Control Engineering Practice 64 (2017) 15–26

Contents lists available at ScienceDirect

Control Engineering Practice

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

Shared control for lane departure prevention based on the safe envelope of steering wheel angle

Dongkui Tan, Wuwei Chen*, Hongbo Wang, Zhengang Gao

School of Automotive and Transportation and Engineering, Hefei University of Technology, 193 Tunxi Avenue, Hefei 230009, China

A R T I C L E I N F O

Keywords:
Lane departure prevention system
Human-machine conflict
Safe envelope
Shared control
Cooperative performance

A B S T R A C T

The ability to prevent lane departure has become an important feature for commercialized vehicles. This paper proposes a shared steering assistance strategy based on a safe envelope of steering wheel angle (SWA). This solves the human-machine conflict issue in lane departure prevention (LDP) system which uses steering control to help the driver keep the vehicle within the correct lane. The system combines a driver steering control model, current vehicle states and vehicle-road deviation. The desired SWAs are calculated when the driver intends to drive along the left or right side of the lane, and then the two angles are used to generate the safe envelope. Next, a driver intention estimator is designed to predict driver's intended SWA and the assistance control is activated by judging whether the driver intended SWA is go beyond the safe envelope. Finally, a H∞ controller and a disturbance observer are developed to determine the assistance torque. In this way, the SWA is limited to safe values to mitigate lane departure and the controller intervention is minimized. The effectiveness of the proposed method is evaluated via numerical simulation with different driving scenarios and human-in-the-loop experiment on a driving simulator. The obtained results show that this method not only can avoid lane departures effectively, but also ensures a good human-machine cooperative performance.

1. Introduction

Traffic accidents remain a common cause of injuries, property damage and death (National Highway Traffic Safety Administration, 2012). The report from the World Health Organization (WHO) indicates that approximately 1.25 million people are killed on the road each year (World Health Organization). One important type of accident is the unintended lane departure due to driver impairment, inattention, fatigue, or operation mistake, resulting in a fatal crash. According to NHTSA's data, 37% of all transportation fatalities in the United States are caused by running off from the road (Barickman, Smith, & Jones, 2007). To reduce such road accidents, lane departure prevention systems (LDPS) have been designed to automatically adjust vehicle's dynamics or trajectory to keep the vehicle within its driving lane (Scanlon et al., 2015).

Several solutions and technologies to solve the LDP problem have been proposed in the literature (Amditis et al., 2010; Tunçer et al., 2010; Alirezaei et al., 2011; Sentouh et al., 2010). According to active control means, the LDPS could be classified into two types: systems using differential braking control and the other one using steering control. Differential braking control can provide high compatibility with the driver's steering maneuvers, because the actuators are different. Nissan (Infiniti) is the first to offer a LDPS in this way (Braitman, McCartt, Zuby, & Singer, 2010). Lee et al. (2014) developed a hierarchical control algorithm for the lane keeping assistance using only direct yaw moment control. To prevent lane departure, a driver assistance control law using a variable combination of steering control and differential braking control was investigated in (Enache et al., 2010). Nevertheless, differential braking will decrease the vehicle speed and make the passengers feel uncomfortable.

Alternatively, most works dealing with lane departure avoidance control use a steering input as the control variable. In this case, the steering wheel is controlled by the driver and the assistance system simultaneously, thus the shared control between the driver and the LDPS has gained considerable attention in the academic research. Alirezaei et al. (2012) proposed a robust road departure avoidance system that utilizes look-ahead information and a driver decision estimator to generate a corrective steering angle. If a road departure is likely to occur, the steering input provided by the driver will be overridden. But, this system can only be used for vehicles equipped with a steer-by-wire (SBW) system. Stephen et al. (Erlien, Fujita, & Gerdes, 2013) presented a control framework for obstacle avoidance and stability control using safe driving envelopes. The control input is also steering angle and the framework is validated via a SBW vehicle.

* Corresponding author.
E-mail addresses: tandongkui@126.com (D. Tan), hfgdcjs@126.com (W. Chen), bob.627@163.com (H. Wang), gzg198510@163.com (Z. Gao).

http://dx.doi.org/10.1016/j.conengprac.2017.04.010
Received 28 September 2016; Received in revised form 19 April 2017; Accepted 20 April 2017
0967-0661/

Using steering angle overlay is beneficial to achieve a shared control, but there are few commercialized vehicles equipped with SBW. Moreover, since the actual steering angle is modified, the counter-intuitive vehicle response may confuse drivers.

An alternative approach is to use steering torque overlay to compensate the driver torque input. This control method is easy to be applied to a vehicle, because a large proportion of vehicles have installed the electrical powered steering (EPS) system. An important issue in developing such LDPS is how to avoid the human–machine conflict situations. Mulder, Abbink, and Boer (2008) proposed a haptic guidance system, in which the driver and assistance system share steering control, showing that continuous haptic support is an efficient way to support drivers during curve negotiation. To improve the human–machine cooperation, Louay et al. (Saleh et al., 2013) showed a shared control law based on the H2-Preview control approach. Through the integration of a driver model to vehicle–road model, the driver's behavior is taken into account in the controller synthesis step. However, the driver model parameters are difficult to be determined online and the impact of such uncertainty on the control performance needs to be considered. Merah, Hartani, and Draou (2016) proposed a lane keeping system based on a fuzzy sliding mode controller. By introducing fuzzy control rules, the controller coefficient is changed continuously according to driver's behaviors. Similarly, in (Nguyen et al., 2015) a driver activity function was introduced to perform online adaption of the assistance level.

