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A NEW OPTIMUM STRATEGY FOR ESC TO SHARE FORCES AMONG FOUR WHEELS

Arman Javadian, javadian.ar@gmail.com Islamic Azad University, Ghaemshahr Branch

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ABSTRACT

One of the most effective methods of controlling the Yaw moment is Direct Yaw moment Control (DYC). This method is based on unequal distribution of tire forces (mainly braking forces) and is particularly effective when tire behavior is in nonlinear zone and loses its sensitivity to the steering input. Different approaches for evaluating the adequate Yaw moment are developed. Here an approach based on Optimal Control theory is used. The main issue which is considered in this paper is evaluating the best distribution of longitudinal tire forces to generate the demanded yaw moment. It is one of the error sources in the function of DYC. This issue is done by solving an online NLP problem. While this problem is defined based on Pacejka combined tire model we can consider the coupling of lateral and longitudinal tire forces and generate desired yaw moment in an optimum way. Simulation results show the effectiveness and improvement in functionality of DYC via utilizing this method.

1. INTRODUCTION

In recent years extended attention to the safety and on the other hand the possibility of vast utilizing of electronic parts persuaded automakers to use active safety systems. Various Chassis control systems for passenger vehicles have been actively studied to improve handling and stability. One of these methods is Direct Yaw moment Control (DYC) which almost works based on differential braking. It is to develop a difference in longitudinal braking forces on two sides of the vehicle to generate the external yaw moment [1]. Vast investigation on it has shown the effect of this technique to improve the dynamic behavior of vehicle. Based on the Toyota researches using ESC has reduced 50% of single car crashes [2]. Anyway the performance of current systems has some important limitations. A completely known shortcoming of current ESC is the possible reduction of the total braking force. In an emergency situation ESC controller would partially release the brakes on one side of the vehicle resulting in a longer stopping distance [3]. Therefore it is necessary to consider the braking demand of driver during the act of ESC. When a µ-split condition exists, the tire force capacities on two sides of the vehicle are different and if the controller doesn't consider this point, the ESC performance might be limited. This issue can be solved by determining the tire forces on each side separately. Furthermore in severe driving situations, it is not easy to determine how much longitudinal and lateral forces are required for each tire in order to obtain the target lateral force and yaw moment. This is because of the interaction between the vehicle's lateral and longitudinal dynamics. Two of the strongest interaction mechanisms are weight shift and nonlinear tire force characteristics. When the vehicle is following a curve, load shift from inner wheels to outer wheels will occur and similar weight shift occurs between front and rear axle during deceleration/acceleration. As a result force capacity of each wheel will be different [4]. Consequently in order to solve these shortcomings and achieve optimum vehicle handling performance, it is necessary to control each tire according to its capacity. The method which is presented here determines the forces of each tire separately. So the mentioned shortcomings of ESC will be minimized. This objective is achieved by defining and solving a NLP problem. Defined NLP problem utilize Combined Pacejka Tire model [5] to consider the Coupling of lateral and longitudinal dynamics and also has an optimum trade-off between braking desire of driver and ESC. Simulation results show the improved performance of this method in compare with a current control method.

2. Structure of Controller System

The first problem of the controller is determining the amount of yaw moment which is necessary to achieve the desired dynamic behavior. As it is shown in figure 1 designed controller consist of two main layers. The first layer utilizes optimal control method to determine the necessary yaw moment. The output of this layer is considered as the desired yaw moment in second layer of controller. The second layer considers this yaw moment and also driver demand for braking/acceleration as input. This layer decides to distribute braking force in an optimum way that satisfies the desires of the first layer and the driver braking/ acceleration demand.

Braking via altering longitudinal slip affects longitudinal and lateral tire forces. In this way tire forces can be controlled. Decision in this layer is based on the capacity of each wheel and the instantaneous working situation on the tire map.

In this way second layer of controller uses combined Pacejka Tire model to generate a nonlinear programming problem which determines optimum amounts of longitudinal slip of each wheel in each moment. The strategy of optimization is minimizing the longitudinal slip of each wheel. This is a strategy that is being researched seriously [6]. The objective of this strategy is maximizing the safety level in ESC. This method is based on keeping the working point as far as possible from nonlinear zone of tire that minimizes the possibility of entrance to the nonlinear zone.

