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EPAS Fail-Safe Control using Differential Braking

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Abstract

One of the main systems for ground vehicles is the Electric Power Assisted Steering (EPAS). Due to its importance, a redundant system is usually implemented. This solution remain however expensive, especially for small urban cars. This paper proposes an alternative fail-safe control algorithm using this time differential braking. Controlling each brake apart generates a yaw moment enabling turning the vehicle. Optimal coordination is ensured due to the importance of this maneuver. Results show that differential braking, that already exist in most of passenger cars, is able to generate a sufficient additional yaw moment to help the driver steer his/her vehicle. This can reduce the space and the cost of the vehicle.

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Keywords: Fail-Safe Control; Control Allocation; Chassis Systems

1. Introduction

Most of researches show that future passenger cars would be electric, connected, fully automated and shared. In the context of automation, control engineers should guarantee a safe operation of the fully automated vehicles in several standardized use-cases. In case of a critical system's failure, fail-safe control strategies should be ensured. A classic method broadly adopted by car manufacturers is to make these critical systems redundant. In [Eschtruth and Bouse \(2014\)](#), this was adopted for the Electric Power Assisted Steering (EPAS) system. In [Anwar and Chen \(2007\)](#) a redundancy-based fault detection and isolation regarding the Steer-By-Wire (SBW) has been proposed to reduce the total number of redundant road-wheel angle sensors while maintaining a high level of reliability. An example has also been given in [Zhang and Jiang \(2002\)](#) to demonstrate the effectiveness of a fault-tolerant control against partial actuator failures.

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However, in order to reach a fully automated vehicle, additional systems could be needed. This would increase the total price of the vehicle. In order to increase the number of systems and still preserve an affordable price of urban vehicles, control engineers should benefit from the synergies that already exist in most of vehicles [Coelingh et al. \(2002\)](#). Since the Electronic Stability Program (ESP) has become mandatory in 2014 according to [Carscoop \(2017\)](#), all new vehicles produced after 2014 should be equipped by a Differential Braking (DB). That means that recent and future passenger cars have the possibility to brake one wheel at a time. Braking only right wheels for example, can create a yaw moment, and therefore make the vehicle turn as explained in [Kissai et al. \(2018a\)](#). Therefore, regarding the EPAS safety, differential braking can be used in order to add an additional yaw moment to the vehicle, and help the driver steer the vehicle when the EPAS is down. Techniques used to solve the redundancy problem can be used to solve coordination of different systems in case of failure. Attention should be given nevertheless to the control technique to employ. Indeed, the control should switch from a system with a given behavior to another one with a different behavior. Control allocation methods are more suitable in this case. The existing reconfiguration methods have to modify controllers to tolerate faults. In contrast, control allocation methods only change allocation laws. This makes it extensible to current vehicles and easy to implement. Moreover, [Yang et al. \(2010\)](#) have shown that stability of the closed-loop system after reconfiguration can be guaranteed.

This paper outlines the advantages of using optimization-based control allocation algorithms in order to make the EPAS system fault-tolerant by using differential braking. The architecture proposed is extensible to additional subsystems, and could be easily adopted for additional chassis systems, as for example the Active Rear Steering (ARS) system or in-wheel motors based Torque Vectoring (TV) if such systems are available [Kissai et al. \(2019\)](#). Promising results were obtained by co-simulation of Matlab/Simulink[®] that inhabits the control logic, and Simcenter Amesim[®] that contains a high-fidelity vehicle model.

The rest of the paper is structured as follows: We start in Section 2 by giving an overview regarding the control architecture. In Section 3, we dig more on the algorithms used for the reallocation in case of failure using Control Allocation algorithms. Section 4 presents results obtained by co-simulation of Matlab/Simulink[®] and Simcenter Amesim[®]. Conclusions and future works are outlined in Section 5.

2. Control Architecture

In this paper, we consider a simple vehicle with an EPAS system and an ESP system. The reason is we want to provide a solution to most passenger cars. Nevertheless, the same logic can be adopted for any chassis system providing a supplementary yaw moment as the Active Rear Steering (ARS) studied in [Kissai et al. \(2018b\)](#).

The objective of the EPAS is to provide an additional steering torque via an electric motor. This reduces the load from the driver. A failure of this system in the middle of a steering maneuver might make the driver panic. In [Safercar \(2016\)](#), it has been reported that this particular failure has caused several accidents. The objective of the EPAS fail-safe control is then to keep the same torque load that the driver would have provided without the EPAS failure. The proposed control architecture is described in Fig. 1.

