

Fault-Tolerant Control for 4WID/4WIS Electric Vehicle Based on EKF and SMC

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ABSTRACT

This paper presents a fault-tolerant control (FTC) algorithm for four-wheel independently driven and steered (4WID/4WIS) electric vehicle. The Extended Kalman Filter (EKF) algorithm is utilized in the fault detection (FD) module so as to estimate the in-wheel motor parameters, which could detect parameter variations caused by in-wheel motor fault. A motion controller based on sliding mode control (SMC) is able to compute the generalized forces/moments to follow the desired vehicle motion. By considering the tire adhesive limits, a reconfigurable control allocator optimally distributes the generalized forces/moments among healthy actuators so as to minimize the tire workloads once the actuator fault is detected. An actuator controller calculates the driving torques of the in-wheel motors and steering angles of the wheels in order to finally achieve the distributed tire forces. If one or more in-wheel motors lose efficacy, the FD module diagnoses the actuator failures first. Then the reconfigurable control allocator accommodates faulty in-wheel motors and reconfigures the control allocation law of the healthy motors to achieve the desired vehicle motion to the greatest extent. Experimental verification is made to show that the proposed FTC algorithm is able to improve the vehicle's stability and handling performance in various driving scenarios.

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INTRODUCTION

The four-wheel independently driven and steered (4WID/4WIS) electric vehicle is a promising vehicle architecture due to its potential in emission and fuel consumption reduction [1]. A 4WID/4WIS electric vehicle utilizes four in-wheel motors and four steering motors to drive and steer the wheels independently, which has become an ideal platform to study the next-generation vehicle control. Such a actuation flexibility together with the in-wheel motors' fast and precise torque responses may enhance the existing vehicle control strategies, e.g., traction control system, direct yaw moment control, and other advanced vehicle stability control systems [2], [3], [4].

Owing to the significantly increased system complexity and number of actuators, the probability for fault taking place is higher. Therefore, the demands on reliability, safety, and fault tolerance for 4WID/4WIS electric vehicle are substantially elevated. Several fault-tolerant control strategies for ground vehicles have been previously suggested in the literature [5], [6], [7] and several fault-tolerant control methods for electric motors are proposed [8], [9], [10]. Some integrated control studies for 4WID/4WIS electric vehicle have been reviewed. For instance, Yang [11] puts forward a hierarchical integrated control strategy for 4WID/4WIS electric vehicle yaw stability which is integrated RBS DYC AFS/ARS ABS/TCS effectively. Zhu [12] considers a novel kind of vehicle-network architecture of the power system based on the 4WID/4WIS electric vehicle. However, most of these algorithms dealt with the problems associated with conventional vehicle architectures, it is thus necessary to design the control

systems which are capable of detecting, identifying, and tolerating faults so as to improve the reliability and safety for the 4WID/4WIS electric vehicle.

In this paper we propose a FTC approach for 4WID/4WIS electric vehicles based on EKF and SMC, as shown in Figure 1. The FD module estimates the in-wheel motor parameters so as to diagnose parameters variations caused by in-wheel motor fault by means of EKF algorithm. A motion controller based on SMC is able to compute the generalized forces/moments to follow the desired vehicle motion. By considering the tire adhesive limits, a reconfigurable control allocator optimally distributes the generalized forces/moments among healthy actuators. An actuator controller calculates the driving torques of the in-wheel motors and steering angles of the wheels.

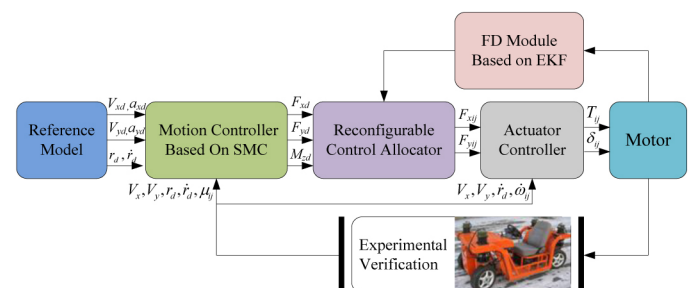


Figure 1. Schematic diagram of the proposed FTC approach.