3. Controller Design

3.1 First Layer

At the first layer in order to calculate the total yaw moment (M_z) required for the vehicle to follow the model responses, the linear optimal theory has been used [7]. This problem is defined based on the linear 2DOF model. Equations of this model are as follow.

$$\dot{X} = AX + E\delta \tag{1}$$

$$X = \begin{bmatrix} v \\ r \end{bmatrix}, \qquad A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \qquad E = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$$

$$A = \begin{bmatrix} -2\dfrac{C_r + C_f}{mu} & 2\dfrac{bC_r - aC_f}{mu} - u \\ 2\dfrac{bC_r - aC_f}{I_z u} & -2\dfrac{b^2 C_r + a^2 C_f}{I_z u} \end{bmatrix}$$

$$E = \begin{bmatrix} \dfrac{2C_f}{m} \\ \dfrac{2C_f}{I_z} \end{bmatrix}$$

The performance index for the infinite-time-horizon LQR controller is defined as [7]

$$I_y = \int_0^{t_f} \frac{1}{2}\left[w_1(v-v_d)^2 + w_2(r-r_d)^2 + w_3 M_z^2\right]dt \tag{2}$$

Where r_d, v_d are desired yaw and lateral velocity responses which can be analytically calculated based on the reference model [8]

$$\dot{X}_d = A_d X_d + E_d \delta_{driver} \tag{3}$$

Considering steady state response, it can be calculated as

$$X_d = \begin{bmatrix} v_d \\ r_d \end{bmatrix} = -[A]_d^{-1}[E]_d \delta_{driver} \tag{4}$$

Also w_1, w_2 and w_3 are weighting factors. By tuning of weighting factors the appropriate control effort can be achieved.

Finally using the optimal control theory [7], the control law in the form of yaw rate and lateral velocity feedbacks, and the steering angle feed forward is found

$$U = [M_z] = [k_v]v + [k_r]r + [k_\delta]\delta_{driver} + [k_c] \tag{5}$$

3.2 Second Layer

3.2.1 Optimum Brake Torque Distribution

The objective of second layer of controller is to find out the optimum brake torque distribution. This distribution with considering the working point in tire map distributes braking force on four wheels in a way that generates desired yaw moment of first layer and driver braking/acceleration demand with the minimum error. To achieve it an optimization problem has been designed that in each step calculates the necessary alter of longitudinal slips of each wheel and generates them via the controller of ABS.

The strategy of this optimization problem is considering safety and is based on minimizing the longitudinal slip of wheels.

3.2.2 Cost Function

The cost function is the summation of some mathematical terms. Any of these terms has been defined to achieve a special goal that finally leads to the mentioned objectives of this layer.

i. Slips

Driver would be unable to control the car if it entered in the nonlinear zone of tire and it would be resulted in a critical situation. Avoiding this situation is the main strategy of this controller. The follow mathematical term is defined for this objective.

$$T_1 = \sum_{i=1}^{4} \left((S_i + dS_i)^2 \right) \tag{6}$$

This term considers the longitudinal slips and tries to keep them as low as possible.

ii. Force and Moment

In each step of solving the mission of this layer is to supply demanded $\Delta F_x, \Delta M_z$ which are defined as below

$$\Delta F_x = F_{x_{driver}} - F_{x_{(i-1)}} \tag{7}$$

$$\Delta M_z = M_{z_{firstlayer}} - M_{z_{(i-1)}} \tag{8}$$

With sufficiently small solving steps

$$\Delta F_x = dF_x \tag{9}$$

$$\Delta M_z = dM_z \tag{10}$$

Based on it the term of forces and moment will be as follow

$$T_2 = \left(dM_z - dM_{z_d}\right)^2 + \left(dF_x - dF_{x_d}\right)^2 \tag{11}$$

Independent parameters in the cost function are $dS_i \quad i = 1,..4$. Using combined tire model terms of could be presented as functions of these independent parameters

$$M_z = f(F_{x_i}) \qquad i = 1,..4 \tag{12}$$

$$dM_z = \sum_{i=1}^{4}\left(\left(\frac{\partial}{\partial F_{x_i}} M_z\right) dF_{x_i}\right)$$

$$dF_{x_i} = \left(\frac{\partial}{\partial S_i} F_{x_i}\right) dS_i$$

$$dM_z = \sum_{i=1}^{4}\left(\left(\frac{\partial}{\partial F_{x_i}} M_z\right)\left(\frac{\partial}{\partial S_i} F_{x_i}\right) dS_i\right)$$

