EVS26
Los Angeles, California, May 6 - 9, 2012

Traction Fault Accommodation System for Four Wheel Independently Driven Electric Vehicle

Wenbo Chu, Yugong Luo, Yifan Dai, Keqiang Li
State Key Laboratory of Automotive Safety and Energy
Tsinghua University, Beijing, 100084, likq@tsinghua.edu.cn

Abstract

This paper presents a traction fault accommodation system(TFAS) for four wheel independent drive electric vehicle (4WID EV), which can comprehensively address issues of drive capability, stability performance, reduce vehicle body impact and protect motor when fault occurs. This fault accommodation system uses available information to reallocate the traction force. Firstly, this strategy takes account of wheel force saturation and rate limitation as constraints; secondly, the strategy utilizes meeting desired longitudinal traction force and yaw moment as optimization objective; thirdly, the strategy takes account of the idea reducing priority in use of failure motor. Then, a dynamic control allocation method using constrained quadratic programming is proposed, which can be solved by active set method. Detailed simulations and trial results with an independent 4WID EV verify that the developed fault accommodation system provides significant benefits in terms of drive capability and stability performance while at the same time also meets demand of motor characteristics in different fault situation.

Keywords: wheel hub motor; electric drive; safety; torque

1 Introduction

In last decades, electric vehicle(EV) has attracted a great deal of interest as a powerful solution to both energy and environmental problems [1], which has already become a significant aspect of vehicle industry. Among various types of EV, four wheel independently driven(4WID) electric vehicle(EV) demonstrates broad prospects in vehicle application in the future. 4WID EV could achieve advanced performance than that of conventional vehicle due to the following advantages [2, 3]:

- High torque response.
- Precise torque generation.
- Precise knowledge of torque and wheel speed.
- Capability of generating traction and brake torque.
- Potentials in energy conservation.
- No adverse effect on driveshaft stiffness.
- In-wheel motors can be installed in rear and front tyres.
- Eliminate series of energy-robbing parts, including clutch, transmission, driveshafts and differentials.
- Make the drivetrain more modular and provide additional space for other devices.

With these attractive property, many advanced vehicle dynamic control strategies have been developed to enhance the vehicle dynamic control performance, including yaw moment control [4], traction control [2] and other advanced control systems. Even though the new structure is very attractive, some new problems arise. As 4WID EV is a complicated system which contains many components, such as motors, inverters, current sensors, batteries, controllers, speed sensors, wires, et al, and all these components continue operation over long life cycles under severe environmental conditions. Although good design practise tries to minimize the occurrence of faults and failures, there is a certain probability that faults will occur during long life running. The motor driven system is one of the most common and important sources of faults among all components. When in-wheel motor fault occurs, the motor can not provide the expected torque and serious traffic accident takes place without suitable control [5].

In order to deal with failsafe control in motor drive system, current study focuses on motor fault diagnosis [6] and motor fault tolerance control [5, 7]. In the EV application field, high reliability and robustness is necessary for various vehicle operation conditions. Many fault tolerant methods have been proposed when speed sensors [5, 8], current sensors [8] , position sensors,etc. fault occur.

These conventional studies on EV failsafe control are focused on how to detect fault states of the constituting components and compensate for the failed situations. A severe drawback of these approaches is that these studies can only deal with a total fault of single motor [8].

In order to maintain the vehicle stability and track desired vehicle motions cooperatively, yaw moment control and longitudinal traction force control should be concerned when we analyze fault conditions. The virtual controllers of 4WID EV consists yaw moment and longitudinal force. As there are four independent drive motors in 4WID EV, the number of actual controllers exceeds virtual controllers(i.e. 4WID EV is an actuation redundancy system). There is a certain probability that the excess number of motor can be exploited to accommodate the faults in the redundancy control problem.

Significant effort has been made in the last 30 years to solve problems in fault tolerant control [9]. The problem of traction fault accommodation system(TFAS) for 4WID EV is closely associated with control allocation in underwater vehicles [10] and aircrafts [11]. In such cases, the problem can be defined as the determination of the independent actuator control values to generate desired virtual control in actuation redundancy system. A control energy cost function is often used as optimization objective.

