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Modular integrated longitudinal and lateral vehicle stability control for electric vehicles[☆]

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ABSTRACT

In this paper, the problem of integrated longitudinal and lateral vehicle stability control is addressed using a modular optimal control structure. The optimization process of the high level model predictive control (MPC) controller determines required longitudinal force and yaw moment adjustments to minimize the error between vehicle longitudinal and lateral vehicle stability dynamic states with respect to the target courses. The low level controller is designed to optimally regulate torque at each wheel based on the control inputs of the high level controller, and distribute required torque between the wheels via actuation system. The actuation system that is utilized to implement the proposed control structure functions based on all-wheel drive technology that can provide active control of both traction and yaw moment control with differential torque. The multi-layered structure of the control system allows modularity in design. The performance of the control structure is investigated by conducting experimental tests. The experimental tests have been performed on an electric Chevrolet Equinox vehicle equipped with four independent motors. The results show that the integration of the vehicle longitudinal and lateral dynamics preserves vehicle stability in a planar motion and improves the vehicle dynamic response, especially in challenging driving maneuvers.

1. Introduction

In recent decades, active vehicle stability control systems have played a significant role in reducing road fatalities. These systems have had remarkable contribution to improve vehicle safety and performance, especially during difficult driving conditions. As the number of electric vehicles (EV) on the market grow, much research has been devoted to design a proper control structure for EV platforms [1]. Parallel advances in control theory and computing systems have enlarged the range of applications where complex control strategies such as Model Predictive Control (MPC) can be employed in real-time [2–4]. A receding horizon controller where the finite-time optimal control law is computed by solving an on-line optimization problem is usually referred to as MPC [5]. With MPC, a plant model is used to predict the future states of the dynamic system over a finite time horizon [6]. Based on this prediction, at each time step t, a cost function is minimized under a set of operating constraints to obtain the sequence of future control inputs that will produce the most desired changes in states. The first of such optimal inputs is taken as the control input applied to the plant at time t. At time $t+1$, the optimization is performed again over a shifted prediction horizon. The systematic capability of the MPC to handle physical and design constraints on both states and control inputs distinguishes this technique from others, and makes this technique particularly useful for applications where the process takes place over a broad operating region and close to the limitations of the admissible states and control inputs. A number of MPC variants have been utilized for vehicle stability control [3,7–12]. The two main classes of MPCs can be divided based on their use of either a linear or nonlinear prediction model. For instance, Falcone et al. reformulated the path-tracking problem of autonomous vehicles where the control utilized the Active Front Steering (AFS) actuation system [7]. The authors assumed that a low level controller is responsible for keeping tire slips at the desired ratios. The MPC formulation relies on two prediction models for comparison purposes: a full four wheel nonlinear and a successive online linearized model. The capability of both controllers in path tracking is shown in simulation results; however, only the Linear Time Varying (LTV)-MPC has been implemented experimentally. Successive linearization of a nonlinear model is a broadly utilized approach to deal with

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the computational complexities and reduce the data processing expenses. Finding a solution for the linear optimization problem is more manageable than in the nonlinear case and only requires solving a Linear Programming (LP) or Quadratic Programming (QP) problem based on the objective function. In another study, Borrelli et al. investigated the nonlinear MPC control approach for an active constrained steering system of an autonomous vehicle [3]. In this study, a nonlinear MPC was used in order to increase the stability region of operation over linear controllers. The computational complexity of using a nonlinear MPC was also examined. The nonlinearity in the model originated from considering both the longitudinal dynamics of the tires and the vehicle's lateral dynamics integrally. Furthermore, the effect of the number of the preview steps on the desired path was studied for different speeds. Although favorable results were obtained even at a relatively high vehicle speed, the computational burden is a serious obstacle for the experimental validation. More accurate prediction can be achieved by using nonlinear prediction models in the vehicle control region; however, those models result in a nonlinear programming problem that is expensive to solve and is often impractical in real-time applications. Barbarisi *et.al* used a linearized bicycle model with a differential braking system to control the vehicle's yaw rate and sideslip angle [8]. Based on estimations of the tire's longitudinal forces, the tire's lateral capacity is determined and the corresponding constrained MPC optimization problem is established. Some simulation results were provided to highlight the competency of the mentioned control approach. In the most of the aforementioned studies, active controllers were designed to control particular lateral vehicle dynamic states of ground vehicles. Another challenging task of vehicle stability control is wheel slip ratio control, which can be defined as the vehicle longitudinal stability control. Some research work has been devoted to investigate this issue individually [13–17]. The longitudinal and lateral capacity of the tire should be occupied optimally to achieve the best performance of the controller. Therefore, the design of a separate module to control the wheel slip ratio may not result in the best achievable performance. An optimal compromise between traction and lateral stability control can be obtained when the wheel and vehicle dynamic states are integrated and studied as a single control structure [18–20]. Zhou *et.al* investigated the integrated wheel slip and vehicle lateral stability control problem since the state variables of their MPC prediction model includes yaw rate, sideslip angle, and slip ratio [21]. The performance evaluation of their controller is shown in the simulation results with the consideration of differential braking as an actuation system.

The main contribution of this paper is designing a modular optimal control structure for integrated longitudinal and lateral stability control that can be implemented on any vehicle configuration in real-time. Compatibility with different actuation systems of electric, hybrid, and conventional vehicles requires a CG based error detection control. Regardless of actuation system functionality and characteristics, an analysis can be conducted on vehicle CG horizontal forces and yaw moment for error detection. The aforementioned module that is responsible of CG error detection can form a high level control for the proposed control structure. Then, the control law can be interpreted to required adjustment at wheels in accordance with available actuation system considering its limitations at low level control module. In addition to accomplishing a general layout compatible with different vehicle platforms, a modular control structure can effectively reduce computational burden and provide a ground for module-to-module development. Although, an electric vehicle platform equipped with torque distributor electric motors as actuators is considered in this research to evaluate the controller performance, the control structure is able to work with active steering and differential braking actuation systems, CG error analysis in high level control module allows further extension to different actuation systems. Moreover, the implementation of the proposed control structure on different vehicles with diverse geometrical and mass properties is possible with MPC model based control strategy.

The paper is organized as follows: in Section 2, an integrated vehicle longitudinal and lateral plant model are proposed to design a high-level LTV-MPC controller. Then, an optimal corner based optimal distribution strategy in the low level is presented. In Section 3, the capability of the proposed control structure is evaluated experimentally using an electric 4WD Chevrolet Equinox vehicle equipped with in-wheel motors. The performance of the controller is studied for various maneuvers on slippery road conditions where both wheel slip ratio and vehicle lateral stability are at risk. Finally, a conclusion has been made based on the performance of controller in different driving scenarios.

2. Control structure design

In order to achieve modularity in control structure, a multilayer structure has been proposed. The proposed control structure is illustrated in Fig. 1. In this control structure, according to the driver's steering θ and torque T commands, the target wheel slip ratios as the indicators of vehicle longitudinal stability, and then lateral velocity, yaw rate and heading angle as the indicators of vehicle lateral stability are measured or estimated, then based on defined target values, error between target and actual vehicle longitudinal and lateral dynamic states is predicted in the assumed control horizon in the high level MPC controller. According to the detected error in longitudinal and lateral dynamic states, required adjustment in longitudinal force δF_x (for vehicle longitudinal stability preservation) and yaw moment δG_z (for vehicle lateral stability preservation) at vehicle CG is computed by solving an MPC optimization problem. The CG longitudinal force adjustment and corrective yaw moment resulting from high level MPC controller is employed in low level controller, where the optimal distribution of the required control signal δT or torque vectoring is accomplished using Holistic Corner Control (HCC) strategy [22–24]. In HCC control methodology, the cost function is defined based on the discrepancies between actual and target CG forces and yaw moment, and the required effort to achieve the control goal. As mentioned, the control input in the low level control block is the torque adjustment at the vehicle wheels. The all-wheel drive control technology allows to independently control the drive torque and adjust driver's torque command. Thus, the vehicle stability is preserved

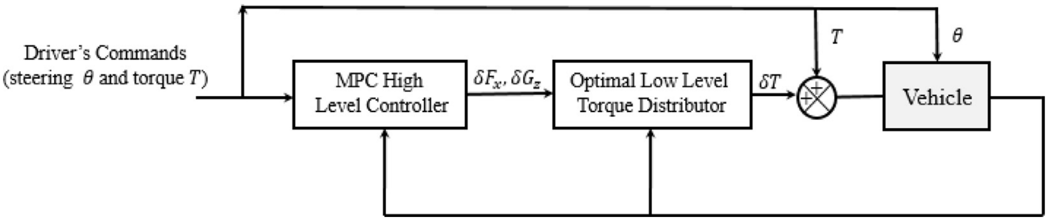

Fig. 1. Schematic of the proposed modular integrated control structure.