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Proposal of trajectory tracking controller for autonomous driving using nonlinear model predictive control

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Smooth and stable driving in accordance with traffic flow is an important requirement for autonomous vehicles. This report proposes a method of trajectory tracking control assuming orbital and rotational motion and illustrates the basic principle and its effectiveness in high-G-range driving at the double apex corners often found on suburban roads. Firstly, we describe the three proposed mechanisms.

The first mechanism reduces lateral deviation from the target trajectory as expected while prioritizing the control of vehicle direction at corners with large change in road curvature. At such corners, a yaw moment must be generated to produce rotational motion so that the direction of the vehicle remains along the target trajectory. While steady straight-line or orbital motion can be effectively controlled by varying the lateral position in the same dimension as the turning radius, rotational motion can be controlled preferentially in the angular dimension to reduce deviation from the target trajectory during transient periods of cornering.

The second mechanism limits the generation of F_y to avoid operation in the yaw resonance frequency band. Because a rigid vehicle body has a yaw resonance frequency, quick operation may cause a greater response or delay than expected, leading to overshooting or wandering toward the trajectory. Thus, constraining the resonance frequency by converting it to the equivalent of the lateral acceleration enables the system to avoid resonance during steering operation.

The third mechanism predicts the state based on future changes in the vehicle speed. The nonholonomic constraint, which allows a vehicle to move only in the forward direction, makes it important to minimize the lateral deviation and the yaw angle from the target trajectory. In model predictive control (MPC), the trajectory tracking performance is improved by predicting the turning trajectory and obtaining accurate vehicle speed information at each prediction point when determining the extent of operation based on the difference from the target trajectory.

Trajectory tracking control using these mechanisms is realized by solving the constrained optimization problem shown in Eq. (1) using the MPC. For Eq. (1), the yaw angle θ and the lateral deviation z from the target trajectory, and input u are used as evaluation factors ($J_\theta + J_z + J_u$), while the input is subject to a constraint condition. The first mechanism involves adjusting the weight of the yaw angle in accordance with the curvature rate $\dot{\rho}_r$ of the target trajectory using Eq. (2), and the second mechanism introduces a limit on the number of operations using Eq. (3). The third mechanism is realized by treating the velocity parameters $f(\theta, z, u, V_r^*, t)$ in the equation of state (1) as time-varying parameters using the target velocity.

$$\min_{u(t)} \ (J_\theta + J_z + J_u) \quad \text{s.t.} \quad u_{min}(t) \le u(t) \le u_{max}(t)\,, f(\theta, z, u, V_r^*, t) = 0 \tag{1}$$

$$J_\theta = \frac{1}{2}\theta^T q_\theta(\dot{\rho}_r)\theta \tag{2}$$

$$u_{max} = u(k|t-\Delta T) + \dot{u}_{Lim}(k)\Delta T, \quad u_{min} = u(k|t-\Delta T) - \dot{u}_{Lim}(k)\Delta T \tag{3}$$

The results revealed by simulation verify that the proposed method reduces lateral deviation z from the target trajectory. A two-wheeled linear vehicle model served as the control target under the simulation conditions of driving into a right-angle corner with a minimum radius of 25 at a constant speed of 40 km/h (Figs. 1–4) where a large variation in curvature was observed and when decelerated from 55 km/h to a speed suitable for cornering (Figs. 5 and 6). For comparison, the MPC with time-invariant speed parameters, fixed weights, and no constraints will be discussed.

Increasing the weight of the yaw angle during cornering with variation in curvature, as shown in Fig. 3, preferentially reduces the yaw angle θ and the peak of the lateral deviation by approximately 31 s. Additionally, it contributes to the reduction of the lateral deviation after 31 s as it reduces the extent of operation at the yaw resonance and thus eliminates pitching behavior, as shown by the spectrum analysis of the extent of operation in Fig. 4. In a scenario with varying speed, as shown in Fig. 6, treating the change in vehicle speed as a time-varying parameter reduces the lateral deviation, as shown in Fig. 5.

In conclusion, it was demonstrated that the proposed method enables driving on suburban roads with fewer lateral deviation.

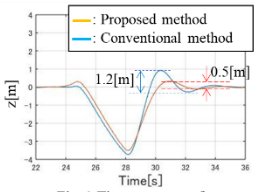

Fig. 1 Time response of z

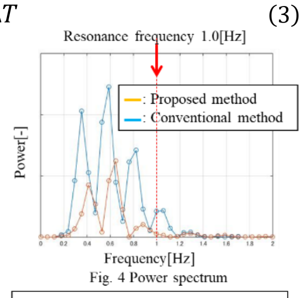

Fig. 4 Power spectrum

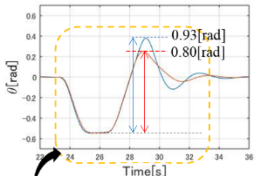

Fig. 2 Time response of θ

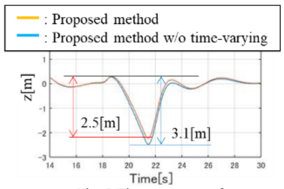

Fig. 5 Time response of z

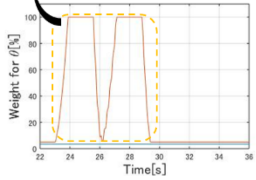

Fig. 3 Weight for θ

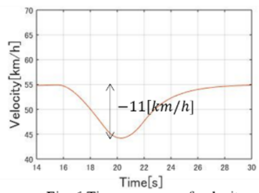

Fig. 6 Time response of velocity