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Research article

A novel technique for optimal integration of active steering and differential braking with estimation to improve vehicle directional stability

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ABSTRACT

This study deals with the enhancement of directional stability of vehicle which turns with high speeds on various road conditions using integrated active steering and differential braking systems. In this respect, the minimum usage of intentional asymmetric braking force to compensate the drawbacks of active steering control with small reduction of vehicle longitudinal speed is desired. To this aim, a new optimal multivariable controller is analytically developed for integrated steering and braking systems based on the prediction of vehicle nonlinear responses. A fuzzy programming extracted from the nonlinear phase plane analysis is also used for managing the two control inputs in various driving conditions. With the proposed fuzzy programming, the weight factors of the control inputs are automatically tuned and softly changed. In order to simulate a real-world control system, some required information about the system states and parameters which cannot be directly measured, are estimated using the Unscented Kalman Filter (UKF). Finally, simulations studies are carried out using a validated vehicle model to show the effectiveness of the proposed integrated control system in the presence of model uncertainties and estimation errors.

1. Introduction

During last years, the enhancement of vehicle safety, handling and stability has become a key research area in designing ground vehicles. In this way, a large number of advanced vehicle control systems such as active front steering (AFS), direct yaw moment control (DYC) and torque vectoring (TV) have been developed to improve the handling characteristics of vehicle.

Active front steering is based on controlling the lateral forces of tires. This method can be easily employed using steer-by-wire (SBW) technology. The main limitation of AFS is due to the inherent saturation property of tire lateral forces. When the tire lateral forces approach saturation, the steer input loses its direct effectiveness on tire lateral forces [1,2]. Hence, the AFS performance is limited within the linear vehicle handling region. In order to compensate this scarcity, DYC is employed to broaden the effectiveness of vehicle control system in nonlinear regimes. In this technique, a corrective external yaw moment can be generated by transverse distribution of the vehicle longitudinal force between the left and right wheels. This method is effective both in linear and nonlinear regions of vehicle dynamics. However, the external yaw moment is considered as an expensive control input which should be kept as low as possible. In Fact, excessive use of DYC leads to some undesirable effects. For example, it slows down the vehicle because a corrective yaw moment is applied to the vehicle through the brakes. This effect must be kept to a minimum so that the driver can feel supported rather than overruled. Furthermore, tire lifespan is also shortened because of excessive braking.

One of the efficient approaches to limit the excessive use of external yaw moment without any deterioration in directional stability is integrating and coordinating DYC and AFS. In this way, the external yaw moment can be only generated to compensate the limitation of steering control. The study of integrated control of AFS and DYC has attracted much attention from many researchers to further enhance the handling and stability performance. In this respect, various control algorithms have been utilized such as sliding mode control [3,4], Fuzzy logic control [5], control allocation method [6], optimal control [7,8], the model predictive control strategy [9], robust control [10] and etc. In Ref. [11], an adaptive integrated control algorithm based on direct Lyapunov method is proposed to coordinate the active front steering and direct yaw moment control. Yang et al. [12] designed an integrated control system include of AFS and DYC based on the optimal guaranteed cost control technique. Baslamisli et al. [13] proposed a gain-scheduled active steering control and active differential design method to preserve vehicle stability in extreme handling situations. An adaptive

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algorithm [14] is proposed for yaw moment distribution to coordinate braking and steering control systems. In Ref. [15], the phase plane method was used for dynamic stability control and accordingly, the sliding mode control method was applied for the active front steering.

In this study, the braking and steering control systems are integrated in an optimal way to improve the directional stability and maneuverability of the vehicle which turns with high speeds on various road conditions. In this respect, the minimum usage of intentional asymmetric braking force for small reduction of vehicle longitudinal speed is desired. Here, a new multivariable nonlinear controller is optimally designed for the integrated DYC and AFS based on the prediction of vehicle nonlinear responses. The performance index is defined using the weighted combination of two control inputs and the next tracking error of yaw motion. Then, the defined performance index is minimized to develop the multivariable control law in the closed form. In order to manage two control inputs and obtain the effective contribution of them, the corresponding weights of control inputs as the free parameters of the multivariable control law are regulated based on fuzzy programming. The input of fuzzy system is the stability index which is obtained from the phase plane analysis of the nonlinear vehicle system. With the proposed fuzzy scheduled method, the designed integrated controller is tuned automatically and the weight factors are changing softly for different driving conditions. The special cases of the integrated control law can easily be obtained by determination of the weighs in limit conditions which leads to the stand-alone braking and steering control laws. The designed optimal multivariable control system makes it possible to calculate the stabilizing external yaw moment as low as possible. In this way, small braking forces are provided which leads to small reduction of vehicle speed.

An optimal nonlinear algorithm for the proper distribution of tire braking forces is also presented in the rest of the paper. In this algorithm, the calculated external yaw moment is converted to the differential braking force between the front left and right wheels. Finally, in order to produce the distributed braking forces, the braking torques calculated by the wheel slip controllers are applied to the wheels.