This paper mainly focus on a novel TFAS for 4WID EV, which can comprehensively address issues of drive capability, stability performance, reduce vehicle body impact and protect motor when fault occurs. Section 2 describes the control architecture of TFAS. A simplified vehicle motion controller is introduced in section 3. In section 4, firstly, a simplified 4WID EV model for TFAS is developed. Secondly, a failure control allocation problem is established. The problem takes account of wheel force saturation and rate limitation as constraints and utilizes fulfill desired longitudinal traction force and yaw moment as optimization objective. A significant algorithm is designed, which can reduce priority in use of failure motor. Thirdly, a dynamic control allocation method is proposed by using constrained quadratic programming, which is solved by active set method. In section 5, control strategy is tested and verified by experiments. The conclusion with potential future work is addressed in the final section.

2 Control architecture

A standard hierarchical TFAS control structure is shown in Fig.1. The state estimator collects the information from 4WID EV and driver. The vehicle motion controller calculates the desired longitudinal traction force F_{xd} and desired yaw moment M_{zd} by suitable algorithm. The control laws derived in the motion controller use the generalized forces F_{xd}, M_{zd} as virtual controls. In normal conditions, the traction force allocator allocates the traction force according to vehicle state. Otherwise, TFAS takes in charge of the allocator. Actual controls (traction force of individual motor) achieved by TFAS will give rise to the desired virtual controls according to well designed rules and constraints when fault occurs.

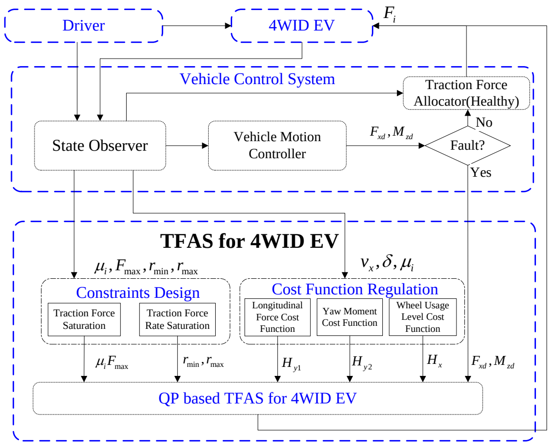

Figure 1: TFAS control architecture

3 Vehicle motion controller

3.1 Desired longitudinal traction force

The desired longitudinal traction force can be considered has linear relationship with acceleration pedal reference α, which can be calculated by Eq. (1) directly.

$$F_{xd} = K_a \alpha \tag{1}$$

where K_a denotes the magnification coefficient of traction force.

3.2 Desired yaw moment

Years of effort has been paid to design the direct yaw moment controller, especially using model matching control theory[4, 12]. However, this paper focuses on fault control not yaw moment calculation. It is assumed that the desired yaw moment should be zero when fault occurs.

$$M_{zd} = 0 \quad (2)$$

Further study will give a detail analysis of yaw moment, which is not included in this paper.

4 TFAS control allocation algorithm

4.1 4WID EV model design

In this paper, the actual 4WID EV model used in control is shown in Fig.2. The vehicle has three planar degrees of freedom for longitudinal motion, lateral motion and yaw motion. The control objective of TFAS is to make the faulty vehicle motion control performance the same as the healthy one. That means the vehicle motion control by TFAS should fulfill the desired longitudinal traction force and yaw moment. The lateral speed is not considered here. In this paper, individual wheels are addressed by the subscripts as presented in Table 1.

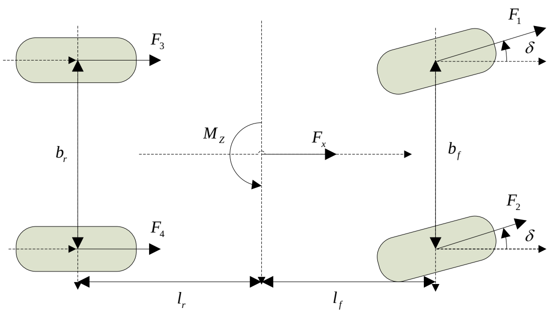

Figure 2: Actual 4WID EV model

Table 1: Abbreviations for the wheel positions

1	Front left	2	Front right
3	Rear left	4	Rear right

The vehicle longitudinal traction force F_x and direct yaw moment M_z generated by in wheel motor can be expressed as Eq. (3)(4).

