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Output-feedback triple-step coordinated control for path following of autonomous ground vehicles

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ABSTRACT

Over the past several decades, the automobile industry has devoted much significant research efforts to developing autonomous ground vehicles (AGVs). One of the most fundamental issues for AGVs is path following, which is concerned with the control strategy for AGVs to follow the scheduled paths. This paper presents a new path following control approach, where an output-feedback triple-step controller is designed to realize coordinated lateral and longitudinal control without a measurement of lateral velocity. The main contribution of this paper is the integrated design of the observer and control gains in the framework of Lyapunov stability and input-to-state stability (ISS) theory. The effectiveness of the proposed control system has been evaluated through simulations.

1. Introduction

Autonomous ground vehicles (AGVs) apply information, sense and control techniques to enhance driving safety and efficiency, and AGVs are considered to be an effective approach to improve traffic safety and reduce fuel consumption. The past three decades have witnessed the rapid development of AGV technologies, which have received considerable interest and efforts from academia, industry and governments [1–6]. For AGVs, one of the most fundamental issues is path following, whose core is the control system that forces a vehicle to follow a predefined path [7,8]. The lateral and longitudinal variables need to converge to the desired ones and complete the path following manipulation.

A considerable amount of practice and research on the path following control of AGVs has been obtained over the past decades. For instance, Hoffmann et al. [1] designed a nonlinear control law for AGV trajectory tracking and demonstrated their approach on a passenger vehicle for off-road operations. A study by Raffo et al. [2] developed an adaptive look-ahead selection with nonlinear model predictive control (MPC) that achieves a good compromise between performance and computational cost. Considering low-speed operation, Werling et al. [9] provided a tight integration of kinematics and dynamics for graceful motion to improve the trajectory tracking capability via Lyapunov-based approaches. Xin and Minor [10] investigated a smooth and graceful vehicle tracking behavior by applying the hierarchical manifolds set to variable structure backstepping control. The 1990's California PATH project [3,4] studied path following by look-ahead distance, and feedforward and feedback control, and it provided solid experimental results. A coordinated lateral and longitudinal controller with state feedback was used by [11] for emergency obstacle avoidance for high-speed AGVs. An automatic driving control system, named Kuafu-II [5], that included both longitudinal and lateral control was designed for high-speed AGVs.

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Nomenclature

φ	The actual heading angle
φ_e	The angular error between φ and the desired φ_d
K_L	The curvature of the desired path
D_L	The look-ahead distance
y_e	The lateral offset from the vehicle to point P
C_a	Aerodynamic drag coefficient
C_f	Front cornering stiffness
C_r	Rear cornering stiffness
F_{xi}	Longitudinal tire force of the ith wheel
F_{yi}	Lateral tire force of the ith wheel
F_x	Longitudinal force acting on the vehicle's center of gravity
F_{yf}	Front lateral tire force
F_{yr}	Rear lateral tire force
M	Mass of the vehicle
I	Wheel rotational inertia
I_z	Yaw inertia of the vehicle
R_e	Tire effective rolling radius
V_x	Vehicle longitudinal speed at the center of gravity
V_{rx}	Vehicle longitudinal speed reference
V_y	Vehicle lateral speed at the center of gravity
Ω_z	Vehicle yaw rate
l_f	Distance from front axle to the center of gravity
l_r	Distance from rear axle to the center of gravity
l_s	Half of the track width
ω_i	Wheel rotational speed of the ith wheel
T_i	Motor torque of the ith in-wheel motor
δ	The ground-wheel steering angle

The coordinated lateral and longitudinal control scheme is clearly one of the key trends in the next generation of AGV path following control systems [6,12–15].

Considering the fact that some of the states, such as lateral speed, may not be easily accessible in practice, numerous previous works have investigated the output-feedback path following problem (see, e.g., [1,2,9,10,16,17] for details). Most of these papers considered the output-feedback path following control problem as the combination of a state-feedback controller with a state observer that is able to estimate the lateral speed or sideslip angle of the vehicle. However, such a separation methodology does not inherently hold for the coordinated path following issue due to system nonlinearity. One example in [18] has indicated that irrespective of how fast the estimation error of the observer converges to zero or how small its initial condition is, initial conditions always exist from which a system escapes to infinity in finite time. In practice, the authors in [10] also observed that overincreasing the observer gains cannot improve estimates rather excite unmodeled dynamics. The effects of the observer in terms of output feedback control have also been discussed in vehicle suspension [19–21] and observer-based adaptive neural network control techniques [22–26]. Recently, [27] proposed an integrated scheme of the observer and control design for the path following of AGVs, but they overlooked model uncertainties and disturbances. In [17,28–30], output-feedback controllers robust against model uncertainties, external disturbances and sensor faults were designed, but these methods have certain conservativeness because only the worst case is considered.

Hence, this paper revisits the output-feedback control problem from an alternative perspective. Our study is strongly motivated by the successful application of the triple-step control approach [31]. From the application perspective, the design procedure of a triple-step controller consists of three advanced steps: a) the steady-state control, b) the reference variation-based feedforward control, and c) the tracking error feedback control. However, the method cannot be applied for multi-input multi-output (MIMO) systems, and model uncertainties are also not specifically considered. To solve these problems, an adaptive triple-step control scheme was presented by [32] for the path following of AGVs. Both model uncertainties and disturbances in vehicle kinematics and dynamics were handled by adaptive control techniques. Nevertheless, the method holds under the state-feedback assumption. Consequently, it cannot directly be used for the output-feedback control problem of AGV path following.

In this paper, an output-feedback triple-step control scheme is proposed for the path following of AGVs. The central idea behind the proposed method is the integrated design of the path following control system based on *a triple-step controller* for tracking control, *a reference generator* for virtual reference and *a reduced-order observer* for estimating vehicle lateral velocity. The proposed control procedure is of significant practical interest: