

Development of Steering Control for Steer-by-Wire Systems Using a Hierarchical Gradient Method

- (First Report) -

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Steer-by-wire (SBW) systems eliminate the mechanical linkage between the steering wheel and road wheels, enabling steering characteristics to be designed through software. This architecture significantly increases the flexibility of vehicle motion control and provides opportunities to improve both handling performance and driving comfort. However, steering commands must be generated in real time while satisfying vehicle dynamic constraints under varying driving conditions.

This study proposes a steering control method for steer-by-wire (SBW) systems based on the integration of a hierarchical gradient method and receding horizon control (RHC). The hierarchical gradient method is a numerical optimization technique for constrained optimal control problems and can explicitly satisfy terminal constraints while minimizing a performance index. In vehicle motion control, target vehicle behavior can be imposed as terminal constraints. Consequently, the method generates steering commands that achieve the target vehicle behavior while satisfying the imposed constraints.

The proposed steering control system consists of a target vehicle behavior calculation block and a front-wheel steering angle calculation block. The target vehicle behavior is calculated from measured vehicle information, including vehicle speed, steering wheel angle, yaw rate, and lateral acceleration. This target behavior is used as the terminal condition for the optimization. The front-wheel steering angle calculation block then calculates the steering input required to achieve the target vehicle behavior. Vehicle lateral dynamics are represented using a linear planar two-wheel vehicle model. The state variables consist of lateral displacement, yaw angle, vehicle slip angle, yaw rate, and front-wheel steering angle, while steering rate is used as the control input. A yaw-rate-based performance index is minimized subject to the terminal constraints. The hierarchical gradient method iteratively updates the steering input by combining the Hamiltonian gradient with a constraint compensation term, thereby generating a control input that achieves the target state while maintaining smooth transient behavior.

Since a conventional hierarchical gradient method requires a predefined maneuver duration and terminal constraints, its direct application to real-time vehicle control is difficult. To address this limitation, the proposed method introduces RHC and extends the optimization framework to a model predictive control (MPC) system, as shown in Fig.1. At each control update step, an optimal steering sequence is calculated over a finite prediction horizon using the current vehicle state and the target terminal state. Only the first steering command is applied, and the optimization is repeated after the horizon is shifted forward. As a result, the controller can continuously adapt to changing driving conditions while preserving the ability to explicitly satisfy terminal constraints.

The effectiveness of the proposed method was evaluated using a driving simulator. Experiments were conducted on a course consisting of a straight section followed by a clothoid-based curve at a constant vehicle speed of 70 km/h. The results demonstrated smoother steering behavior, reduced corrective steering inputs, and improved cornering stability, as shown in Fig.2. These findings indicate that the proposed MPC-based steering control framework is effective for steer-by-wire systems and contributes to stable vehicle behavior during cornering.

Future work will focus on target vehicle behavior generation based on driver models, consideration of occupant perception characteristics in constraint design, and validation through real vehicle testing.

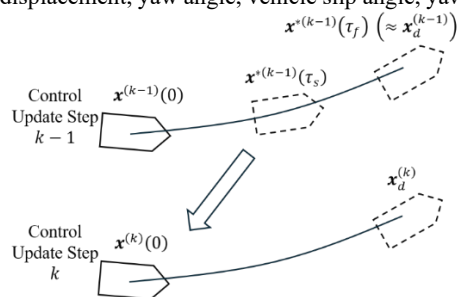


Fig.1 Update of the Optimal Trajectory
by Receding Horizon Control

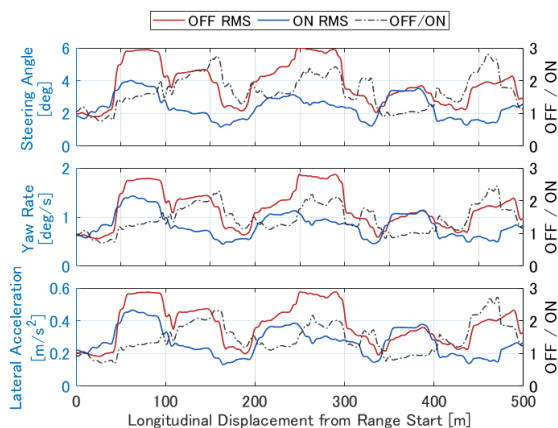


Fig.2 Residual RMS Trends