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Output-feedback robust control for vehicle path tracking considering different human drivers' characteristics

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ABSTRACT

A dynamic output-feedback, robust, shared controller considering different drivers' characteristics is proposed to assist human drivers for path tracking. The uncertain, diverse parameters for describing different drivers' characteristics including delay time, preview time, and steering proportional gain are considered and handled by a polytope. The regional pole placement is applied in the proposed dynamic output-feedback controller to improve the stability and performance of the driver-vehicle system. A method to convert the multi-objective H_∞ robust control into the single objective control is also introduced. Simulation results indicate that performance of path following for the driver-vehicle systems with different human drivers are improved with the proposed controller. Meanwhile, physical workloads of the inexperienced drivers are significantly reduced. Simulation results also show that the delay time of the driver-vehicle system can be adjusted by the pole placement, and the preview time of the driver can also be reduced to some extent with the proposed controller. Robustness of the controller is preserved against parameter variations and disturbance.

1. Introduction

In the variety of vehicle-related accidents, most of the casualties and injuries are caused by drivers' operating mistakes [1]. To improve the driving safety, advanced vehicle driver assistance systems (ADAS) to assist the driver in recognizing and reacting to potentially dangerous traffic situations, were applied for improving driving comfort and traffic safety [2]. The ADASs have been intensively studied in recent years, including pedestrian protection system [3], blind spot warning system [4,5], lane-departure detection and avoidance systems [6,7], collision threat assessment and avoidance systems [8–10], etc. The inchoate ADASs provided alarm information for the driver primarily when detecting the imminent danger, while current ADASs mainly concentrate on avoiding accidents and reducing the damage by providing active auxiliary control of the vehicle for the driver. The essence of ADASs is to achieve better control effects for vehicles through the combination of assistance control systems and drivers. In other words, the assistance control system shares the control authorities of maneuvering with the human driver together, rather than taking over the driver's authorities [11]. Therefore, the human driver can be regarded as a controller to some extent, and it will be more accurate to design the shared controller if we gain further insight into the characteristics of different drivers, including the age, gender, driving experience, physical limitation, and psychology factors, etc.

In practice, providing natural and effective shared control between the assistance control system and the human driver is one of the most formidable challenges involved in designing ADAS [12]. The characteristics differ greatly among different drivers. For example, expert drivers are capable of handling some emergent maneuvering conditions, such as emergency obstacle avoidance beyond the capacity of novice drivers. Aggressive and conservative drivers who possess different driving propensities also behave differently even though under the identical traffic conditions, showing different management on the variation of vehicle velocity, fuel consumption, and exhaust emission [13,14]. Consequently, the effort and influence of the shared control in terms of different drivers may also differ, how to understand and explain the driver's control behavior reasonably becomes the first step to achieve the assistance control. Preview time and delay time are two key parameters for describing drivers' properties and characteristics [15]. Relationships between these two parameters can be found through testing on vehicles driven by different drivers in diverse maneuvering scenarios. Generally, drivers with longer delay time need more preview time to maintain vehicle stability during path tracking, and the tracking accuracy might be diminished due to the large preview time. On the contrary, drivers with shorter delay time need less preview time to maintain vehicle stability, with capability of better tracking accuracy. Besides, as reported in [16], young and aged drivers appear with diverse combinations of steering

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proportional gain and delay time in the same maneuver. The aged drivers might possess a smaller steering proportional gain and a longer delay time when compared with the young drivers.

LMI-based state-feedback and output-feedback robust control are two prevalent control algorithms used in vehicle dynamics community. LMI has extensive applicability, with which problems can be addressed by numerically tractable means. Since LMI is a convex constraint, as for convex optimization problem [17,18], solving LMIs can be converted into one kind of convex optimization problem that without equality constraints [19]. The most critical shortcoming of state-feedback robust control is that all state variables are required to be measurable, which leads to a huge cost in sensors when encountering expensively obtainable state variables. To decrease the cost in implementing the controller while maintaining the control performance, LMI-based output-feedback robust control has been extensively studied, see [20–23], and the references therein. LMI-based static output-feedback control has perfectly solved the optimization problem under bilinear matrix inequality non-convex constraints [21]. However, it is worth mentioning that the pole placement in static output-feedback control is still an open problem. In [24], the author has proved that the problem of pole placement via static output-feedback is NP-hard. Since pole placement has a significant influence on the control performance, especially on the relative stability of the closed-loop system, it is necessary to explore how to append pole placement to the output-feedback control.

Dynamic output-feedback control is a viable solution for pole placement which few research efforts have been paid to. Many published literatures either only studied the design feasibility of the dynamic output-feedback controller, or there existed linear matrix equality (LME) constraints in the pole placement control, which increased the computational complexity for the optimal solution. In [25,26], the authors designed dynamic output-feedback controllers for vehicle suspension system in the presence of control delay and output constraints, but without consideration of pole placement. In [27], dynamic output-feedback control for network controlled system with uncertain time-delay was investigated, however, the authors made no allowance for pole placement either. In [28], the problem about pole placement control for linear continuous-time system was addressed under dynamic output-feedback control, nevertheless sufficient conditions for design feasibility were outlined with respect to a set of LMIs and LMEs. Few existing literatures have explored vehicle dynamics problems including parameter uncertainties through dynamic output-feedback control with simultaneous consideration of pole placement, whose sufficient condition is derived as LMIs. In this paper we introduce the dynamic output-feedback control with pole placement for addressing the shared controller to assist human drivers for trajectory following.

