

Robust Control of a Four-Wheel-Independent-Steering Electric Vehicle for Path Tracking

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ABSTRACT

Compared with the traditional front-wheel-steering (FWS) vehicles, four-wheel-independent-steering (4WIS) vehicles have better handling stability and path-tracking performance. In view of this, a novel 4WIS electric vehicle (EV) with steer-by-wire (SBW) system is proposed in this paper. As to the 4WIS EV, a linear quadratic regulator (LQR) optimal controller is designed to make the vehicle track the target path based on the linear dynamic model. Taking the effect of uncertainties in vehicle parameters into consideration, a robust controller utilizing μ synthesis approach is designed and the controller order reduction is implemented based on Hankel-Norm approximation. In order to evaluate the performance of the designed controllers, numerical simulations of two maneuvers are carried out using the nonlinear vehicle model with 9 degrees of freedom (DOF) in MATLAB/Simulink. Simulation results show that the robust controller is superior to the LQR optimal controller in tracking accuracy in terms of the nominal vehicle model. Furthermore, the robust controller can make the vehicle track the target path well under the circumstances of different vehicle velocities and road friction coefficients, which indicates the robust controller has strong robust stability and good robust performance against parametric perturbations.

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INTRODUCTION

During recent years, automatic driving technology has become an emerging research focus for intelligent transportation systems to reduce traffic problems. Path tracking is the rudimentary capability and primary task for the autonomous ground vehicle (AGV). The designed path-tracking controller is required to make the vehicle track the target path with small tracking errors including the lateral offset and the heading error [1].

Numerous studies have been carried out regarding the control strategies of path tracking on traditional FWS vehicles. For optimal controller design, Goodarzi et al. [2] proposed a control strategy for automatic path control that integrates the active steering control (ASC) and direct yaw moment control (DYC) utilizing the optimal control theory. Based on backstepping and LQR method, Hu et al. [3] designed the path-following controller which can make the lateral offset and heading error converge to zero simultaneously, even in large-curvature roads. Salehpour et al. [4] used the particle swarm optimization (PSO) method to optimize the LQR controller so as to improve the path-tracking capability of passenger vehicles. Though these optimal controllers designed aforementioned have good path-tracking capability, they are only suitable for nominal models without parametric perturbations and external disturbances. To solve the problem of controller design for perturbed models, sliding mode control (SMC), robust control, model predictive control (MPC) etc. have been applied. Hu et al. [5] proposed the composite nonlinear feedback (CNF) and SMC algorithm for AGVs to eliminate the

steady-state errors in the path tracking and reject the impacts caused by the system uncertainties and time-varying reference. Wang et al. [6] studied the robust H_∞ state-feedback controller for AGVs with delay and data dropout to achieve the path tracking and vehicle lateral control simultaneously. You et al. [7] designed a robust controller via μ synthesis approach for active front steering (AFS) vehicles and carried out performance comparisons between full-order controller and reduced-order controller. Yakub et al. [8] proposed the model predictive control (MPC) with proportional-integral (PI) controller for coordination of AFS and DYC maneuvers for path-tracking control in a AGV and verified that the proposed control methods are useful to maintain and enhance vehicle stability along the desired path and have the ability to eliminate the effect of crosswind.

Four-wheel-steering (4WS) vehicles have superior maneuverability, handling stability and path-tracking capability than FWS vehicles [9, 11], and they are more suitable for regarding as AGVs. Since the path-tracking problem of the 4WS vehicle is more complex than that of the FWS vehicle, the control strategies of path tracking for 4WS vehicles are still relatively limited. Mashadi et al. [10] applied the LQR technique to 4WS vehicles for path-tracking controller design and drew the conclusion that the 4WS vehicle shows potential for path-tracking control of an AGV. An automatic path-tracking controller of a 4WS vehicle based on SMC theory is proposed in [11], and the controller has a more precise path-tracking capability than 2WS controller and has robust capability against system uncertainties. Yakub et al. [12] studied the MPC approach of 4WS

AGVs for path-tracking control and demonstrated that MPC is useful to maintain vehicle stability along the desired path and has an ability to eliminate the crosswind effect. An integrated 4WS+DYC robust control system for AGVs is designed in [13], and simulation results show that the controller has a profound ability to make the vehicle track the desired path in the presence of uncertainties.