Defining constants

$$A_i = \left(\frac{\partial}{\partial F_{x_i}} M_z\right)\left(\frac{\partial}{\partial S_i} F_{x_i}\right)$$

$$dM_z = \sum_{i=1}^{4}\left(A_i dS_i\right) \tag{13}$$

$$T_3 = \left(\sum_{i=1}^{4} A_i dS_i - dM_{z_d}\right)^2 + \left(\sum_{i=1}^{4}\left(\left(\frac{\partial}{\partial S_i} F_{x_i}\right) dS_i\right) - dF_{x_d}\right)^2$$

3.2.3 Mathematical Constraints

- Traction Constraint

There are two mechanisms to control the longitudinal slip; braking by ABS system and cutting the engine torque. Anyway

- Effect of ABS

The effect of ABS braking system is avoiding tire to enter the nonlinear zone. Second layer must consider this point when is calculating slips. It has been added to the optimization problem via an unequal constraint.

$$-0.15 \le dS_i + S_i \le 0.15 \qquad\qquad i = 1,...,4$$

Final Configuration of the NLP problem

The NLP problem is summation of defined terms with considering the nonlinear constraints. Based on it the NLP problem has been defined as follow

$$j = w_l\left(\sum_{i=1}^{4}\left(w_{s_i}\left(S_i + dS_i\right)^2\right)\right) + w_f$$

$$\left(w_{M_z}\left(\sum_{i=1}^{4}\left(C_i dS_i\right) - dM_{z_d}\right)^2 + w_{F_x}\left(\sum_{i=1}^{4}\left(\left(\frac{\partial}{\partial S_i}F_{x_i}\right)dS_i\right) - dF_{x_d}\right)^2\right) \qquad (14)$$

Constraints

$g_{1\,..4}$

$-0.15 \le dS_i + S_i \le 0 \qquad i = 3,4$

$g_{5\,..8}$

$-0.15 \le dS_i + S_i \le P_s \qquad i = 1,2$

Kuhen and Tuker have developed the necessary and sufficient conditions of optimum answer of these sorts of problems [9]. Anyway because of complexity of the defined problem, analytical solution is not possible. This quadratic problem can be solved based on numerical methods [10].

4. Simulation results

To evaluate the effect of optimum share of tire forces the functionality of designed controller has been compared with a vehicle equipped with ESC but without using the optimization method to evaluate the optimum tire force share and a passive vehicle model without ESC. The vehicle simulation model is a nonlinear model with 8DOF [11]. The model contains a rigid sprung mass with 4DOF (longitudinal motion, lateral motion, roll and yaw motion). The remaining 4 degrees are the rotation of the four wheels. In the vehicle simulation model the tire forces are obtained by nonlinear tire model (Combined Magic Formula) in which the combined lateral and longitudinal forces are obtained by integrating the distributed tire deformations in the contact patch. Also in this nonlinear tire model, the coefficient of friction was treated as a function of tire vertical load as well as its slip velocity.

The first simulation consists of a severe lane change maneuver at speed of 25 m/s $\delta_{\max} = 4$ deg and $\mu_{road} = 1$. The simulated vehicle is inherently oversteer. The results have been illustrated in Figure [2]. As can be seen in such a situation the passive vehicle can not track the desired path but the vehicle equipped with ESC is able to do the maneuver. The new controller due to the optimum sharing of forces has better performance. The better performance is the consequence of considering the interaction between the vehicle's lateral and longitudinal dynamics. Anyway the new method can not make a big difference. To show the importance of sharing forces another simulation has been executed. The second simulation is dedicated to a break in turn maneuver at speed of 25m/s, $\delta_{\max} = 5$ deg and $\mu_{road} = 1$. At the same time the driver has braked to achieve the longitudinal declaration of $a_x = -0.4g$. In this severe maneuver it is evident that the performance of ESC has been improved via the better sharing of forces. Defined NLP problem through Combined Pacejka Tire model is able to consider the Coupling of lateral and longitudinal dynamics and as a result has an optimum trade-off between braking desire of driver and ESC. It is the main advantage of this method.

Generally the simulation results show while ESC is capable to stabilize the vehicle in many cases, the interaction between the driver braking desire and the effort of ESC is a major shortcoming. In this case only the new controller with considering both driver and ESC is able to control the vehicle.