This paper extends the previous work on vehicle trajectory following considering different drivers' steering characteristics [29] by adjusting delay time as well as modifying preview time of the driver-vehicle system. The proposed dynamic output-feedback controller enclosing regional pole placement could commendably share the authority of the vehicle with different drivers, by providing more assistance to the inexperienced driver and less or even no assistance to the sophisticated driver. In addition, with the continuous assistance of proposed controller, a novice driver can behave like an experienced driver. The main contributions of this paper are as follows: (1) A Linear Parameter-Varying (LPV) full-order dynamic output-feedback robust controller is proposed, and the three uncertain drivers' characteristic parameters including delay time, preview time, and steering proportional gain are disposed by a modified polytope. (2) To achieve performance improvement of the closed-loop driver-vehicle system, the regional pole placement control based on the quadratic *D*-stability is considered. By introducing the pole placement, the delay time of the driver-vehicle system can be adjusted, as well as the preview time can be modified to some extent. (3) The multi-objective H_∞ robust control is transformed into the single objective control with a smaller interference suppression degree.

The notation throughout the paper is fairly standard. A letter with bold font is used to represent a matrix, and for a real symmetric matrix $\mathbf{W}$, $\mathbf{W}\succ 0(\mathbf{W}\prec 0)$ denotes its positive (negative) definiteness. $\mathbf{0}$ and $\mathbf{I}$ are used to denote the zero matrix and identity matrix of appropriate dimensions, respectively. The symbol $*$ represents the block matrix which is identifiable from the symmetry, while • means an irrelevant block matrix.

The remainder of this paper is structured as follows. Section 2 describes the model of the driver-vehicle system and experimental test for drivers' characteristic parameters estimation. Section 3 presents the design of the dynamic output-feedback robust controller. In Section 4, simulation results are shown to verify effectiveness of the proposed controller for assisting different drivers to finish the slalom maneuvers under different scenarios. This is then followed by conclusion of the paper in Section 5.

2. Modeling and drivers' characteristic parameters estimation

2.1. Modeling

In this section, we apply the single-point preview model to describe the driver's maneuver in path tracking, as shown in Fig. 1. The vehicle has mass m and moment of inertia I_z about the vertical axis through its center of gravity (CG). V_x and V_y are vehicle longitudinal and lateral velocity, respectively. l_f and l_r are distances from front and rear axle to the vehicle CG, respectively. ψ is vehicle yaw angle, and β is the vehicle sideslip angle, which can be approximately represented as $\beta = V_y/V_x$ under the assumption of small angle. F_{yf} and F_{yr} are the front and rear lateral tire force, which are related to the front and rear tire slip angle α_f and α_r, respectively. δ_f is front tire steering angle, and Y is lateral position of vehicle CG along the global coordinates.

By assuming small front tire steering angle and vehicle heading angle, the driver-vehicle dynamics can be characterized as [29]

$$\begin{cases} \dot{V}_y = -V_x\dot{\psi} + \frac{1}{m}(F_{yf} + F_{yr}) + d_1 \\ \ddot{\psi} = \frac{1}{I_z}(l_f F_{yf} - l_r F_{yr}) + d_2 \\ \dot{Y} = V_x\psi + V_y + d_3 \\ \ddot{\delta}_{fd} = -\frac{1}{a_0 {T_d}^2}\delta_{fd} - \frac{1}{a_0 T_d}\dot{\delta}_{fd} + \frac{R_g G_h}{a_0 {T_d}^2}[Y_p - (Y + T_p V_x \psi)] + d_4 \end{cases} \tag{1}$$

where δ_{fd} is the driver's portion of front-tire steering angle, T_d is the delay time, T_p is the preview time, and G_h is the steering proportional gain. a_0 is a constant, and R_g is the gear ratio of the vehicle steering system. Y_p and $Y{+}T_p V_x \psi$ describe the lateral deviation of the preview point and the predicted position for the vehicle, respectively. d_i $(i = 1,2,3,4)$ is the modeling error resulting from linearization approximation. We consider the uncertain preview time, delay time, and steering proportional gain as varying parameters, and denote $\boldsymbol{\rho} = [\rho_1,\ \rho_2,\ \rho_3]^T$ with $\rho_1 = T_d$, $\rho_2 = T_p$, $\rho_3 = G_h$. We define the system state as $\boldsymbol{x} = [x_1,\ x_2,\ x_3,\ x_4,\ x_5,\ x_6,\ x_7]^T$, with $x_1 = V_y$, $x_2 = \dot{\psi}$, $x_3 = \psi$, $x_4 = Y$, $x_5 = \delta_{fd}$, $x_6 = \dot{\delta}_{fd}$, and $x_7 = \int_0^t (Y_p - Y - T_p V_x \psi)dt$. We also define $w = Y_p$ as the reference, i.e. the position of the preview point, and $u = \delta_{fc}$ as the assistance steering control to be designed. Then the driver-vehicle model can be described as

$$\dot{\boldsymbol{x}} = \mathbf{A}(\boldsymbol{\rho})\boldsymbol{x} + \mathbf{B_u}u + \mathbf{B_w}(\boldsymbol{\rho})w + \boldsymbol{d} \tag{2}$$

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