

## **Passive Fault Tolerant Control of In-wheel Motor for Independently Driven Electric Vehicle**

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### **Summary**

This paper presents a passive fault tolerant control for an independently driven electric vehicle that is applied four in-wheel motors. The in-wheel motors are exposed from the vehicles, so this structure causes the motor fault easily. In this paper, the vehicle was mathematically modelled, and fuzzy control is used to distribute traction forces to each wheels. From modelling the vehicle, a passive fault tolerant control algorithm including model predictive control (MPC) was suggested to increase the reliability of the four in-wheel vehicle. The algorithm was confirmed by conducting a simulation, and the simulation was co-simulated MATLAB/Simulink and CarSim.

*Keywords: EV(Electric Vehicle), Torque, Safety, Prediction, Simulation*

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### **1 Introduction**

An independently driven Electric Vehicle(EV) applied in-wheel motors is one kind of the eco-friendly vehicle. The independently driven EV has the advantage of increasing reliability due to possibility of distributing each wheel torques[1],[2]. The independent control of wheel torque helps in generating vehicle's yaw moment to be stable.

However, the in-wheel motors of independently driven EV are exposed from the vehicle so that the in-wheel motors are occurred fault easily. This problem leads to unstable vehicle motion despite the advantage of independently driven vehicle for stability. Thus, the independently driven EV needs a fault tolerant control about motor fault cases.

Considering the motor fault, the permanent magnet motor which is type of in-wheel motor applied independently driven EV is developed to tolerate unstable drive[3]. Also, Liu[4] suggests a motor fault detection method. Furthermore, an active fault tolerant control for EV is researched to ensure safety of vehicle[5],[6]. However, the fault detection and the active fault tolerant control need sensors and more control steps to make the vehicle stable. These requirements cause increasing cost of vehicle and delay of vehicle control. In contrast, a passive fault tolerant control only needs existing sensors and modifying the control algorithm, so the passive fault tolerant control solve the disadvantage of the active fault tolerant control. The passive fault tolerant control is proposed from some research. For instance, Chao[7] developed the passive fault tolerant control composed of Model Predictive Control(MPC) and control allocation. This paper suggests a different strategy of the passive control from other passive fault tolerant controls, and MPC in this controller is verified at the motor fault case.

In this paper, we proposed the passive fault tolerant control strategy included MPC and fuzzy control. First section describes a mathematical vehicle model used in MPC. Next, the vehicle controller based on MPC and fuzzy control is introduced. The performance simulation was carried out by using the developed vehicle model and controller. The proposed controller was verified at the motor fault case in Dual Lane Change(DLC) test from the simulation results.

## 2 Vehicle Model

To design the vehicle controller, a planar model of EV with four in-wheel motors is considered. This mathematical vehicle model is modified from a bicycle model[8]. Figure 1 represents the planar model of EV.

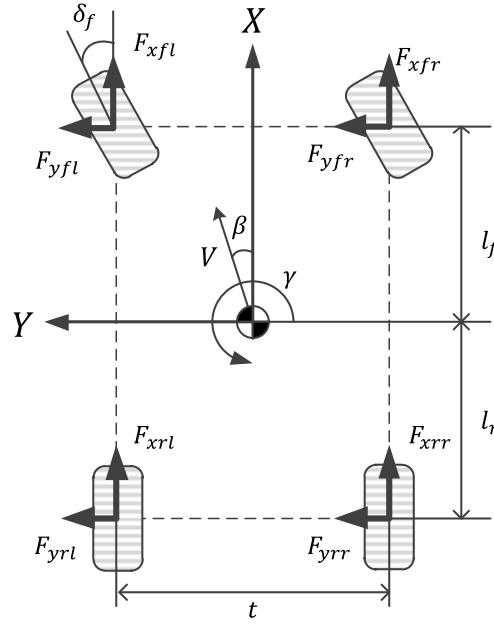


Figure 1: Vehicle model

$$\begin{aligned}
 mV(\dot{\beta} + \gamma) &= F_{yfl} + F_{yfr} + F_{yrl} + F_{yrr} \\
 I_{zz}\dot{\gamma} &= M_z + M_t \\
 M_z &= \frac{t}{2}(F_{xfr} - F_{xfl} + F_{xrr} - F_{xrl}) \\
 M_t &= l_f(F_{yfl} + F_{yfr}) - l_r(F_{yrl} + F_{yrr})
 \end{aligned} \tag{1}$$