5. Figures

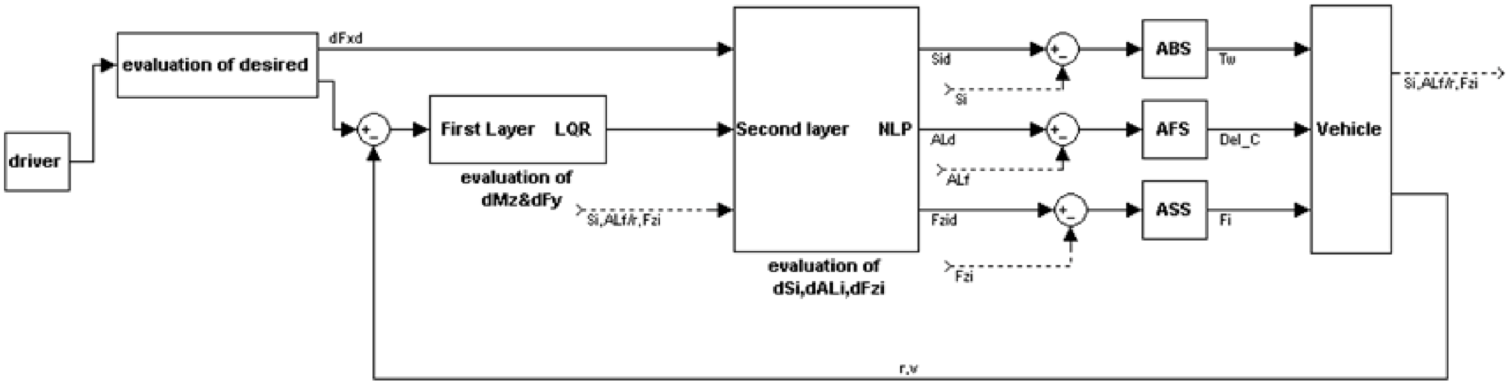
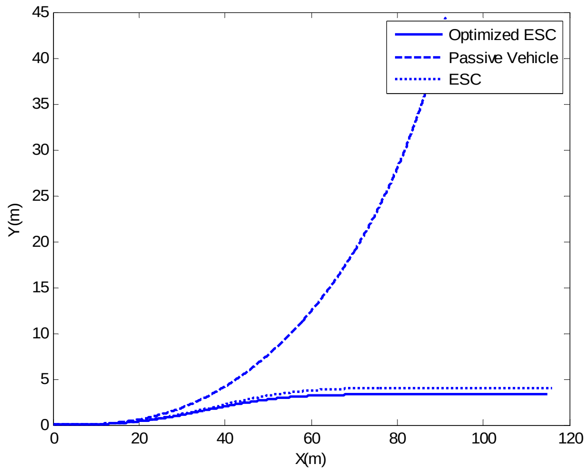
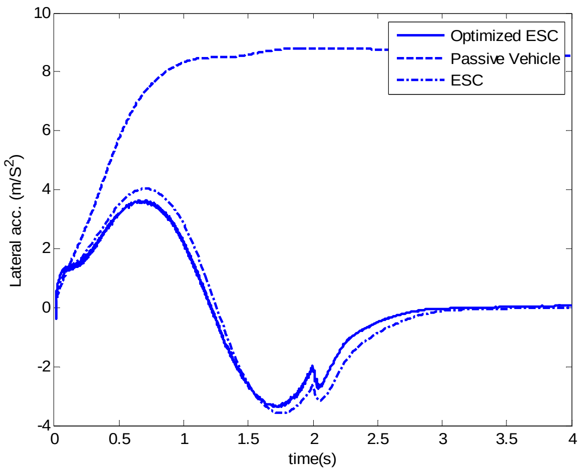