Another contribution of this study is utilizing Unscented Kalman Filter (UKF) for estimation of the required vehicle states and parameters from the measured data. In the proposed control system, the longitudinal vehicle speed and the vehicle side slip angle as the states and the road friction coefficient as the parameter of vehicle are required to be estimated. Many researches in the field of vehicle dynamics estimation concentrate on the application of Kalman Filter (KF) or Extended Kalman Filter (EKF) [16–18]. The EKF is applied for state estimation of nonlinear systems. However, it relies on linearization to propagate the mean and covariance of the state. Therefore, the EKF can be difficult to tune and often gives unreliable estimates if the system nonlinearities are severe [19]. The UKF is an extension of the Kalman filter that reduces the linearization errors of the EKF and provides significant improvement over the EKF. Recently, the UKF as an efficient derivative-free algorithm is applied for computing approximate solutions to nonlinear optimal filtering problems as well as vehicle state estimation [20,21]. This filter is able to achieve a great performance than the EKF through the use of unscented transformation.

Finally, in the simulation studies section, different control strategies including the stand-alone braking control and the integrated braking and steering control are examined to control the vehicle during different maneuvers. All simulation results are performed using a nonlinear vehicle model which has been previously developed and validated by experimental results for combined braking and steering maneuvers [22].

2. Control system design

The overall structure of the proposed control system with two layers is shown in Fig. 1. In the upper layer, according to the driver steering angle (δ_{fd}) and its corresponding reference yaw rate (r_d), the external yaw moment and the corrective lateral force of the front wheels (M_z, ΔY_{fc}) are firstly calculated from a multi-variable optimal nonlinear controller. The controller weights (w_m, w_d) are automatically tuned by fuzzy programming. Then, a distribution algorithm for tire braking forces is proposed from the calculated external yaw moment. In the lower layer, the slip controller for four wheels is designed to generate the final distributed braking forces. The braking torque of each tire calculated in the lower layer along with the corrective front steer angle are imported to the vehicle model. All states of the system and the road coefficient of friction required for both controllers are estimated by UKF method.

In the following, at first, the required vehicle states and parameters are estimated from the vehicle outputs which are measurable in practice. Then, the controllers of two layers are developed.

2.1. Estimation of vehicle states and parameters

According to the current technology in commercial vehicles, measuring the vehicle yaw rate, longitudinal and lateral accelerations in addition to rotational speeds of four wheels are practically feasible and cost-effective. However, the longitudinal and lateral speeds of vehicle along with the road coefficient of friction which is considered as a parameter of system have to be estimated from the measured outputs. The Unscented Kalman Filter (UKF) is employed for estimating these states and parameter based on the nonlinear eight degrees-of-freedom (8-DOF) vehicle model shown in Fig. 2. This model contains the rotation of four wheels in addition to longitudinal, lateral, yaw and roll movements of car body.

The governing equations of vehicle body motions are derived as follow:

$$m\dot{v}_x = mv_y r - F_{tfR} - F_{tfL} - F_{trR} - F_{trL} \tag{1}$$

$$m\dot{v}_y = -mv_x r + F_{sfR} + F_{sfL} + F_{srR} + F_{srL} \tag{2}$$

$$\begin{aligned} I_{zz}\dot{r} &= a(F_{sfR} + F_{sfL}) - b(F_{srR} + F_{srL}) \\ &\quad + [(F_{tfL} + F_{trL}) - (F_{tfR} + F_{trR})]\frac{T_w}{2} \end{aligned} \tag{3}$$

$$I_{xx}\dot{p} = -m_s d\dot{v}_y - m_s d v_x r + m_s g d \sin\phi_s - K_\phi \phi_s - C_\phi p \tag{4}$$

Description of all vehicle and tire parameters are presented in Table 1. Note that the product of inertia with respect to the roll and yaw axes is taken to be zero [18]. Also, the coupling effect of roll motion and center of mass movement on the lateral acceleration is ignored for simplicity.

The rotational dynamics of each wheel for a given braking torque T_b, can be modeled from Fig. 3 as follows:

$$\dot{\omega}_i = \frac{1}{I_{wi}}[RF_{ti} - T_{bi}] \qquad i = fR, fL, rR, rL \tag{5}$$

Accordingly, the longitudinal slip of each tire during braking can be defined as,

$$\lambda_i = 1 - \frac{R\omega_i}{v_x} \qquad i = fR, fL, rR, rL \tag{6}$$

The tire forces are modeled by the non-linear Dugoff's tire model that is based on the friction ellipse idea and contains the saturation property of tire forces [22]. In this model, the relation for longitudinal and lateral forces of each tire is as follows:

$$F_t = \frac{C_\lambda \lambda}{1-\lambda} f(S) \tag{7}$$

$$F_s = \frac{C_\alpha \tan\alpha}{1-\lambda} f(S) \tag{8}$$

where the $f(S)$ can be calculated as follows: