

# A Control Allocation Algorithm for Improving the Fail-Safe Performance of an Electric Vehicle Brake System

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## ABSTRACT

The ample electrical power supply makes brake-by-wire technology more suitable for application in electric vehicles than in conventional vehicles. The fail-safe performance of a brake-by-wire system is a key factor regarding its application on production vehicles. A new control allocation algorithm for improving the fail-safe performance of an electric vehicle brake system is proposed. The electric vehicle is equipped with a four-wheel independent brake-by-wire and steer-by-wire system. The main objective of the algorithm is to maintain the vehicle braking performance as close to the desired level as possible by reallocating the control inputs to the actuators in cases of partial or full failure of the brake-by-wire system. The control algorithm is developed using a two degrees of freedom vehicle model. A pseudo control vector is calculated by a sliding mode controller to minimize the difference between the desired and actual vehicle motions. A pseudo-inverse controller then allocates the control inputs according to the pseudo control vector and the failure mode which is assumed to have been determined by some diagnostic algorithms. The control algorithm is evaluated in Matlab/Simulink. Cases of the brake-by-wire system's partial failure and full failure are all covered while performing the simulations. In cases of partial failure, the control algorithm reallocates the braking forces to the failure-free wheels and corrects the steering angles of the four wheels to compensate the yaw moment generated by the possible asymmetric braking. In the case of full failure, the wheels on each of the two axles are steered in opposite directions to generate braking forces. Simulation results show that the algorithm works effectively to ensure safe braking in case of brake system failures.

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## INTRODUCTION

"Control-by-wire" technology on vehicles has caught a lot of attentions with the development of automotive electronics and network technology. By using the control-by-wire technology, the conventional hydraulic, pneumatic or mechanical actuators are replaced by electric driving actuators, resulting in better controllability and faster response. Due to their ample demand for electricity supply, control-by-wire technology is made more suitable for application in electric vehicles than in conventional vehicles.

As a typical control-by-wire system, the fail-safe performance of the brake-by-wire system is a key factor regarding its application on production vehicles. In brake-by-wire systems, braking of wheels is usually controlled by independent actuators. From the viewpoint of control at vehicle level, failure of one or more brake actuators results in two possible undesirable consequences: 1) vehicle deceleration is less than desired one since the total braking force acting on vehicle is reduced, and, in the worst case,

failure of the whole brake-by-wire system results in no braking force; 2) brake force distribution becomes possibly asymmetric, creating a yaw moment [1].

An electric vehicle featured a four-wheel independent brake-by-wire and steer-by-wire system is an over-actuated system with redundancy of actuators. Although the redundancy improves system design flexibility, it brings challenges as well. It's a control allocation problem about how to reasonably make use of the redundancy to maximize the system performance. Control allocation for an over-actuated system was first proposed in flight control system design, and gradually applied in aerospace [2,3,4,5], navigation [6, 7], automobile [8], robot and other fields. Many control allocation algorithms have been developed in recent years, mainly including direct control allocation method, pseudo-inverse based methods, daisy chaining method, linear programming methods, and quadratic programming based methods, etc [3].

D. Doman and M. Oppenheimer [1] proposed an optimal control algorithm for dealing with failures of brake actuators in a vehicle featured a brake-by-wire system and a steer-by-wire system. By using dynamic inversion of vehicle model in conjunction with optimal control allocation and efficient methods of linear programming, the control inputs can be determined to minimize the difference between the desired and actual vehicle motions, while satisfying actuator constraints. However, the algorithm is only for the failure of one actuator. Failure of multiple actuators and failure of the whole brake-by-wire system are not covered.

A new control allocation algorithm for improving the fail-safe performance of an electric vehicle brake system is proposed in this paper. The electric vehicle is equipped with a four-wheel independent brake-by-wire and steer-by-wire system. The main objective of the algorithm is to maintain the vehicle braking performance as close to the desired level as possible by redistributing the control inputs to the actuators in cases of partial or full failure of the brake-by-wire system. The control algorithm is evaluated in Matlab/Simulink. Cases of the brake-by-wire system's partial failure and full failure are all covered while performing the simulations. Simulation results show that the algorithm works effectively to ensure safe braking in case of brake system failures.

