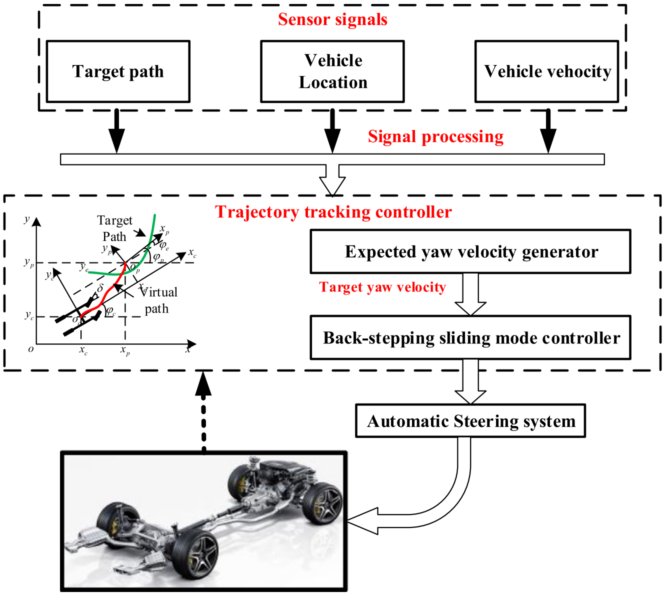

Fig. 1. Architecture of IV trajectory tracking control system.

3. Combined IV and ASS dynamic models

The IV dynamic and ASS models are nonlinear and time delay which greatly increase the difficulty in designing the trajectory tracking controller. To study the influence of ASS on the trajectory tracking accuracy of IV, the IV dynamic and ASS models are established in this section.

3.1. Vehicle dynamic model

It is obviously that the two degree-of-freedom (DOF) vehicle dynamic model cannot effectively describe the complicated characteristics of IV, and the IV motion control algorithm based on it cannot meet the movement requirements of all working conditions of IV, such as steering condition and high speed condition. So in this paper, the 7DOF vehicle dynamic model combined with nonlinear tire model is established as shown in Fig. 2, and should meet two conditions in order to further study its coupling mechanism, these are

Condition (1): the vertical movement of vehicle is ignored so that the ride performance of IV is not considered.

Condition (2): the lateral acceleration of vehicle must be less than 0.4 g to make sure that IV run in stable condition.

The 7DOF vehicle dynamic model is given as [21,22]

$$m(\dot{v}_x - v_y\omega_c) = (F_{x1} + F_{x2})\cos\delta - (F_{y1} + F_{y2})\sin\delta + F_{x3} + F_{x4} \tag{1}$$

$$m(\dot{v}_y + v_x\omega_c) = (F_{y1} + F_{y2})\cos\delta + (F_{x1} + F_{x2})\sin\delta + F_{y3} + F_{y4} \tag{2}$$

$$\begin{aligned} I_z\dot{\omega}_c \;=\; & [(F_{y1} + F_{y2})\cos\delta + (F_{x1} + F_{x2})\sin\delta]l_f - (F_{y3} + F_{y4})l_r \\ & + [-(F_{x1} - F_{x2})\cos\delta + (F_{y1} - F_{y2})\sin\delta]\frac{t_f}{2} - (F_{y3} - F_{y4})\frac{t_f}{2}\cos\delta \end{aligned} \tag{3}$$

where m, I_z,ω_c are the mass, yaw inertia and yaw velocity respectively. F_{x1},F_{x2},F_{x3},F_{x4} are the longitudinal forces of four tires, and F_{y1},F_{y2},F_{y3},F_{y4} are the lateral force of four tires. The tire model has been established according to the Dugoff model [23,24].

3.2. ASS dynamic model

ASS consists of mechanical structure and physical structure, which cannot be described accurately by mathematical models. In order to facilitate the analysis of the kinematics and dynamics for the ASS, the ASS dynamic model is simplified by the reduced order processing in the premise of basic structure of the system, and some key physical models

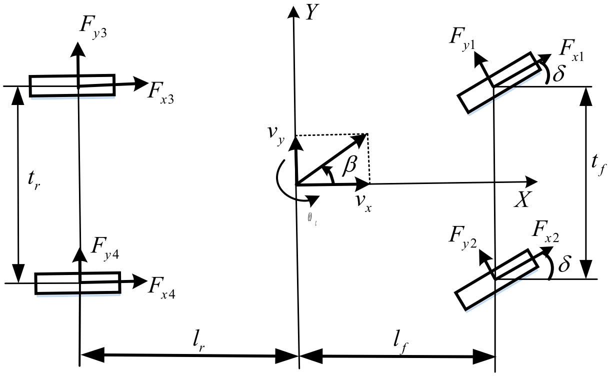

Fig. 2. 7DOF vehicle dynamic model.