It should be noted that a Model Predictive Controller (MPC) is used for trajectory control to generate the steering wheel angle δ_{sw} , and consequently, the driver torque T_d in our simulations. However, this goes beyond the scope of this paper and will not be detailed. Usually, a reference steering current I_{ref} 2D map is used for the EPAS control as in [Zhang et al. \(2017\)](#). The same map can be used but this time to generate a reference driver steering torque T_{dref} rather than a current after few straightforward mathematical transformations. The real driver torque is then captured and controlled in a closed-loop thanks to a high-level robust controller. This high-level controller is only activated when a failure occurs thanks to failure flag provided by the equipment supplier of the EPAS. In case of failure of the EPAS, a worst-case scenario would be the loss of the driver torque sensor also. In this case an observer should be implemented as in [Lee et al. \(2007\)](#).

Since the driver torque sensor could generate noises, a deadzone is used in order to transfer only large errors $\varepsilon_{T_d}^*$ indicating a failure status. In case of a failure, the required yaw moment M_z is generated, and an optimization-based control allocation strategy ensure an optimal force distribution to the four tires. The low-level control layer ensure the transformation of the longitudinal tire forces $F_{x_{ij}}$ to braking torques T_{bij} . The gain values of the high-level controller have been determined through trial and error using the high-fidelity vehicle model used in Amesim[®]

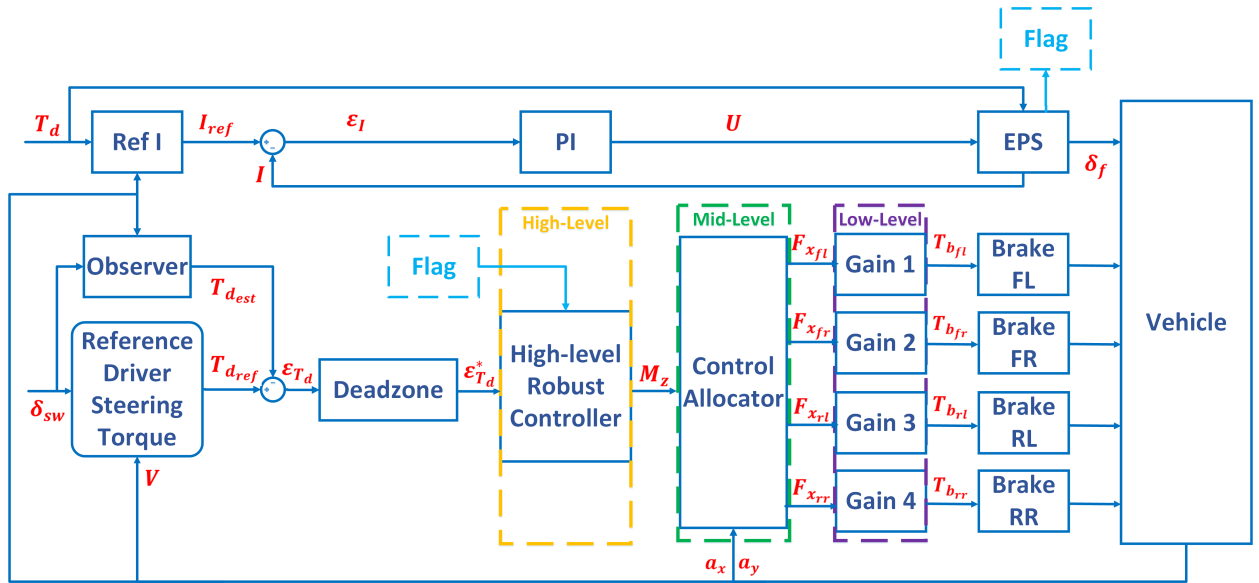


Fig. 1. Proposed EPAS fail-tolerant control architecture

3. Control Reallocation Method

The goal of mid-level control allocator is to optimally distribute the generalized yaw moment that should be applied at the vehicle’s center of gravity. This layer generate more outputs than inputs, which makes the problem over-actuated. One could opt for pseudo-inverses but this will not be optimal and cannot be accepted for safety critical systems. Optimization-based control allocation techniques are then selected to handle the forces distribution problem.

The control allocation problem is defined as follows [Johansen and Fossen \(2013\)](#): find the control vector, $\vec{u} \in \mathbb{R}^n$ such that

$$\mathbf{B}\vec{u} = \vec{v}_{des} \tag{1}$$

subject to

$$\begin{cases} \vec{u}_{min} \leq \vec{u} \leq \vec{u}_{max} \\ \dot{\vec{u}} \leq \dot{\vec{u}}_{max} \end{cases} \tag{2}$$

where $\mathbf{B} \in \mathbb{R}^{m \times n}$ is a control effectiveness matrix, $\vec{u}_{min} \in \mathbb{R}^n$ and $\vec{u}_{max} \in \mathbb{R}^n$ are the lower and upper position limits, respectively, $\dot{\vec{u}} \in \mathbb{R}^n$ is the control rate, $\dot{\vec{u}}_{max} \in \mathbb{R}^n$ is the maximum control rate, $\vec{v}_{des} \in \mathbb{R}^m$ are the desired accelerations, n is the number of control effectors, and m is the number of axes to control.