Equation (1) represents the vehicle planar model from force equilibrium.  $m$  is the vehicle mass,  $F_{xij}$  and  $F_{yij}$  are longitudinal and lateral forces at four tires, and the subscript  $ij$  denotes tire position such as  $fl$  (front left).  $I_{zz}$  is yaw moment of inertia of vehicle,  $M_z$  is the yaw moment, and  $M_t$  is the moment caused by tire and road. The disturbance moment caused by side wind and driving corner is ignored in this model.  $t$  is the tread of vehicle, and  $l_f$  and  $l_r$  are the length of front and rear axle from the center of gravity.  $V$  is vehicle speed,  $\beta$  is side slip angle,  $\delta_f$  is the steering angle for front wheel and  $\gamma$  is the yaw rate.

Lateral force of four tires expressed by the linearized tire model like Equation (2).

$$F_{yfl} = C_{fl}\alpha_f, F_{yfr} = C_{fr}\alpha_f, F_{yrl} = C_{rl}\alpha_r, F_{yrr} = C_{rr}\alpha_r \tag{2}$$

In Equation (2),  $C_{ij}$  is the cornering stiffness, and  $\alpha_f$  and  $\alpha_r$  is front and rear slip angle. For small angles, the cornering stiffness and slip angle can be written

$$\begin{aligned} C_{fl} &= C_{fr} = C_f \\ C_{rl} &= C_{rr} = C_r \\ \alpha_f &= -\beta - \frac{l_f}{V} \gamma + \delta_f, \alpha_r = -\beta + \frac{l_r}{V} \gamma \end{aligned} \quad (3)$$

By substituting Equation (2) and (3) to Equation (1), matrix form equation can be expressed.

$$\begin{bmatrix} \dot{\beta} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} -\frac{2(C_f+C_r)}{mV} & -1 - \frac{2(l_f C_f - l_r C_r)}{mV^2} \\ -\frac{2(l_f C_f - l_r C_r)}{I_{zz}} & -\frac{2(l_f^2 C_f + l_r^2 C_r)}{I_{zz} V} \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \end{bmatrix} + \begin{bmatrix} \frac{2C_f}{mV} & 0 \\ \frac{2l_f C_f}{I} & \frac{1}{I_{zz}} \end{bmatrix} \begin{bmatrix} \delta_f \\ M_z \end{bmatrix} \quad (4)$$

From the Equation (4), the vehicle planar model is represented as the state space representations.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \\ x(t) &= \begin{bmatrix} \beta \\ \gamma \end{bmatrix}, u(t) = \begin{bmatrix} \delta_f \\ M_z \end{bmatrix}, y(t) = \gamma, \end{aligned} \quad (5)$$

$$A = \begin{bmatrix} -\frac{2(C_f + C_r)}{mV} & -1 - \frac{2(l_f C_f - l_r C_r)}{mV^2} \\ -\frac{2(l_f C_f - l_r C_r)}{I_{zz}} & -\frac{2(l_f^2 C_f + l_r^2 C_r)}{I_{zz} V} \end{bmatrix}, B = \begin{bmatrix} \frac{2C_f}{mV} & 0 \\ \frac{2l_f C_f}{I} & \frac{1}{I_{zz}} \end{bmatrix}, C = [0 \quad 1]$$

The vehicle system inputs are steering angle and yaw moment, and system output is defined the yaw rate. The states of the vehicle system are side slip angle and yaw rate.

### 3 Control Algorithms

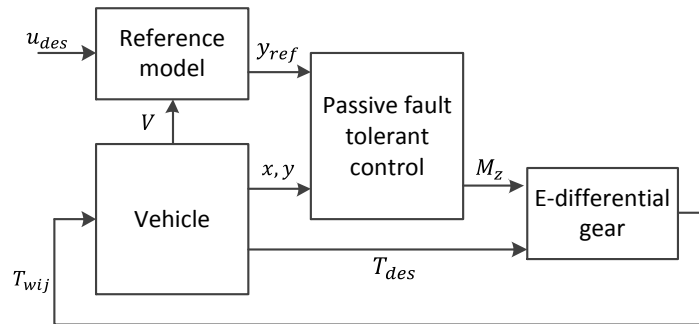


Figure 2: Control algorithm based on MPC and E-differential

Figure 2 shows a block diagram of overall control system. From the vehicle, the vehicle states and output values of state space model transfer to the passive fault tolerant control. Also, the reference output pass to the passive controller from reference model. The passive controller determines yaw moment, and total desired torque is calculated by motor speed-torque curve from vehicle speed. These two values input to electric differential gear. The electric differential gear distributes the torque to four tires and torque values input to the vehicle model.

### 3.1 Passive Fault Tolerant Control

The passive fault tolerant control is developed including MPC[9]. Since MPC can be predictive system perform and control system input by minimizing output of system, the controller with MPC determine system input faster and more smooth than the controller without MPC.

The MPC in the passive controller is designed as discrete time controller, but the state space equation is continuous model. Thus, state space equation (5) is changed to discrete-time state space model for applying discrete MPC. The discrete-time state space model is as follow.

$$\begin{aligned} x_m(k+1) &= A_m x_m(k) + B_m \Delta u(k) \\ y_m(k) &= C_m x_m(k) \end{aligned} \quad (6)$$

$$x_m(k) = \begin{bmatrix} \Delta x(k+1) \\ y(k+1) \end{bmatrix}, A_m = \begin{bmatrix} A & 0 \\ CA & I \end{bmatrix}, B_m = \begin{bmatrix} B \\ CB \end{bmatrix}, C_m = [0 \quad 1]$$

In Equation (6),  $k$  is the sample time. The object of MPC is predicting system behaviour, and future state and output are calculated to use for reducing error between past output and future output. Based on state space model, Equation (7) for calculating future state and output is formulated

$$Y = Gx(k_i) + H\Delta U \quad (7)$$

Cost function of MPC is defined by

$$J = (R_s - Y)^T (R_s - Y) + \Delta U^T R \Delta U \quad (8)$$

The first term of cost function is related to error between future and past output. The last term is about future control movement.  $R_s$  and  $R$  is coefficient matrix which is defined as  $R_s = I_{N_c \times N_c} \cdot x(k_i)$ ,  $R = I_{N_c \times N_c}$ . Equation (9) is for making the error of output as small as possible and finding optimal control input.

$$\frac{\partial J}{\partial \Delta U} = 0 \quad (9)$$

A prediction horizon( $N_p$ ) of MPC is set  $N_p = 10$ .

### 3.2 Electric Differential Gear

An electric differential gear is distributing traction force to four tires, so it preforms like a mechanical differential. To distributing traction force, fuzzy controller is used. Before the rule of fuzzy controller is designed, input and output of fuzzy control are chosen. The Independently driven EV controls the four in-

Table 1: Fuzzy rule-base to distribute traction torque

| $T_{fl} / T_{fr} / T_{rl} / T_{rr}$ |    | $M_z$       |             |             |             |             |
|-------------------------------------|----|-------------|-------------|-------------|-------------|-------------|
|                                     |    | NB          | NS          | ZE          | PS          | PB          |
| $T_{des}$                           | NB | NB/ZE/NB/ZE | NB/NS/NB/NS | NS/NS/NB/NB | NS/NB/NS/NB | ZE/NB/ZE/NB |
|                                     | NS | NB/PS/NB/PS | NS/ZE/NB/ZE | NS/NS/NS/NS | ZE/NS/ZE/NB | PS/NB/PS/NB |
|                                     | ZE | NS/PS/NB/PB | NS/PS/NS/PS | ZE/ZE/ZE/ZE | PS/NS/PS/NS | PS/NS/PB/NB |
|                                     | PS | NS/PB/NS/PB | ZE/PS/ZE/PB | PS/PS/PS/PS | PS/ZE/PB/ZE | PB/NS/PB/NS |
|                                     | PB | ZE/PB/ZE/PB | PS/PB/PS/PB | PS/PS/PB/PB | PB/PS/PB/PS | PB/ZE/PB/ZE |

wheel motor's torque, so output of fuzzy control is in-wheel motor torque. The output of fuzzy control is related to yaw moment and total desired torque which is required by driver. Therefore, the fuzzy logic rule is designed containing two inputs and one output considering Equation (1) showing relationship between yaw moment and wheel torque.

#### 4 Simulation and Discussion

In this research, the model of vehicle is KIA Ray which was gasoline model and was remodelled as independently driven EV. Therefore, the parameters of vehicle model(Table 2) is measured from the remodelled model.

The DLC test simulation is conducted by MATLAB/Simulink and CarSim to verify operating the passive fault tolerant control correctly. Three simulation cases are set. One is reference model without fault case, another is fault case with the passive fault tolerant controller with MPC, and the last simulation is fault case without the passive controller. The simulation condition is that the initial velocity of vehicle is 30km/h, and Accelerator Pedal(AP) signal is constant 1 value to imitate that driver want to full accelerator condition. Figure 3 presents steering angle input, and steering angle control is open loop control as yaw motion of vehicle is only affected by motor torque.

Table 2: Parameters of vehicle model

| Symbol   | Parameter                            | Unit           | Value |
|----------|--------------------------------------|----------------|-------|
| $m$      | Vehicle mass                         | $kg$           | 1463  |
| $t$      | Tread length                         | $m$            | 1.406 |
| $l_f$    | Distance from C.G. to front axle     | $m$            | 1.311 |
| $l_r$    | Distance from C.G. to rear axle      | $m$            | 1.255 |
| $C_f$    | Front equivalent cornering stiffness | $N/rad$        | 40000 |
| $C_r$    | Rear equivalent cornering stiffness  | $N/rad$        | 50000 |
| $I_{zz}$ | Yaw moment of inertia                | $kg \cdot m^2$ | 2065  |

In motor fault case, front left in-wheel motor has fault at 8 sec. The motor fault case is mechanical fault such as breaking shaft and bearing, so the motor torque value is multiplied by random factor( $n, 0 \leq n \leq 1$ ) at vehicle input signal to providing motor fault response. Two cases of motor fault are applied same random factor to compare.

Figure 4 and Figure 5 present the results of the simulations. Figure 4 is about global coordinate of vehicle. Considering motor fault case, the left side wheel torque is lower than right side, so counter clock wise yaw moment is occurred. Hence, vehicle is always driven to the left in open loop steering control. From the Figure 4, the trend of vehicle motion is detected driving to the left in motor fault case. For reducing counter clock wise yaw moment, the passive fault tolerant controller with MPC is used and improvement of motion of vehicle is observed in Figure 4. The passive controller cannot eliminate trend of driving to the left perfectly because the motor fault is mechanical fault. Also, from Figure 5, the longitudinal velocity of vehicle with MPC controller is slower than the vehicle without MPC. This result is caused by decreasing total traction force determined by controller.

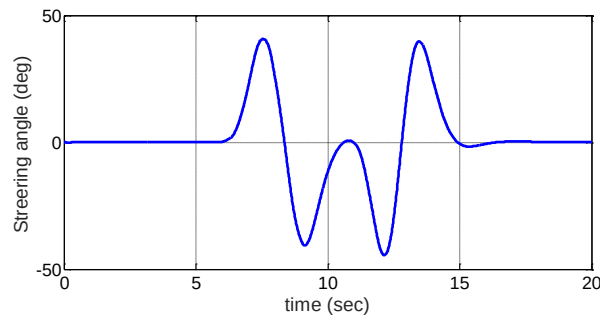


Figure 3: Steering angle reference

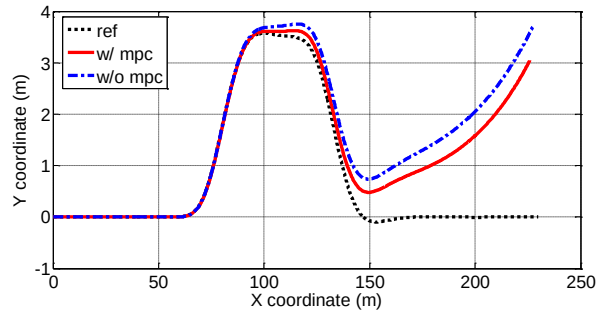


Figure 4: Global coordinate of vehicle

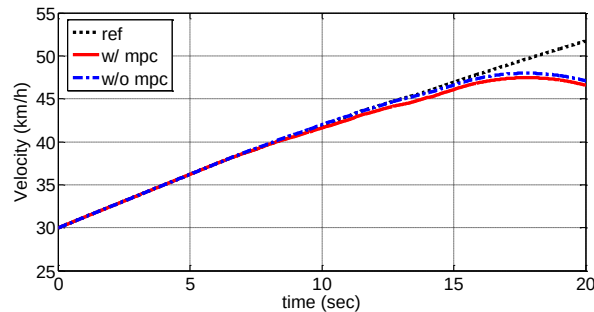


Figure 5: Vehicle longitudinal velocity

## 5 Conclusion

The passive fault tolerant control system was developed based on MPC and fuzzy control for Independent driven EV applied in-wheel motor. The simulation results are compared the control system with another control system without MPC. The simulation results indicated that MPC can reduce the yaw moment caused by motor fault, but applying MPC for fault tolerant control also lead to decrease total torque. In the future work, the controller will be modified to follow the reference motion despite motor fault case without decreasing total traction force.

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