## CONTROL ALLOCATION ALGORITHM

The framework of the control system using a control allocation algorithm is shown in Figure 1. The system includes a pseudo controller and a control allocation controller. The task of the pseudo controller is calculating pseudo control input,  $v_n$ , according to vehicle responses,  $x$ . Then the actual control input,  $u_m$ , to the vehicle actuators is calculated according to  $v_n$  by the allocation controller. In failure situations, the allocation controller has to reallocate the elements of  $u_m$  according to failure modes.

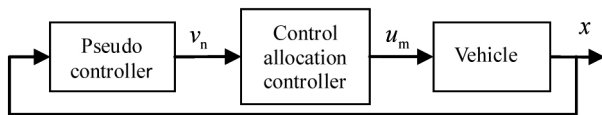


Figure 1. The framework of the control system

## Sliding Mode Pseudo Controller

A sliding mode algorithm is adopted for the pseudo controller. The pseudo controller is designed by using a 2-DOF four-wheel vehicle model shown in Figure 2, where lateral and yaw motions are concerned. In the figure,  $m$  and  $I_z$  are vehicle mass and vehicle angular moment of inertia around vertical axis;  $k_f$  and  $k_r$  are total cornering stiffness of front wheels and rear wheels, respectively;  $t_{wf}$  and  $t_{wr}$  are wheel tracks of front axle and rear axle, respectively;  $F_{xi}$  and

$F_{yi}$ ,  $i=1, 2, 3, 4$ , are longitudinal and lateral forces applied on the four tires;  $\delta_i$ ,  $i=1, 2, 3, 4$ , are steering angles of the four wheels;  $\alpha_i$ ,  $i=1, 2, 3, 4$ , are sideslip angles of the four wheels;  $a$  and  $b$  are the horizontal distance from vehicle center of gravity (COG) to front and rear axles, respectively;  $L$  is wheel base;  $\beta$  is vehicle sideslip angle at COG;  $u$ ,  $v$  and  $r$  are vehicle longitudinal speed, lateral speed and yaw rate, respectively.

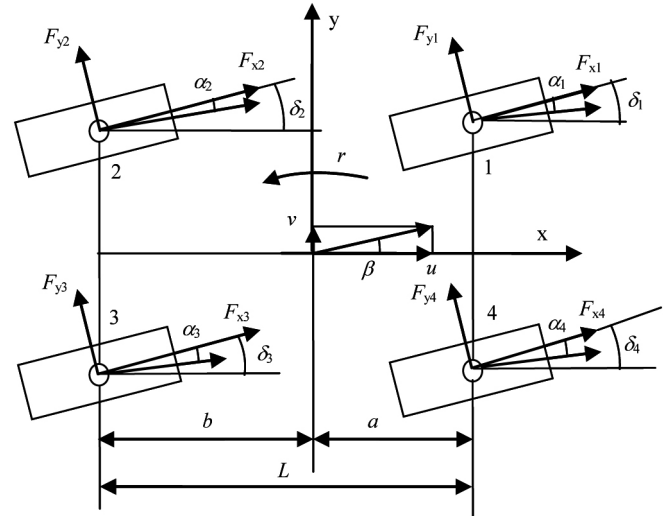


Figure 2. A 2-DOF four-wheel vehicle model

The over-actuated system of the vehicle can be described by the following equation [9]:

$$\dot{x} = Ax + Bu_m \quad (1)$$

where

$$x = [v \quad r]^T$$

$$A = \begin{bmatrix} \frac{\sigma}{mu} & \frac{\rho}{mu} - u \\ \frac{\rho}{I_z u} & \frac{\kappa}{I_z u} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{-k_f}{m} & \frac{-k_r}{m} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-k_f a}{I_z} & \frac{k_r b}{I_z} & -\frac{t_{wf}}{2} & -\frac{t_{wr}}{2} & \frac{t_{wr}}{2} & \frac{t_{wf}}{2} & 0 & 0 \end{bmatrix}$$

$$u_m = [\delta_f \quad \delta_r \quad F_{x1} \quad F_{x2} \quad F_{x3} \quad F_{x4} \quad \Delta\delta_f \quad \Delta\delta_r]^T$$

with some notations defined as below:

$$\delta_f = (\delta_1 + \delta_4)/2, \quad \delta_r = (\delta_2 + \delta_3)/2;$$

$$\Delta\delta_f = (\delta_1 - \delta_4)^2 \text{ and } \Delta\delta_r = (\delta_2 - \delta_3)^2;$$

$$\sigma = k_f + k_r, \quad \rho = ak_f - bk_r \text{ and } \kappa = k_f a^2 + k_r b^2.$$

Matrix A contains u as a variable parameter, so the system is non-linear.

Let  $v_n = [v_{n1} \ v_{n2}]^T = Bu_m$  and thus Eq. (1) becomes  $\dot{x} = Ax + v_n$ . Furthermore, it can be expanded as

$$\begin{cases} \dot{v} = \frac{\sigma}{mu} v + \left[ \frac{\rho}{mu} - u \right] r + v_{n1} \\ \dot{r} = \frac{\rho}{I_z u} v + \frac{\kappa}{I_z u} r + v_{n2} \end{cases} \quad (2)$$

The pseudo controller is a state-following controller by forcing x follow its desired value  $x_d = [v_d \ r_d]^T$ . Let  $v_d = 0$  in order to ensure good vehicle stability.  $r_d$  is determined according to the steering wheel angle input  $\delta_{sw}$  to represent

$$r_d = \frac{\delta_{sw} u}{i_s L}$$

the driver's steering intention, and  $i_s L$  for a neutral steering vehicle ( $i_s$  is steering ratio for vehicles with a conventional mechanical steering system).

Define a switching function for the sliding mode pseudo controller as  $S_1 = v - v_d$ , and then its derivative can be expressed as

$$\dot{S}_1 = \dot{v} - \dot{v}_d \quad (3)$$

Let

$$\dot{S}_1 = -K_{S1} \cdot \arctan(S_1) \quad (4)$$

where  $K_{S1}$  is a positive design parameter.

Substituting Eq. (4) and the first equation of (2) into (3) yields

$$-K_{S1} \arctan(S_1) = \frac{\sigma}{mu} v + \left[ \frac{\rho}{mu} - u \right] r + v_{n1} - \dot{v}_d \quad (5)$$

so,

$$v_{n1} = -K_{S1} \arctan(S_1) - \frac{\sigma}{mu} v - \left[ \frac{\rho}{mu} - u \right] r + \dot{v}_d \quad (6)$$

Similarly,  $v_{n2}$  can be calculated as follows by defining another switching function as  $S_2 = r - r_d$

$$v_{n2} = -K_{S2} \arctan(S_2) - \frac{\rho}{I_z u} v - \frac{\kappa}{I_z u} r + \dot{r}_d \quad (7)$$

where  $K_{S2}$  is another positive design parameter.

It is assumed that the values of u and v can be known by some estimation algorithm [10,11,12].

## Control Allocation Controller

For the electric vehicle featured a four-wheel independent brake-by-wire and steer-by-wire system, the total braking force can be expressed as

$$F_{total} = Cu_m \quad (8)$$

where,  $C = \begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 1 & \frac{1}{2}k_f & \frac{1}{2}k_r \end{bmatrix}$ . If Eq. (8) is

expanded, the last two items, i.e.  $\frac{1}{4}k_f \Delta\delta_f$  and  $\frac{1}{4}k_r \Delta\delta_r$ , are actually braking forces due to brake-by-steering (the two wheels on the same axle are additionally steered in opposite directions to generate braking effects) on front axle and rear axle, respectively. The desired value of  $F_{total}$  is determined according to the force on the brake pedal. In order to apply the control allocation algorithm,  $v_n = Bu_m$  and Eq. (8) can be combined as follows

$$w = Du_m \quad (9)$$

where

$$D = \begin{bmatrix} \frac{-k_f}{m} & \frac{-k_r}{m} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{k_f a}{I_z} & \frac{k_r b}{I_z} & -\frac{t_{wf}}{2} & -\frac{t_{wr}}{2} & \frac{t_{wr}}{2} & \frac{t_{wf}}{2} & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & \frac{1}{4}k_f & \frac{1}{4}k_r \end{bmatrix}$$

$$w = [v_{n1} \ v_{n2} \ F_{total}]^T$$

The control allocation controller can be described as

$$u_m = D^\# w \quad (10)$$

where  $D^\#$  is the pseudo-inverse of D, and  $D^\# = W^{-1} D^T (DW^{-1} D^T)^{-1}$  [13]. W is a weighted diagonal matrix.  $DW^{-1} D^T$  is a constant coefficient matrix and it can be easily proved to be revertible. If some control inputs in  $u_m$  exceed their operation limits, the inputs should be replaced with their saturated values. The derivation of Eq. (10) is described in Appendix.

## Reallocation Control Algorithm

A reallocation control algorithm can be used when a brake-by-wire failure occurs. In this case, a new solution for the control allocation problem can be found by modifying the