Regarding the use of differential braking in case of EPAS failure:

$$\vec{u} = \begin{bmatrix} F_{xfl} \\ F_{xfr} \\ F_{xrl} \\ F_{xrr} \end{bmatrix} \tag{4}$$

\vec{u}_{min} and \vec{u}_{max} reflect tire limits with respect to the friction ellipse concept [Pacejka \(2006\)](#):

$$\begin{cases} F_x \leq \sqrt{(F_z)^2 - F_y^2} & (5) \\ F_y \leq \sqrt{(F_z)^2 - F_x^2} & (6) \end{cases}$$

Regarding vertical forces, we have [Soltani \(2014\)](#):

$$F_{z_{fl}} = \frac{1}{2}Mg\frac{l_r}{L} - \frac{1}{2}Ma_x\frac{h}{L} - \frac{1}{2}Ma_y\frac{h}{t} \quad (7)$$

$$F_{z_{fr}} = \frac{1}{2}Mg\frac{l_r}{L} - \frac{1}{2}Ma_x\frac{h}{L} + \frac{1}{2}Ma_y\frac{h}{t} \quad (8)$$

$$F_{z_{rl}} = \frac{1}{2}Mg\frac{l_f}{L} + \frac{1}{2}Ma_x\frac{h}{L} - \frac{1}{2}Ma_y\frac{h}{t} \quad (9)$$

$$F_{z_{rr}} = \frac{1}{2}Mg\frac{l_f}{L} + \frac{1}{2}Ma_x\frac{h}{L} + \frac{1}{2}Ma_y\frac{h}{t} \quad (10)$$

where:

- g : gravitational acceleration,
- a_x : vehicle's longitudinal acceleration,
- a_y : vehicle's lateral acceleration,
- l_f : distance between the front axle and the vehicle's CoG,
- l_r : distance between the rear axle and the vehicle's CoG,
- t : vehicle's track.
- L : vehicle's wheelbase,
- h : height of vehicle's centre of gravity.

The desired acceleration \vec{v}_{des} in this case is the total yaw moment M_z . Using simple geometrical relations, the corresponding effectiveness matrix can be derived as follows:

$$\mathbf{B} = \begin{bmatrix} \cos(\delta_f) & \cos(\delta_f) & 1 & 1 \\ b_{2,1} & b_{2,2} & -\frac{t}{2} & \frac{t}{2} \end{bmatrix} \quad (11)$$

where δ_f is the steering angle of the front wheels and:

- $b_{2,1} = l_f \sin(\delta_f) - \frac{t}{2} \cos(\delta_f)$,
- $b_{2,2} = l_f \sin(\delta_f) + \frac{t}{2} \cos(\delta_f)$.

Regarding the problem solving, we use the Weighted Least Squares (WLS) formulation that solves the bounded least squares problem using one stage Active Set Algorithm (ASA) [Harkegard \(2002\)](#). This method is used for its extensibility, flexibility to express multiple objectives, and for its relative rapidity [Kissai et al. \(2018c\)](#). The optimal

solution is then:

$$\vec{u}_{opt} = \arg \min_{\vec{u}_{min} \leq \vec{u} \leq \vec{u}_{max}} \sum_l \gamma_l \|\mathbf{W}_l (\mathbf{B}_l \vec{u} - \vec{v}_l)\|^2 \quad (12)$$

- \vec{u}_{opt} : optimal control vector,
- l : number of objectives,
- γ_l : weight of the l^{th} objective,
- \mathbf{W}_l : non-singular weighting matrices defining preferences of each axis,
- \vec{v}_l : desired vector of the l^{th} objective,
- \mathbf{B}_l : effectiveness matrix relating the control vector to the desired l^{th} objective.

4. Co-Simulation Results

The solver has been written in Matlab R2017b[®] for its strong numerical computation. Regarding AMESim[®], it proposes a wide vehicle dynamics library for high-fidelity modeling. To take advantage from each software, both are co-simulated. To evaluate the effectiveness of the method proposed, we consider a fraction from the race track of Magny-Cours area in France as depicted in Fig. 2.

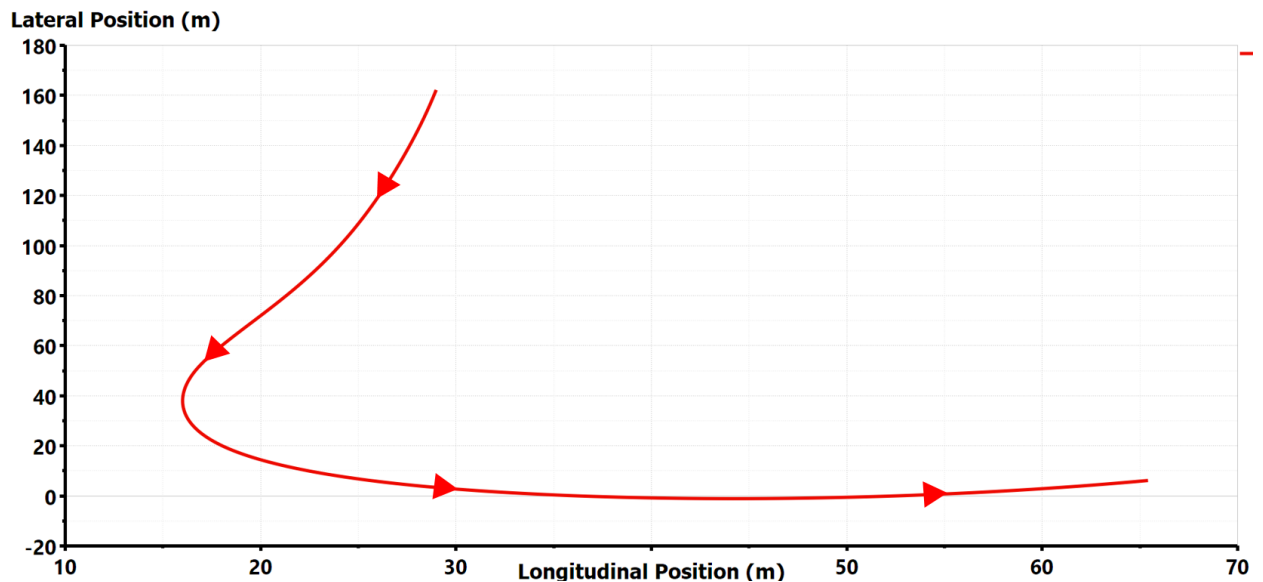


Fig. 2. Fraction from the Magny-cours track where the failure occurs.

As mentioned before, an MPC has been used to ensure trajectory tracking. The goal of our simulations is to keep the same trajectory and the same speed profile, and to compare the scenarios without any failure, with failure and without differential braking and then with failure and with differential braking to evaluate the benefits of the strategy proposed. It is important to recall that for all the scenarios, the trajectory is always the same.

The main aspect to be optimized is the driver steering torque. Fig. 3 show the results in terms of T_d . When the failure occurs, the driver has to put more effort in order to steer the vehicle. This issue can be avoided using differential braking optimized by control allocation algorithms. The reason why in case of using DB the torque is even lower than without a failure, is that we use a security margin to prepare our experimentation. The control strategy is “oversized”.

In terms of steering wheel angle, the results are shown in Fig. 4. As expected again, the driver has to provide