$$F_x = F_1 + F_2 + F_3 + F_4 \quad (3)$$

$$M_z = \frac{b_f}{2}(F_2 - F_1) + \frac{b_r}{2}(F_4 - F_3) \quad (4)$$

where $F_i, i = \overline{1,4}$ denotes the tyre longitudinal force generate by in wheel motor, b_f is front axle track and b_r is rear axle track. By writing the relationship to a matrix form, Eq. (5) is generated.

$$\mathbf{y} = \mathbf{B}\mathbf{x} \quad (5)$$

$$\mathbf{y} = [F_x, M_z]^T$$

$$\mathbf{x} = [F_1, F_2, F_3, F_4]^T$$

$$\mathbf{B} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -\frac{b_f}{2} & \frac{b_f}{2} & -\frac{b_r}{2} & \frac{b_r}{2} \end{bmatrix}$$

where $\mathbf{y}$ is virtual control, $\mathbf{x}$ is actual control, $\mathbf{B}$ is the control effectiveness matrix.

4.2 Constraints design

As shown in Fig.1, the major approach to deal with the fault motor is setting up linear constraints which depend on failure factor, motor response rate and maximum traction force. Considering different fault situations, the motor is typically allowed to continue operation in a fault constraint, as shown in Eq. (6)

$$0 \le F_i \le \mu_i F_{\max} \quad (6)$$

$$\begin{cases} \mu_i = 0 & \text{Total fault} \\ 0 < \mu_i < 1 & \text{Partial fault}, \quad i = \overline{1,4} \\ \mu_i = 1 & \text{No fault} \end{cases}$$

μ_i is the fault factor, which can be obtained from motor fault diagnosis system. $F_{\max}$ is the maximum traction force generated from each wheel in healthy condition. The constraints described by Eq. (6)should be simplified and rewritten in matrix form:

$$\underline{\mathbf{x}} \le \mathbf{x} \le \overline{\mathbf{x}} \quad (7)$$

$$\begin{cases} \underline{\mathbf{x}} = [0, 0, 0, 0]^T \\ \overline{\mathbf{x}} = [\mu_1, \mu_2, \mu_3, \mu_4]^T F_{\max} \end{cases}$$

Rate constraints should also be taken into account in the control allocation problem. The rate constraint for motor is given by Eq. (8)

$$\mathbf{r}_{\min} \le \dot{\mathbf{x}} \le \mathbf{r}_{\max} \quad (8)$$

where $\mathbf{r}_{\min}, \mathbf{r}_{\max}$ denotes the minimum and maximum rate constraint of the motor.
It is reasonable to approximate the time derivative as

$$\dot{\mathbf{x}}(t) = \frac{\mathbf{x}(t) - \mathbf{x}(t-T)}{T} \quad (9)$$

where T is the sample time, t is real time.
Combining Eq. (7)-(9) yields over all constraints at time t.

$$\underline{\mathbf{x}}^* \le \mathbf{x} \le \overline{\mathbf{x}}^* \quad (10)$$

$$\begin{cases} \underline{\mathbf{x}}^* = \max\{\underline{\mathbf{x}}, \mathbf{x}(t-T) + T\mathbf{r}_{\min}\} \\ \overline{\mathbf{x}}^* = \min\{\overline{\mathbf{x}}, \mathbf{x}(t-T) + T\mathbf{r}_{\max}\} \end{cases}$$

4.3 Cost function regulation

A control allocation problem can be formulated now. The optimization objective of control allocation is to fulfill longitudinal traction and yaw moment demands with the constraints in Eq. (10). The control strategy utilizes desired longitudinal traction force and yaw moment as optimization objective. Such problems can take the form of a cost function shown in Eq. (11)

$$\Omega = \arg \min_{\underline{\mathbf{x}}^* \leq \mathbf{x} \leq \overline{\mathbf{x}}^*} \|\mathbf{H}_y(\mathbf{B}\mathbf{x} - \mathbf{y}_d)\|_2 \quad (11)$$

$$\mathbf{y}_d = [F_{xd}, M_{zd}]^T$$

$$\mathbf{H}_y = \text{diag}(H_{yF}, H_{yM})$$

where H_{yF} is the weighting function of longitudinal force, H_{yM} is the weighting function of yaw moment, $\mathbf{y_d}$ is desired virtual control.
$\mathbf{H}_y$ should be tuned by real-time vehicle status, when vehicle velocity is low and steering angle is small, TFAS tends to fulfill longitudinal traction force F_x, H_{yF} should increase; when vehicle velocity is high or steering angle is big, TFAS tends to fulfill yaw moment M_z, H_{yM} should increase to fulfill the desired yaw moment. One possible way to dynamic regulate $\mathbf{H}_y$ is Eq. (12)(13).