In this paper, a novel 4WIS EV with steer-by-wire (SBW) system is proposed and two controllers are designed for path tracking. The comparative study of LQR+4WIS+DYC and μ synthesis+4WIS+DYC for path tracking is implemented via numerical simulations in MATLAB/Simulink. The aim is to design an advanced controller to improve path-tracking capability and obtain good robust performance against parametric perturbations and external disturbances.

CONFIGURATION OF 4WIS EV

A novel 4WIS EV is proposed and manufactured as shown in Figure 1. To realize four wheels steering independently, the 4WIS EV consists of four SBW systems. From Figure 2, we can clearly see that the SBW system is an integrated design of steering system and suspension system, and it is mainly composed of steering motor, worm and gear reducer, shock absorber, wheel steering angle sensor, etc. The wheel can rotate around the kingpin that is actuated by the steering motor through reducer, upper sliding column, upper swing arm, lower swing arm and lower sliding column. The wheel steering angle sensor is used to measure the real-time steering angle signal of each wheel for path-tracking control. Structural parameters of the 4WIS EV are displayed in Table 1.



Figure 1. 4WIS EV.

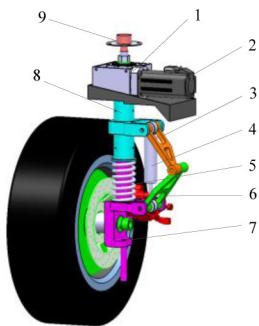


Figure 2. SBW system. 1, worm and gear reducer; 2, steering motor; 3, upper swing arm; 4, shock absorber; 5, spring; 6, lower swing arm; 7, lower sliding column; 8, upper sliding column; 9, wheel steering angle sensor.

Table 1. Structural parameters of 4WIS EV.

Parameter	Symbol	Unit	Value
Vehicle mass	m	kg	300
Vehicle moment of inertia	I_z	$\text{kg} \cdot \text{m}^2$	264
Distance from CG to front axle	l_f	m	0.8437
Distance from CG to rear axle	l_r	m	0.6903
Front tire cornering stiffness	k_f	N/rad	10200
Rear tire cornering stiffness	k_r	N/rad	13400
Wheelbase	L	m	1.534

MODELING

Dynamical Model of 4WIS EV

In this section, the dynamical model of the 4WIS EV is simplified as a single track model with 2 DOF. As shown in Figure 3, only lateral and yaw motions are taken into consideration to minimize the complexity of modeling with the assumption of constant longitudinal velocity u . The single track model has three inputs: the front steering angle δ_f , the rear steering angle δ_r , and the external yaw moment ΔM_z . The nonlinear dynamical equations of the signal track model can be derived as follows [14]

$$\begin{cases} F_{yf} \cos \delta_f + F_{yr} \cos \delta_r = m(\dot{v} + ur) \\ l_f F_{yf} \cos \delta_f - l_r F_{yr} \cos \delta_r + \Delta M_z = I_z \dot{r} \end{cases} \quad (1)$$

where v is the lateral velocity of vehicle, r is the yaw rate of vehicle, F_{yf} and F_{yr} are the lateral tire forces of the front and rear, respectively.

Based on the Dugoff tire model, the lateral tire force can be expressed as

$$F_{yi} = k_i \tan \alpha_i f(\lambda_i) \quad (2)$$

where the subscript i denotes the front (f) and rear (r) tires, α_i denotes the tire slip angle which can be written as

$$\begin{aligned} \alpha_f &= \delta_f - \arctan \frac{v + l_f r}{u} \\ \alpha_r &= \delta_r - \arctan \frac{v - l_r r}{u} \end{aligned} \quad (3)$$

$f(\lambda_i)$ is a nonlinear function and it is given as

$$f(\lambda_i) = \begin{cases} \lambda_i(2 - \lambda_i) & \lambda_i < 1 \\ 1 & \lambda_i \geq 1 \end{cases} \quad (4)$$

$$\lambda_i = \frac{\mu_i F_{zi}}{2k_i |\tan \alpha_i|} \quad (5)$$

where μ_i is the friction coefficient between the tire and road, F_{zi} is the vertical load on the tire.