Although the continuous haptic feedback is more compatible with the driver's steering actions, Winter and Dodou (de Winter & Dodou, 2011) argued that continuous assistance would decline the driver's driving skills, and the intervention should be provided as soon as a risk criterion exceeded the predefined threshold, i.e., support during critical driving situation was important. Moreover, evaluation results from (Katzourakis et al., 2014) showed that haptic feedback had a profound impact on the measured steering wheel torque, but no significant effect on SWA or vehicle path. To this end, Enache et al. Enache et al., (2009) presented a lane departure avoidance system using steering torque overlay and proposed two activation rules with respect to the driver's actions and vehicle position. The steering assistance was designed to take action only if necessary. Tan et al. (Dongkui et al., 2015) proposed a human-machine shared decision-making and control method for LDP. When the assistance intervention is activated, an authority allocation module is utilized to reduce human-machine conflict.

Conclusions drawn from the above studies are as follows. First, for vehicles equipped with a conventional steering column, steering torque overlay is an appropriate assistance means to avoid lane departure. Second, a good steering assistance system should not only be able to prevent lane departure, but also share control with the driver in a minimally invasive manner while giving the driver more freedom to fully control the vehicle.

In the paper, to develop a human-machine cooperative steering assistance system, a shared control algorithm using the safe envelope of SWA is proposed. The system design procedure is separated into two stages. In the first stage, the safe envelope of SWA is computed to guide the vehicle within the lane boundary. Then, a decision-making strategy is designed by combining the SWA envelope with a driver intention estimator. In the second stage, a H∞ controller in conjunction with a disturbance observer determines the assistance torque. The proposed system is analyzed via numerical simulation and tested in a human-in-the-loop driving simulator. Different driving scenarios are used to confirm the effectiveness of the proposed method.

The main contributions of this paper are:

(1) A nonlinear steering control model that is applicable at any speed.
(2) A novel shared control method for handling the interactions between the driver and the assistance system that combines the driver intended SWA and its safe envelope.
(3) An assistance control law coupled with a disturbance observer that achieves better trade-off between control accuracy and driver's comfort.

The contents of this paper are organized as follows: Section 2 presents the reference vehicle model and the EPS system model. The envelope computation and the decision-making strategy are described in Section 3. The structure of the proposed method is given in Section 4, then the robust controller and the disturbance observer are designed. In Section 5 and Section 6, the simulation and experimental results are presented respectively. Finally, paper conclusions are made in Section 7.

2. System modeling

2.1. Reference vehicle model

Note that the LDPS will work when the vehicle is about to deviate from the lane, but vehicle dynamic state is generally within the linear region in this case. Thus, using the two-degree-of-freedom, linear parameter varying (LPV) model which involves variable longitudinal speed $v_x(t)$ as a reference vehicle model to design a LDPS is appropriate. As shown in Fig. 1, the model can be expressed as follows

$$\begin{aligned}\dot{\beta} &= -\frac{a_1}{mv_x(t)}\beta-\left(1+\frac{a_2}{mv_x^2(t)}\right)\omega+\frac{2C_f}{mv_x(t)}\delta_f\\ \dot{\omega} &= -\frac{a_2}{I_z}\beta-\frac{a_3}{I_z v_x(t)}\omega+\frac{2l_f C_f}{I_z}\delta_f\end{aligned} \quad (1)$$

where

$$a_1 = 2C_f+2C_r,$$

$$a_2 = 2l_f C_f-2l_r C_r,$$

$$a_3 = 2l_f^2 C_f+2l_r^2 C_r.$$

The definitions and the numerical values of the above parameters are given in Table 1. ω, β and δ_f are used to represent the yaw rate, the vehicle sideslip angle and the front steering angle, respectively.

2.2. Dynamic model of the EPS system

The motor in EPS system is used as an actuator for assistance control. The steering mechanism includes steering column, motor, rack, pinion, torque and angle sensors, etc. Fig. 2 shows the model of a steering mechanism equipped with a direct-current motor. According to Newton's laws of motion (Chabaan & Wang, 2001), the motion equation with respect to steering column can be written as:

$$J_c\ddot{\theta}_c+B_c\dot{\theta}_c = T_d-K_c\left(\theta_c-\frac{x_r}{r_p}\right)-F_c sign(\dot{\theta}_c) \quad (2)$$

where T_d is the driver torque, θ_c is the SWA, x_r is the rack position, r_p is the pinion radius, J_c, B_c, K_c and F_c are, respectively, the steering column moment of inertia, damping, stiffness and friction.

The dynamic of the motor shaft is given by:

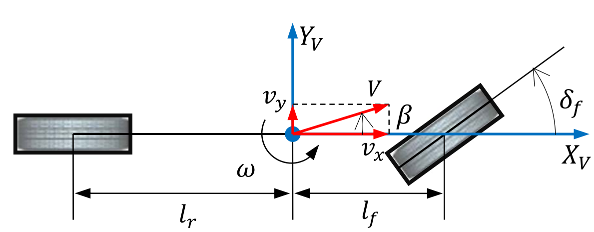

Fig. 1. Simplified two-DOF vehicle dynamics model.