$$H_{yF} = c_1 \mathrm{e}^{-c_2|v_x|} + c_3 \mathrm{e}^{-c_4|\delta_f|} \quad (12)$$

$$H_{yM} = c_5 \mathrm{e}^{c_6|v_x|} + c_7 \mathrm{e}^{c_8|\delta_f|} \quad (13)$$

where $c_j, j = \overline{1,8}$ are positive real parameters, v_x can be estimated by the method developed by our group[13]. The solution of Eq. (11) satisfies the demand of the driver but not an optimal solution. Considering the idea of reducing the usage level of fault wheel, a further optimization objective is developed, as shown in Eq. (14).

$$u = \arg \min_{\mathbf{x} \in \Omega} \|\mathbf{H}_x \mathbf{x}\|_2 \quad (14)$$

$$\mathbf{H}_x = \text{diag}(\frac{1}{\mu_1 + \eta}, \frac{1}{\mu_2 + \eta}, \frac{1}{\mu_3 + \eta}, \frac{1}{\mu_4 + \eta})$$

where $\mathbf{H}_x$ denotes the usage level weighting function matrix. By increasing usage level weighting coefficient of fault wheel, the usage level of failure wheel is reduced. η is a very small positive real parameters.
By combining Eq. (11)(14), a new cost function can be obtained.

$$u = \arg \min_{\underline{\mathbf{x}}^* \leq \mathbf{x} \leq \overline{\mathbf{x}}^*} \|\mathbf{H}_x \mathbf{x}\|_2^2 + \lambda \|\mathbf{H}_y(\mathbf{B}\mathbf{x} - \mathbf{y}_d)\|_2^2 \quad (15)$$

where λ is a penalty factor. λ is normally chosen to be very large in order to emphasize the importance of fulfill longitudinal traction and yaw moment demands.

4.4 QP problem solve algorithm

The control allocation problem of Eq. (15)can be transformed to a standard QP problem form, shown in Eq. (16).

$$\begin{aligned} \min \quad & \frac{1}{2}\mathbf{x}^T \mathbf{H} \mathbf{x} + \mathbf{c}^T \mathbf{x} \\ s.t. \quad & \mathbf{A}\mathbf{x} \geq \mathbf{b} \end{aligned} \quad (16)$$

$$\mathbf{H} = 2(\mathbf{H}_x^T \mathbf{H}_x + \lambda \mathbf{B}^T \mathbf{H}_y \mathbf{H}_y^T \mathbf{B})$$

$$\mathbf{c}^T = -2\lambda \mathbf{y}_d^T \mathbf{H}_y \mathbf{H}_y^T \mathbf{B}$$

$$\mathbf{A} = [\mathbf{I}_4 \ \ -\mathbf{I}_4]^T$$

$$\mathbf{b} = [\underline{\mathbf{x}}^* \ \ -\overline{\mathbf{x}}^*]$$

This QP problem can be solved by active set algorithm [14].

5 Experimental results

Experimental validation of TFAS is carried out over a test 4WID EV developed by our group, shown in Fig.3 [15].

Figure 3: Experimental vehicle for TFAS

A series of tests is conducted to verify TFAS. In this paper. experiment data of two manoeuvres are considered here, as shown in Table 2.

Table 2: Experimental Manoeuvre

Case No.	Manoeuvre	Tendency
A1	FR wheel fault, low speed	F_x
A2	FR wheel fault, high speed	M_z

Experiment is carried out on good road, and motor fault occurs when the vehicle is running. In order to guarantee comparability of each experiment, the desired traction force F_{xd} is equally distributed to four wheels in healthy condition, which is defined as F^*.

Fig.4 corresponding to A1. In A1, vehicle velocity is low and steering angle is small, the tendency of the strategy is to fulfill the longitudinal traction demand, H_{yF} increases. At 1.3s, front right wheel is partial fault, $\mu_2 = 0.2$. The increasing force of rear wheel compensates the lost force of front right wheel. Both the longitudinal traction force and yaw moment demands are satisfied. At 2.8s, front right wheel recover partial function, $\mu_2 = 0.5$. The failure coordinate control strategy works well. At 4s, the front right wheel is totally faulty, $\mu_2 = 0$. In case A1, TFAS increases the force of all the healthy wheels to maintain traction demand but generate a small yaw rate, which can be compensated by steering angle.

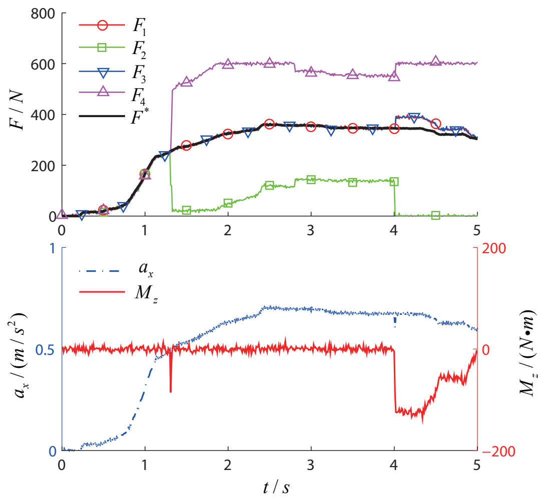

Figure 4: Experiment data of A1

Fig.5 corresponding to A2. In A2, vehicle velocity is high and steering angle is small, the tendency of the strategy is to fulfill the yaw moment demand, H_{yM} increases. At 3.2s, front right wheel is partial fault, $\mu_2 = 0.2$. The increasing force of rear wheel compensates the lost force of front right wheel. Both the longitudinal traction force and yaw moment demands are satisfied. At 5.8s, front right wheel recover partial function, $\mu_2 = 0.5$. At 7.6s, the front right is totally faulty, $\mu_2 = 0$. In case A2, TFAS works well and controls the forces of all the wheels to fulfill yaw moment demand.

6 Conclusion

Traction fault accommodation system for four wheel independently driven electric vehicle has been proposed. The validation of the proposed TFAS is verified by reasonable and acceptable experiment results. TFAS can maintain traction ability and stability of 4WID EV, reducing vehicle body impact and protecting motor when fault occurs. TFAS is also fit for independent drive vehicle with multi-wheels. Further research should concentrated on fault diagnosis and yaw moment calculation when fault occurs.

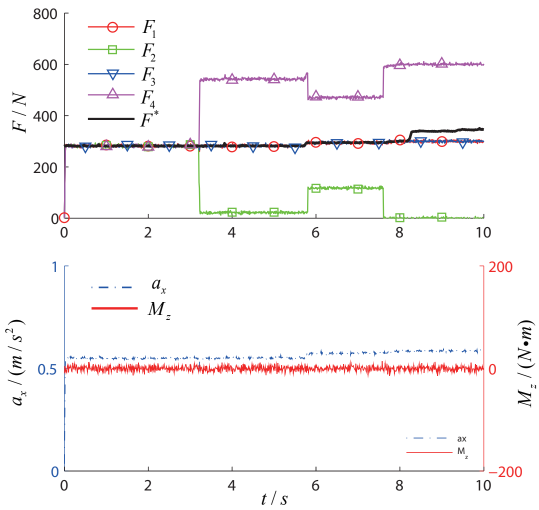

Figure 5: Experiment data of A2

Abbreviations

TFAS	Traction Fault Accommodation System
4WID	Four Wheel Independently Driven
EV	Electric Vehicle
QP	Quadratic Programming

Acknowledgments

The authors greatly appreciate the support from the National Basic Research Program of China (Grant No. 2011CB711204) and the State Key Laboratory of Automotive Safety and Energy (zz2011-092).

References

[1] U. Eberle et.al., *Sustainable transportation based on electric vehicle concepts: A brief overview*, Energy & Environmental Science, ISSN 1754-5692, 3(2010), 689-699.

[2] Y. Hori. *Future Vehicle Driven by Electricity and Control-Research on Four-Wheel-Motored "UOT Electric March II"*, IEEE Transactions on Industrial Electronics, ISSN 0278-0046, 51(2004), 954-962.

[3] P. Raksincharoensak et.al., *Vehicle Motion Control Issue Using Micro Electric Vehicle "NOVEL"*, World Electric Vehicle Journal, ISSN 2032-6653, 2007, 244-250.

[4] C. Geng et.al., *Direct Yaw-Moment Control of an In-Wheel-Motored Electric Vehicle Based on Body Slip Angle Fuzzy Observer*, IEEE Transactions on Industrial Electronics, ISSN 0278-0046, 56(2009), 1411-1419.

[5] M.E.H. Benbouzid et.al, *Advanced Fault-Tolerant Control of Induction-Motor Drives for EV/HEV Traction Applications: From Conventional to Modern and Intelligent Control Techniques*, IEEE Transaction on Vehicular Technology, ISSN 0018-9545, 56(2007), 519-528.

[6] B. Akin et.al., *A Simple Real-Time Fault Signature Monitoring Tool for Motor-Drive-Embedded Fault Diagnosis Systems*, IEEE Transactions on Industrial Electronics, ISSN 0278-0046, 58(2011), 1990-2001.

[7] S. Khwan-on et.al., *Fault tolerant, matrix converter, permanent magnet synchronous motor drive for open-circuit failures*, Electric Power Applications, ISSN 1350-2352, 5(2011), 654-667.

[8] N. Mutoh. *Front and Rear Wheel Independent Drive Type Electric Vehicle (FRID EV) with the Outstanding Driving Performance Suitable for Next-Generation*, World Electric Vehicle Journal, ISSN 2032-6653, 3(2009).

[9] H. Noura et.al., *Fault-tolerant Control Systems*, ISBN 978-1-84882-652-6, Springer Publishers, 2009.

[10] E. Omerdic et.al., *Thruster fault diagnosis and accommodation for open-frame underwater vehicles*, Control Engineering Practice, ISSN 0967-0661, 12(2004), 1575-1598.

[11] O, Härkegård. *Backstepping and Control Allocation with Applications to Flight Control*, Dissertation, Linkoping University, Linkoping, Sweden.

[12] M. Nagai et.al., *Study on integrated control of active front steer angle and direct yaw moment*, JSAE Review, ISSN 0389-4304, 23(2002), 309-315.

[13] W.B. Chu et.al., *Speed Estimation for All-wheel Drive Vehicles Based on Multi-information Fusion*, Automotive Engineering, ISSN 1000-680X, (33)2011, 962-966.

[14] Å Björck. *Numerical Methods for Least Squares Problems*, ISBN 0-89871-360-9, SIAM Publishers, 1996.

[15] B. Wang et.al., *Four wheel independent electric drive off road vehicle test bed*, Journal of Tsinghua University (Science and Technology), ISSN 1000-0054, 49(2009), 1838-1842.

Authors

Wenbo Chu received the B.Tech. degree from Tsinghua University, Beijing, China, in 2008. He is currently a Ph.D. candidate at the Department of Automotive Engineering, Tsinghua University. His research interests is about vehicle dynamics control and hybrid electric vehicles.

Yugong Luo received the Ph.D. degree from Tsinghua University, Beijing, China, in 2003, and the B.Tech. and M.S. degrees from Chongqing University, Chongqing, China, in 1996 and 1999 respectively. He is currently an Associate Professor with the Department of Automotive Engineering, Tsinghua University, Beijing, China. His active research interests include Vehicle & EV dynamics and control, and Vehicle NVH analysis and control. He has authored over 30 journal papers and is a coinventor on 15 patent applications.

Yifan Dai received the B.Tech. degree from Tsinghua University, Beijing, China, in 2008. He is currently a Ph.D. candidate at the Department of Automotive Engineering, Tsinghua University. His research interests include advanced active safety control and electric vehicle control.

Keqiang Li received M.S. and Ph.D. degrees from Chongqing University in 1988 and 1995 respectively, and the B.Tech. degree from Tsinghua University in 1985. He is currently a Professor with the Department of Automotive Engineering, Tsinghua University. His main areas of research interest include vehicle dynamics and control for driver assistance systems and hybrid electrical vehicles. He has authored over 90 papers and is a co-inventor of 12 patents in China and Japan.