For controller design, assuming that the tire slip angle is much small, the tire force has a linear relationship with respect to the tire slip angle and Equation (2) can be rewritten as

$$F_{yi} = k_i \alpha_i \quad (6)$$

Substituting Equation (6) into Equation (1), the linear dynamical equations of the signal track model can be expressed as

$$\begin{cases} \dot{v} = -\frac{k_f + k_r}{mu} v - \left(\frac{l_f k_f - l_r k_r}{mu} + u \right) r + \frac{k_f}{m} \delta_f + \frac{k_r}{m} \delta_r \\ \dot{r} = -\frac{l_f k_f - l_r k_r}{I_z u} v - \frac{l_f^2 k_f + l_r^2 k_r}{I_z u} r + \frac{l_f k_f}{I_z} \delta_f - \frac{l_r k_r}{I_z} \delta_r + \frac{\Delta M_z}{I_z} \end{cases} \quad (7)$$

Path Tracking

The path-tracking model of the 4WIS EV is illustrated in Figure 3. The xy body coordinate frame denotes the vehicle direction on its actual path, and $x_d y_d$ coordinate frame denotes the vehicle direction on its target path. In this paper, the problem of path tracking is equivalent to minimize the lateral position error Δy and yaw angle error which can be expressed as

$$\Delta \psi = \psi - \psi_d \quad (8)$$

Taking a derivative with respect to time, Equation (8) can be rewritten as

$$\Delta \dot{\psi} = \dot{\psi} - \dot{\psi}_d = r - \frac{u}{\rho} \quad (9)$$

where ρ is the radius of curvature of the target path.

The derivation of lateral position error Δy can be derived as

$$\Delta \dot{y} = v + u \Delta \psi \quad (10)$$

Combining Equations (7), (9) and (10), the dynamical equations of the 4WIS EV for path tracking can be written in the state-space form.

$$\begin{aligned} \dot{X} &= AX + BU + EW \\ Y &= CX + DU \end{aligned} \quad (11)$$

where the state vector $X = [v \ r \ \Delta y \ \Delta \psi]^T$, control input vector $U = [\delta_f \ \delta_r \ \Delta M_z]^T$ and external input vector $W = 1/\rho$, coefficient matrices A , B , C , D and E are given by

$$A = \begin{bmatrix} -\frac{k_f + k_r}{mu} & -\frac{l_f k_f + l_r k_r}{mu} - u & 0 & 0 \\ \frac{l_f k_f - l_r k_r}{I_z u} & -\frac{l_f^2 k_f + l_r^2 k_r}{I_z u} & 0 & 0 \\ 1 & 0 & 0 & u \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} \frac{k_f}{m} & \frac{k_r}{m} & 0 \\ \frac{l_f k_f}{I_z} & -\frac{l_r k_r}{I_z} & \frac{1}{I_z} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$D = [0]_{2 \times 3}, \quad E = [0 \ 0 \ 0 \ -u]^T.$$

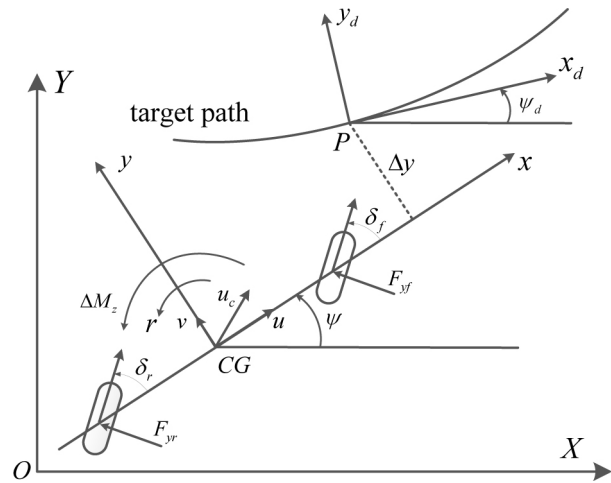


Figure 3. Dynamical model of 4WIS EV for path tracking.

OPTIMAL CONTROL

An optimal controller utilizing LQR approach is designed in this section, which aims to minimize the tracking error so as to make the 4WIS EV obtain the best path-tracking performance. The tracking error can be defined as

$$X_e = X - X_d \quad (12)$$

where X_d is the desired value.

$$X_d = [v_d \ r_d \ \Delta y_d \ \Delta \psi_d]^T = \begin{bmatrix} 0 & \frac{u}{\rho} & 0 & 0 \end{bmatrix}^T \quad (13)$$