The rest of the paper is organized as follows: the fault detection module is introduced in [section 2](#). The motion controller based on SMC is described in [section 3](#). The reconfigurable control allocator and actuator controller are presented in [section 4](#) and [5](#). Experimental results of FTC algorithms are given in [section 6](#) followed by conclusive remarks.

FAULT DETECTION MODULE DESIGN

The reliability of in-wheel motor has been considered as one of the major factors of the 4WID/4WIS EV. The fault detection (FD) module is designed to detect parameter variations caused by in-wheel motor fault by means of parameter estimation.

In-wheel Motor Model

The in-wheel motor has trapezoidal electromotive force (EMF) and quasi-rectangular current waveforms. The model of in-wheel motor is represented by

$$\begin{bmatrix} u_{as} \\ u_{bs} \\ u_{cs} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + k_e \omega \begin{bmatrix} f_{as}(\theta) \\ f_{bs}(\theta) \\ f_{cs}(\theta) \end{bmatrix}$$

$$\frac{d\omega}{dt} = \frac{p}{J} (T_e - T_l)$$

$$\frac{d\theta}{dt} = \omega$$
(1)

where, u_{is} and i_{is} are armature voltage and current, respectively. R and L denote resistance and equivalent inductance, respectively. k_e represents back-EMF coefficient, ω represents the wheel speed in rad/s, p represents pole pairs, J represents inertia, T_e and T_l represent electromagnetic torque and load torque, the functions $f_{as}(\theta)$, $f_{bs}(\theta)$ and $f_{cs}(\theta)$ have the same shape as back-EMF e_a , e_b and e_c with a maximum magnitude of ± 1 . The functions $f_{as}(\theta)$ is defined as

$$f_{as}(\theta) = \begin{cases} = 1 & \theta \in (0^\circ, 120^\circ) \\ = \frac{6}{\pi}(\pi - \theta) - 1 & \theta \in (120^\circ, 180^\circ) \\ = -1 & \theta \in (180^\circ, 300^\circ) \\ = \frac{6}{\pi}(\theta - 2\pi) + 1 & \theta \in (300^\circ, 360^\circ) \end{cases}$$
(2)

For similar equations $f_{bs}(\theta)$ and $f_{cs}(\theta)$, refer to the [figure 2](#). The back-EMF (e_a , e_b , e_c) and phase current (i_a , i_b , i_c) are shown in [Figure 2](#).

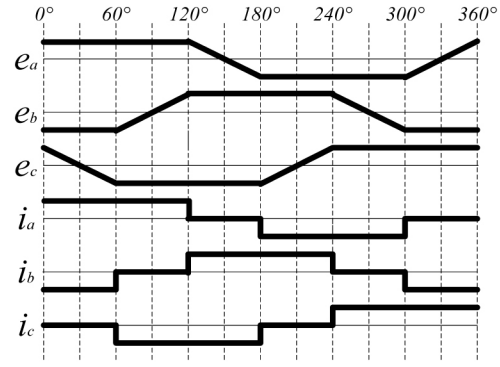


Figure 2. Signal waveforms in the BLDC motor

The [equations \(1\)](#) can be rewritten as a matrix equation,

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases}$$

(3)

where,

$$x = [i_a, i_b, i_c, \omega, \theta, R]^T$$

$$A = \begin{bmatrix} -R/L & 0 & 0 & -k_e T f_{as}(\theta)/L & 0 & 0 \\ 0 & -R/L & 0 & -k_e T f_{bs}(\theta)/L & 0 & 0 \\ 0 & 0 & -R/L & -k_e T f_{cs}(\theta)/L & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1/L & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/L & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/L & 0 & 0 & 0 \end{bmatrix}^T$$

$$u = [u_a, u_b, u_c]^T$$

$$y = [i_a, i_b, i_c]^T$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

Parameter Estimation Based on EKF

The Extended Kalman Filter (EKF) is an efficient state estimator for nonlinear systems, and it consists of the prediction and correction equations. By means of the state variables (x_k) and input variables (u_k), the estimated state variables ($\hat{x}_{k+1/k}$) and the estimation error covariance matrix ($P_{k+1/k}$) at the instant are predicted.

It is necessary that, from model (3), representing a continuous state space model, the following equivalent discrete-time system be deduced,

$$\begin{cases} x_{k+1} = Fx_k + Gu_k + w_k \\ y_k = Cx_k + v_k \end{cases} \quad (4)$$

If the continuous system is sampled with interval T , the matrices of the discrete-time system (4) can be obtained by Euler's approximation

$$F = I + AT, \quad G = BT \quad (5)$$

Because of measurement errors and inaccuracy of the machine model, measurement noise vector (v_k) and system noise vector (w_k) are introduced, which are supposed to be Gaussian white noises. They have a zero expectation and are characterized by their covariance matrix (R, Q).

The prediction equations are as follows

$$x_{k+1/k} = Fx_{k/k} + Gu_k \quad (6)$$

$$P_{k+1/k} = JP_{k/k}J^T + Gu_k + Q \quad (7)$$

The correction equations can be described as

$$K_k = P_{k/k-1}H^T [HP_{k/k-1}H^T + V_kR_kV_k^T]^{-1} \quad (8)$$

$$x_{k/k} = x_{k/k-1} + K_k[y_k - Hx_{k/k-1}] \quad (9)$$

$$P_{k/k} = [I - K_kH]P_{k/k-1} \quad (10)$$

where,

$$J = \frac{\partial(Fx_k + Gu_k)}{\partial x_k} \Big|_{x_k = x_{k/k}} \quad (11)$$

$$H = \frac{\partial(Hx_k)}{\partial x_k} \Big|_{x_k = x_{k/k}} \quad (12)$$

The estimated resistance by EKF algorithm is shown in Figure 3. The normal value of resistance is 0.36 Ω . After a 1.1 Ω resistance mutation fault is injected, the EKF algorithm can timely reflect the real change of motor parameters.

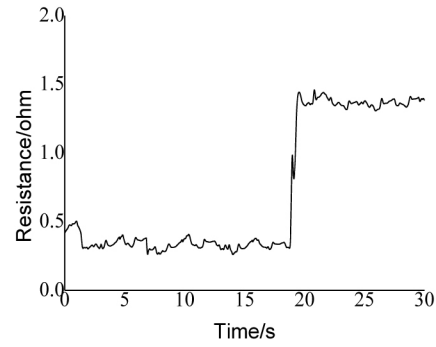


Figure 3. Estimated R (EKF)

MOTION CONTROLLER DESIGN

A motion controller is designed to determine the generalized forces/moments to track the desired vehicle dynamics, and it is based on reference model, vehicle model and sliding mode control (SMC) theory.

Reference Model

The reference model maps the relationship between the driver's inputs and the desired vehicle motion. All the desired longitudinal velocity V_{xd} , the desired lateral velocity V_{yd} and the desired yaw rate r_d are generated from the reference model. The reference model is written as follows

$$\begin{cases} V_{xd} = V_0 + \int_{t_0}^t a_{xd} dt \\ V_{yd} = 0 \\ r_d = \frac{V_x/(l_f + l_r)}{1 + KV_x^2} \cdot \frac{\delta_{sw}}{i_{sw}} \quad \{|r_d| \leq \mu g/V_x\} \end{cases} \quad (13)$$

where V_{xd} and V_{yd} are the desired longitudinal and lateral velocities of vehicle at cog, V_0 is the initial longitudinal velocity, V_x is respectively the longitudinal velocity of vehicle at cog, a_{xd} is the driver acceleration or deceleration command, δ_{sw} is the steering wheel angle, i_{sw} is the steering system ratio, $i_{sw} = \delta_{sw}/\delta_p$, K is the stability factor, μ is the resultant tire-road friction coefficient, g is the gravitational constant (9.8m/s²), l_f and l_r are longitudinal distances of cog to front axle and rear axle.

Vehicle Model

A 3-DOF double track vehicle model considering the planar motion and ignoring the vertical, pitch and roll motions is employed for the model-based controller design. The vehicle model is expressed as

$$\begin{cases} a_x = \dot{V}_x - V_y r = \frac{1}{m} F_x \\ a_y = \dot{V}_y + V_x r = \frac{1}{m} F_y \\ M_z = I_z \cdot \dot{r} \end{cases}$$