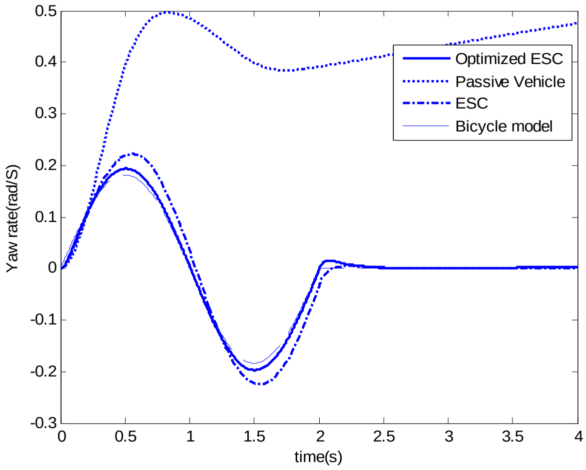
Figure 1. Block diagram of the optimum distribution technique



a. Vehicle path

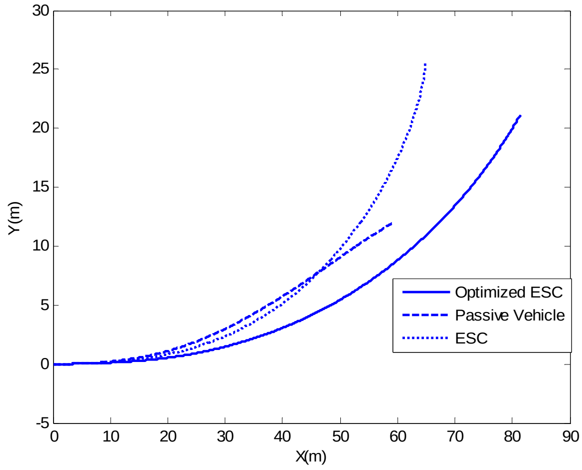


b. Lateral acceleration



c. Yaw velocity

Figure 2. Simulation results of lane change maneuver



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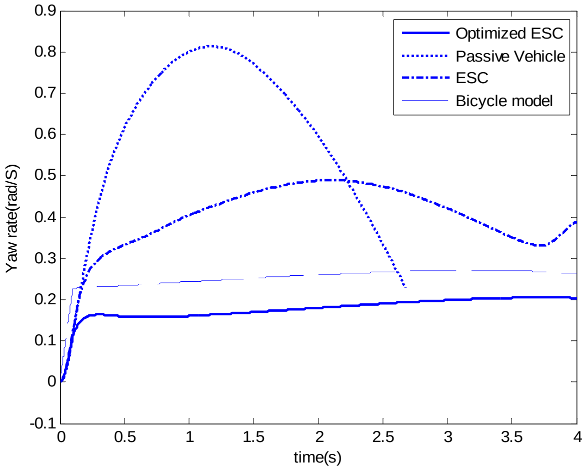
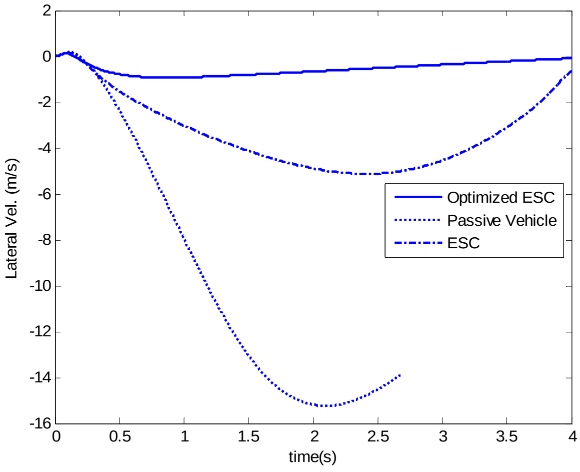
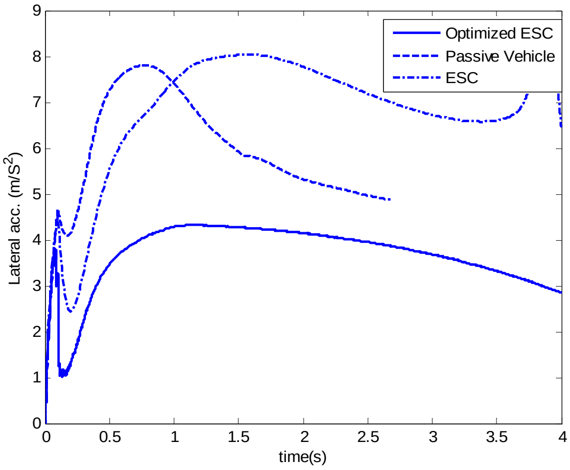


b. Yaw velocity



c. Lateral velocity



d. Lateral acceleration

Figure 3. Simulation results of brake in turn maneuver

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