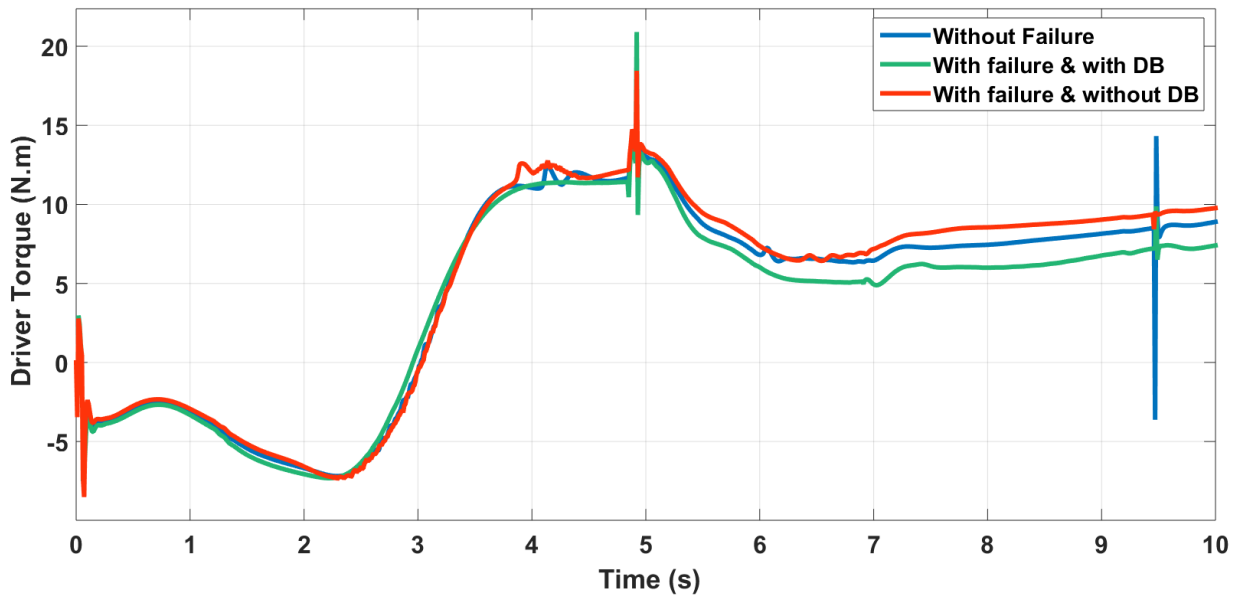


Fig. 3. Driver steering torque comparison.

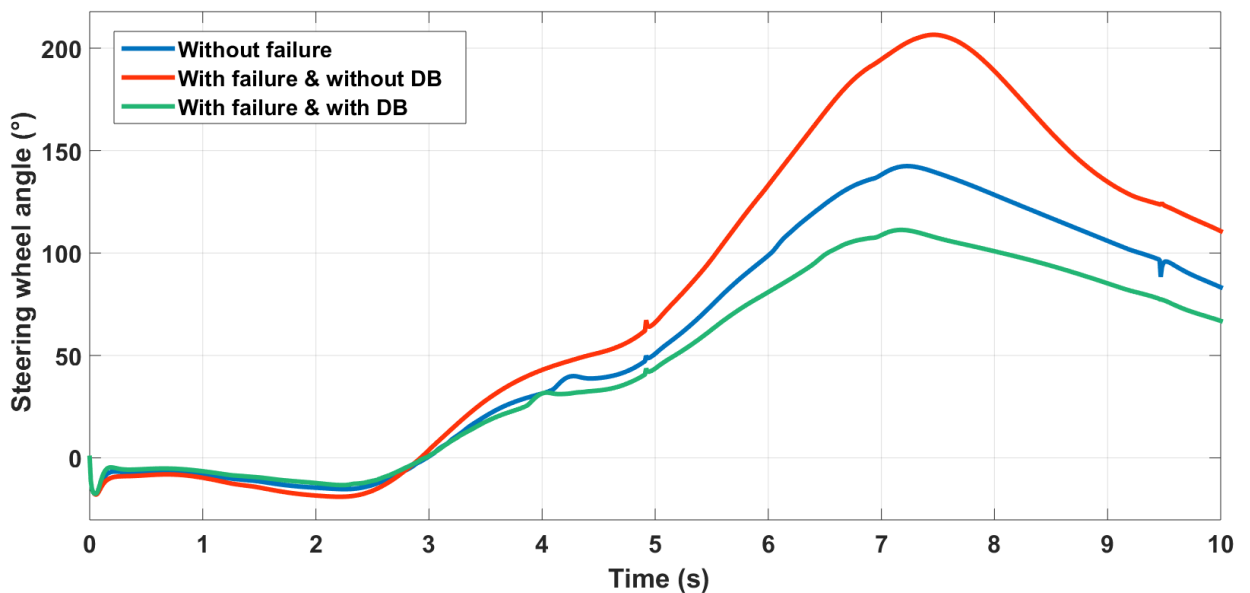


Fig. 4. Driver steering wheel angle comparison.

more steering angle to the steering wheel in order to make the vehicle turn without the EPAS to help him. However, in the MPC, we did not take into account the “strength” of the driver. It could be impossible for certain drivers to move the steering wheel in some scenarios. In this case, even the trajectory will not be controlled. Hence the need of experimentation with real drivers to clarify this point. In any case, the use of DB facilitates the maneuver to the driver as it acts as a secondary assistance system.

5. Conclusions

In this paper, a new approach for EPAS fail-safe control has been presented. The method is based on an optimization-based control allocation algorithm to coordinate the brakes and provide a supplementary yaw moment to help the driver steer the vehicle. Results showed promising results to provide a degraded mode to most of passenger cars. This demonstrates the need of implementing this strategy in order to cut costs due to systems' redundancies.

The authors recognize that more evidence should be provided by means of real experiments before proposing any standards. For this reason, future works will focus on the implementation of this strategy in real vehicles thanks to our collaboration with Renault.

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