Mechanical Systems and Signal Processing 104 (2018) 171–187

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Vehicle lateral motion regulation under unreliable communication links based on robust H_∞ output-feedback control schema

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ARTICLE INFO

Article history:
Received 20 February 2017
Received in revised form 6 August 2017
Accepted 8 September 2017

Keywords:
Vehicle dynamics
Lateral motion regulation
Data dropout
Robust control
Static output-feedback

ABSTRACT

This paper presents a robust control schema for vehicle lateral motion regulation under unreliable communication links via controller area network (CAN). The communication links between the system plant and the controller are assumed to be imperfect and therefore the data packet dropouts occur frequently. The paper takes the form of parallel distributed compensation and treats the dropouts as random binary numbers that form Bernoulli distribution. Both of the tire cornering stiffness uncertainty and external disturbances are considered to enhance the robustness of the controller. In addition, a robust H_∞ static output-feedback control approach is proposed to realize the lateral motion control with relative low cost sensors. The stochastic stability of the closed-loop system and conservation of the guaranteed H_∞ performance are investigated. Simulation results based on CarSim platform using a high-fidelity and full-car model verify the effectiveness of the proposed control approach.

1. Introduction

The vehicle lateral dynamics, i.e. yaw motion stabilization and lateral velocity control, have important influence to the vehicle handling performance and safety [1]. To regulate the vehicle lateral dynamics, the active control methods such as active front steering (AFS) and direct yaw-moment control (DYC) have been established to assure the handling performance and safety [2]. However, to utilize the active control methods, many additional components (i.e. steering motor, and the corresponding sensors and actuators) have to be equipped on the vehicle. With the complicated subsystems used in active control schema, it is urgently to employ the in-vehicle network system to exchange the signals between the controllers, sensors, and actuators. Recently, the controller area network (CAN) has attached more and more attentions in modern vehicles [3–5]. The vehicle states and control signals are always transmitted from the sensors to controllers via CAN. Many control strategies have been well studied and implemented in engineering field, such as adaptive robust control [6], adaptive backstepping control [7], gain-scheduling approach [8], and Robust non-fragile H_∞ control [9]. However, due to the bandwidth of the network and the noise caused by electro-magnetic effect, the measurement and control signals transmitted on the network

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https://doi.org/10.1016/j.ymssp.2017.09.012
0888-3270/

might be delayed or dropped. Thus, the vehicle dynamics control can be treated as a networked control system (NCS) under unreliable communication links, where the control performance may be degraded because of the network-induced delay or data packet dropout [10].

To regulate the vehicle lateral dynamics under unreliable communication links, a controller combined AFS and DYC for four-wheel-independent-drive electric vehicles was presented in [10], and the NCS problem in CAN with time-varying delays was handled by expressing delay uncertainties in the form of a polytope using Taylor series expansion. In [11], an driver assistance system for automated highway system (AHS) was proposed by graph technology to handle the communication links (vehicle-to-vehicle) with random packet dropouts. In [12], a sampled-data NCS with delays, data packet dropouts, and measurement quantization consideration was modeled as a nonlinear time-delay system, and the problem of network-based H_∞ control was solved. In [13], the tracking problem in NCS with delay was discussed. It is assumed that the probability for the occurrence of each delay was assumed to be known. In [14,15] deterministic approaches were chosen to handle the delays and packet dropout in NCS, and the maximum delays were considered in the controller design. The aforementioned approaches mostly treated delay or dropout as certain values, i.e. maximum time of delay, or maximum number of data dropout. In practice, the delay time or data dropout probability may be time-varying, and cannot always reach the maximum values. Therefore, conservations might be introduced in the aforementioned closed-loop control system.

To handle the aforementioned problem, some researchers treated the data dropouts as random binary numbers that obey Bernoulli distribution. In [16] the delay and data packet dropout in NCS were assumed to obey certain probability distributions, and a packet dropout separation method was proposed to separate packet dropouts from the lump sum of network-induced delays and packet dropouts. In [17], a H_∞ fuzzy control for nonlinear systems under unreliable communication links was proposed. In [19], the nonlinear analysis of a tractor-semitrailer vehicle system with time delay was discussed. In [20], the time-varying delays compensation algorithm for powertrain active damping of an electrified vehicle was given. In [21], variance-constrained control for uncertain stochastic systems with missing measurements was proposed. In [22], the robust H_∞ control for networked systems with random packet losses was discussed. In [23], a packet loss model for the network was proposed with which the results for discrete-time linear systems with Markovian jumping parameters could be applied. However, the aforementioned literatures generally adopted the state-feedback control, where all the system states are assumed to be known in the control loop. Note that the vehicle lateral velocity is always a system state to be measured in state-feedback based control schema. The measurement of vehicle lateral velocity needs expensive sensors, e.g., dual antenna GPS system or optical sensors, which cost too much for commercial cars.

Generally, from the practical application perspective, the output-feedback control is a feasible alternative control schema to reduce the measurement cost. Many output-feedback control strategies for vehicle handling and stability improvement have been proposed in previous research works [24]. In [25] a fuzzy control strategy of non-linear networked discrete-time system with missing measurements was presented. In [26], a robust static output-feedback controller design for vehicle dynamics subjected to external disturbance and unknown sensor faults was designed. In [27], a static output-feedback design procedure for robust emergency lateral control of a highway vehicle was presented. An observer-based fuzzy controller was proposed in [28], where integrated H_∞ control and optimal control strategies were based on output-feedback control schema. A static output-feedback controller was designed in [29] for vehicle suspensions.

Nevertheless, to the best knowledge of the authors, few literatures investigated the vehicle lateral dynamic control with output-feedback control schema under unreliable communication links. To handle the data dropout problem in vehicle lateral motion regulation, this paper presents a robust H_∞ static output-feedback controller considering the parameter uncertainties and external disturbances. The aim of the proposed controller is to make the vehicle track the desired yaw rate with AFS, while improving the vehicle stability under unreliable communication links. The main contributions of this paper are listed as follows: (1) The probability of data dropout is considered in the vehicle lateral motion regulation, and the form of parallel distributed compensation (PDC) is adopted in the paper; (2) Both of the yaw rate and the lateral velocity are simultaneously controlled based robust H_∞ static output-feedback control schema; (3) Both of the tire cornering stiffness and the external disturbances are considered to enhance the robustness of the proposed controller.

The rest of the paper is organized as follows. The modeling of vehicle lateral dynamics with parameter uncertainties under unreliable communication links are discussed in Section 2. The robust H_∞ static output-feedback controller design is presented in Section 3. Simulation based on a high-fidelity and full-vehicle model via CarSim-Simulink joint platform is presented in Section 4, followed by the conclusion in Section 5.

2. System modelling and problem formulation

2.1. Vehicle modelling with parameter uncertainties

A bicycle model of the vehicle is shown in Fig. 1. Assuming the front-wheel steering angle is small, the vehicle's handling dynamics in the yaw plane can be expressed as:

$$\begin{cases} \dot{v}_y = \frac{F_{yf}+F_{yr}}{m} - r v_x \\ \dot{r} = \frac{l_f F_{yf} - l_r F_{yr}}{I_z}, \end{cases} \tag{1}$$