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Fault-tolerant control of electric vehicles with in-wheel motors using actuator-grouping sliding mode controllers

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ABSTRACT

Although electric vehicles with in-wheel motors have been regarded as one of the promising vehicle architectures in recent years, the probability of in-wheel motor fault is still a crucial issue due to the system complexity and large number of control actuators. In this study, a modified sliding mode control (SMC) is applied to achieve fault-tolerant control of electric vehicles with four-wheel-independent-steering (4WIS) and four-wheel-independent-driving (4WID). Unlike in traditional SMC, in this approach the steering geometry is re-arranged according to the location of faulty wheels in the modified SMC. Three SMC control laws for longitudinal velocity control, lateral velocity control and yaw rate control are designed based on specific vehicle motion scenarios. In addition the actuator-grouping SMC method is proposed so that driving actuators are grouped and each group of actuators can be used to achieve the specific control target, which avoids the strong coupling effect between each control target. Simulation results prove that the proposed modified SMC can achieve good vehicle dynamics control performance in normal driving and large steering angle turning scenarios. In addition, the proposed actuator-grouping SMC can solve the coupling effect of different control targets and the control performance is improved.

1. Introduction

In recent years, due to the considerable potential in the reduction of emissions and fuel consumption, electric vehicles have been regarded as the promising vehicle architecture of the future. Because of the use of electric motors, such vehicles can have both four-wheel-independent-steering (4WIS) and four-wheel-independent-driving (4WID). In 4WID vehicles, four in-wheel motors are used to drive the four wheels and each individual wheel can be independently driven or controlled. Similarly, 4WIS electric vehicles can also have different steering angles for each wheel. Thus, for a 4WIS and 4WID electric vehicle, there is a total of eight control actuators which can be utilised to enhance the performance of traction control and direct yaw-moment control, and other advanced vehicle control strategies like energy-efficient control [1–4].

Compared with conventional vehicles, however, the probability of an in-wheel motor fault is a crucial issue due to the system complexity and large number of control actuators. The in-wheel motor fault may be caused by mechanical problems, over-heating of the motors or a fault associated with the motor drivers [5]. In addition, uneven road conditions can cause the

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individual wheel to lose contact with the road, thus losing friction force and this can cause a fault in an individual wheel. The fault of the in-wheel motor compromises the vehicle's dynamic control performance when conventional controllers are applied, so the design of the fault-tolerant controllers for electric vehicles is especially important.

Previously, to improve the robustness of the vehicle traction control, the model following control (MFC) approach has been proposed. This only required the input information of vehicle torque and wheel rotation speed [6–8]. Then the maximum transmissible torque estimation (MTTE) approach was developed to further improve the robust control performance of MFC [9]. Recently, a fault-tolerant control method based on MTTE has been suggested using a proportional-integral (PI) type disturbance observer [10], but this method only concerned the uncertainties of the mathematical model and sensor faults and did not focus on the failure of one specific wheel.

Driving actuator failure could be handled using the well-known H_∞ robust control method, but the dynamic performance of the vehicle under healthy conditions was also compromised [11]. To overcome this disadvantage, various active fault-tolerant controllers (AFTC) have been proposed based on the application of a fault detection and isolation (FDI) module [12,13]. According to the fault severity, different control structures and control parameters are selected after the fault is detected. In [14], two control structures in the AFTC approach were proposed to achieve the fault-tolerant control of an induction-motor affected by a speed-sensor fault. The first control structure was the PI controller for the healthy mode and the second controller was the H_∞ robust controller for the faulty mode.

This means, however, that specific controller strategies can be implemented only after the fault has been detected and therefore fault diagnosis is important for fault-tolerant control. In the literature, a number of fault diagnosis control strategies for conventional ground vehicles have been suggested, but these control methods are not for electric vehicles [15–17]. Several fault diagnosis methods for electric vehicles have been proposed [18,19], but motor failures are hard to diagnose using only the current and voltage sensors in the in-wheel motor. In [5,20], the faulty wheel could be identified by estimating the individual motor control gain without the knowledge of the specific tyre-road friction coefficient.

Apart from the fault of a sensor or a fault caused by the disturbance and model uncertainty, much study has been done into the failure of the specific in-wheel motor. A control method has been proposed in which the faulty wheel and its opposite side wheel were isolated but this degrades the performance and stability of the vehicle [21]. Wenbo et al. proposed a control strategy to enhance the performance of the vehicle in a small turn or at low speed, but conditions where the vehicle is moving in a sharp turn or at high speed were not discussed [22]. Xin et al. classified the control strategy into the failure-driving mode, which guaranteed the vehicle continued moving and the failure-stopping mode, which stopped the vehicle [23]. In [5], a sliding mode controller (SMC) was implemented as the high level controller to achieve the desired longitudinal velocity, lateral velocity and yaw rate, then the four driving torques of each wheel could be generated to achieve these values. An adaptive-control-based passive fault-tolerant controller was also designed to maintain vehicle stability and track the desired vehicle motion [20]. Wang and Wang also introduced an improved passive fault-tolerant controller which grouped the actuators having similar effects on the control of the system into one sub-system [24]. This control method was promising due to the direct distribution of the high-level control targets to each of the group of actuators in the lower level.

The adaptive control method, however, has the problem of high computational cost compared with the SMC method. For this reason many see SMC control in fault-tolerant control of 4WID vehicles as quite promising. In order to achieve better control performance, however, SMC needs large control gains and this will cause a large chattering effect. Alipour et al. suggested the proportional-integral sliding mode control (PISMC) strategy to improve the fault-tolerant control performance of the traditional SMC so that a smaller control gain could be selected and the chattering effect could be reduced [25]. Although the SMC control gain can be reduced significantly, however, the improvement of the actual dynamics control performance over the traditional SMC is not assured. Song et al. applied terminal sliding mode control (TSMC) to achieve the finite-time convergence and quick responsiveness on the terminal sliding manifold [26]. If the SMC method is applied in a 4WID vehicle to achieve multiple control targets, the control effort is allocated into the driving actuators of four wheels. One big problem is the coupling effect between different control targets and grouping the driving actuators is one of the solutions to solve this problem. For instance, the two front wheels can be considered as one group in order to control the body slip angle only, while the two rear wheels can also be regarded as one group in order to achieve the desired yaw rate. In this way, the control actuators related to the body slip angle will not have a strong effect on the control performance of the yaw rate. Except for [25] however, it appears that few researchers have examined the grouping of the driving actuators. Actuators having a similar control effect were grouped in [25], but this was not related to the coupling effect between different control targets.

This paper focuses on the fault-tolerant control method and the location of the specific faulty wheel is assumed to be known. This assumption is reasonable according to the literature [5,19,20,24]. The newly proposed SMC fault-tolerant controller focuses primarily on 4WIS-4WID electric vehicles. The main contribution of this paper is to solve the coupling effect of different control targets by grouping the actual driving actuators in fault-tolerant control of a 4WID vehicle. In addition, due to the fault of one specific wheel, the steering geometry of the whole vehicle will be re-arranged and the actual steering actuators will be adjusted in the 4WIS vehicle.

The rest of this paper is organised as follows: vehicle modelling is presented in Section 2. The steering geometry during the wheel fault is discussed in Section 3. The SMC method and its modification are shown in Section 4. The simulation results of comparing the SMC method with other stability controllers are shown in Section 5. Section 6 describes the strategy of grouping driving actuators in the SMC method to achieve better control performance. Section 7 shows the advantage of grouping the driving actuators in SMC over the traditional SMC methods. Finally, the conclusion is given in Section 8.

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