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Robust H_∞ output-feedback control for path following of autonomous ground vehicles

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ABSTRACT

This paper presents a robust H_∞ output-feedback control strategy for the path following of autonomous ground vehicles (AGVs). Considering the vehicle lateral velocity is usually hard to measure with low cost sensor, a robust H_∞ static output-feedback controller based on the mixed genetic algorithms (GA)/linear matrix inequality (LMI) approach is proposed to realize the path following without the information of the lateral velocity. The proposed controller is robust to the parametric uncertainties and external disturbances, with the parameters including the tire cornering stiffness, vehicle longitudinal velocity, yaw rate and road curvature. Simulation results based on CarSim–Simulink joint platform using a high-fidelity and full-car model have verified the effectiveness of the proposed control approach.

1. Introduction

Increasing demands and developing technologies on mobility, efficiency, and safety motivate the development of intelligent transportation means. Autonomous ground vehicle (AGV), with the improved security and better road utilization, has become an emerging research focus [1–3]. One of the most rudimentary issues for AGVs is path following [4,5], which is concerned with the control law design that forces a vehicle to reach and follow a predefined path that is specified without a temporal law, i.e., the desired path is not parameterized by time [6]. The path following errors (i.e., the lateral offset and the heading error) need to converge to zero to complete the path following manipulation.

The presences of the model uncertainties and external disturbances increase difficulties in path following control for AGVs, where model uncertainties may stem from the variations of the vehicle/environment parameters and the vehicle states. Several control strategies were proposed to handle these problems, such as, PID control [7], sliding mode control (SMC) [8], model predictive control (MPC) [9], artificial neural network control [10], chained systems theory [11], and optimal control [12]. These literatures generally regarded that the vehicle lateral speed (or sideslip angle) can be measured, however, typically the vehicle lateral speed can only be measured by expensive sensors, e.g., dual antenna GPS system or optical sensors. From the practical application perspective, the output-feedback control is a feasible alternative to be adopted in the path following control of AGVs to reduce the vehicle cost.

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Although numerous output-feedback strategies for vehicle handling and stability control were proposed in previous research works [13–15], literatures which applied output-feedback strategies in the path following control of AGVs were relatively limited. Ref. [16] proposed a robust weighted gain-scheduling H_∞ control design possessing steer-by-wire and drive/brake-by-wire functions for ground vehicles. Ref. [17] presented the design of a piecewise affine output-feedback controller for vehicle lane keeping, based on bilinear matrix inequalities optimization procedure, which was solved using the *V*–*K*-method. In [18], vision-based control strategies were presented for decentralized stabilization of unmanned vehicle formations, and an output-feedback approach using a high-gain observer was proposed to estimate the derivative of vehicles' relative position. In [19], an output-feedback adaptive neural network (NN) control was presented for transportation vehicles, incorporating a linear dynamic compensator to achieve stable dynamic balance and tracking of the desired given trajectories. An observer-based fuzzy controller was proposed in [20], which integrated H_∞ control and optimal control strategies so that without knowing the road's curvature, the vehicle could still keep its lane on a curved highway.

Nevertheless, few literatures simultaneously dealt with the uncertainties of the vehicle/environment parameters and the vehicle states, as well as the external disturbances, in the output-feedback path following control for AGVs. To this end, this paper proposes a robust H_∞ output-feedback path following controller for AGVs considering the external disturbances and parameter uncertainties. The proposed controller aims at making the vehicle track the desired path with the desired lateral and longitudinal velocities, with the integrated control of active front-wheel steering (AFS) and direct yaw-moment control (DYC). The main contributions of this paper lie on two aspects: 1) A robust H_∞ static output-feedback controller based on the mixed genetic algorithms (GA) [21]/linear matrix inequality (LMI) strategy is designed to regulate the controlled outputs without using the information of vehicle lateral velocity; 2) The uncertainties of the tire cornering stiffness, the vehicle longitudinal velocity and yaw rate, and the road curvature, as well as the external disturbances are simultaneously considered in the robust controller design.

The rests of the paper are organized as follows. The modeling of path following and vehicle lateral dynamic are discussed in Section 2. The robust static output-feedback controller is presented in Section 3. Simulation based on a high-fidelity and full-vehicle model via CarSim–Simulink is presented in Section 4, followed by the conclusion in Section 5.

2. System modelling and problem formulation

2.1. Path following model

The path following model is shown in Fig. 1, where e denotes the lateral offset from the vehicle center of gravity (CG) to the closest point T on the desired path. The heading error ψ is defined as the heading error between actual heading angle ψ_h and desired heading angle ψ_d, thus $\psi = \psi_h - \psi_d$, and $\dot{\psi}_h = r$, with r being the yaw rate of the vehicle. v_x and v_y is the longitudinal and lateral velocity of the vehicle, respectively. σ denotes the curvilinear coordinate (arc-length) of point T along the path from an initial position predetermined, while we know $\sigma \geq 0, \dot{\sigma} = d\sigma/dt$. $\rho(\sigma)$ represents the curvature of the desired path at the point T. The curvilinear coordinate of the point T along the path σ can be given as

$$\dot{\sigma} = \frac{1}{1 - e \cdot \rho(\sigma)} (v_x \cos\psi - v_y \sin\psi). \tag{1}$$

Based on the Serret–Frenet equation [22], the path following dynamics of vehicle can be modeled as follows:

$$\begin{cases} \dot{e}_1 = v_x \sin\psi + v_y \cos\psi \\ \dot{\psi} = r - \rho(\sigma) v_x \end{cases}, \tag{2}$$

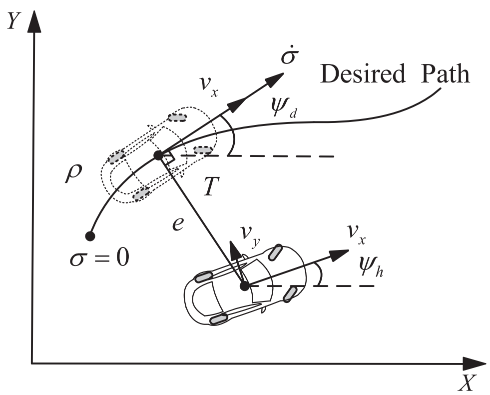

Fig. 1. Schematic diagram of path following model.