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DEVELOPMENT OF A MODEL-FREE ADAPTIVE STEERING CONTROL FOR AUTONOMOUS VEHICLES PATH TRACKING USING COST-BASED GAIN ADAPTATION WITH INTEGRAL ACTION

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Abstract—This paper presents a model-free adaptive steering control algorithm for path tracking of autonomous vehicles. To design steering controllers for autonomous vehicle path tracking, a mathematical model is needed, but it may have high nonlinearity and complexity that increases computation time and effort. To resolve this problem, a model-free adaptive steering controller was designed for vehicle path tracking. As the design method, the feedback control scheme with adaptive feedback gain was applied so that the adaptation gain can be adjusted based on cost-based integral action. Simulation results show that the designed model-free adaptive controller with the cost-based gain adaptation method can achieve satisfactory tracking accuracy under the curved path tracking scenario.

Keywords-model-free adaptive control; autonomous vehicle; path tracking; gain adaptation; integral action

I. INTRODUCTION

The development of autonomous driving technology has enhanced driving safety and convenience, reduced traffic congestion, and improved driving energy efficiency. The path tracking controller is a key component for autonomous driving control and various studies have been conducted to achieve accurate, stable, and steady path tracking performance.

Sun et al [1] proposed a model predictive controller (MPC) for autonomous vehicle path tracking with switched tracking errors. The authors compared the performance of three MPCs with different tracking errors, and the strengths of two methods using the steady-state sideslip and real-time sideslip were combined into the proposed MPC with switched tracking error method. The performance evaluation was conducted using the CarSim-Simulink platform with the results showing improved performance. Cui et al. [2] proposed an MPC-based path following controller with steering angle envelopes. The trade-off between the tracking performance and real-time computational capability was considered by formulating the constraints pertaining to the feasible road regions and stable handling dynamics as the steering angle envelopes. Ahn et al. [3] developed an integrated autonomous driving control system for autonomous vehicles equipped with four independent in-wheel motors. For this, the autonomous driving controller and chassis controller were functionally integrated to improve vehicle stability as well as path tracking performance. Performance evaluations were conducted by simulating a double lane change, a high-speed circle entry, and a single lane-change scenario. Wang et al. [4] proposed an MPC using fuzzy adaptive weight control to solve the problem of autonomous vehicle in the process of path tracking. Tracking accuracy and vehicle dynamics stability could be ensured by the proposed controller based on the vehicle dynamic model. Simulation studies confirmed that the proposed controller can improve the tracking performance in terms of tracking accuracy and steering smoothness compared to the conventional MPC controller.

In this study, an adaptive feedback-based steering control algorithm for path tracking of autonomous vehicles is proposed using the cost-based gain adaptation with integral action. Lateral and yaw angle errors were used as feedback information and feedback gains were updated based on the gradient descent method with sensitivity. The feedback gain sensitivity with respect to error was estimated using recursive least squares (RLS) with a forgetting factor. The adaptation gains for the feedback gain determination were self-tuned by conditionally integrating the time derivative of the cost function. The weighting factors in the cost function were designed using the longitudinal velocity to consider the variation of change rates in errors with respect to velocity. Using a vehicle planar model under a curved-path tracking scenario, the proposed controller's performance was evaluated. The rest of the paper is organized as follows.

In Section Ⅱ, the model-free adaptive steering control algorithm for autonomous vehicles path tracking is presented and evaluation results and analysis are provided in Section Ⅲ. Finally, Section Ⅳ includes concluding remarks with future extensions.

II. Model-Free Adaptive Steering Control for Autonomous Vehicles Path Tracking

A. *Model-Free Adaptive Steering Controller*

Fig. 1 shows an overall model schematics for the model-free adaptive steering control algorithm designed in the study.

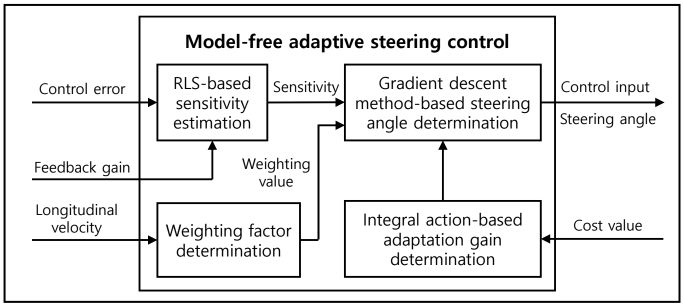

Figure 1. Model schematics for the model-free adaptive steering controller.

This controller consists of four blocks such as sensitivity estimation block, steering angle determination block, weighting factor determination block, and adaptation gain determination block. In the sensitivity estimation block, feedback gain sensitivity with respect to the control error is estimated using recursive least squares with a forgetting factor. Weighting value in the cost function is calculated in the weighting factor determination block and an adaptation gain is obtained in the integral action-based adaptation gain determination block. In the next subsection, the determination method for the adaptation gain will be explained in detail. Based on the sensitivity, weighting value, and adaptation gain, control inputs are computed in the gradient method-based steering angle determination block. The following equations are the cost function, the weighting function, and the sensitivity function.

$$J = (1/2) w_1 e_1^2 + (1/2) w_2 e_2^2 . \quad (1)$$

$$w_1 = a v_x + b . \quad (2)$$

$$\dot{e}_1 = C_{11}\dot{k}_1 + C_{12}\dot{k}_2 ,\ \dot{e}_2 = C_{21}\dot{k}_1 + C_{22}\dot{k}_2 . \quad (3)$$

where e_1 and e_2 represent the lateral error at preview point and the yaw angle error at vehicle mass center, respectively. C_{ij} ($i, j = 1, 2$) is the feedback gain sensitivity (function coefficient). w_i ($i = 1,\ 2$) represents weighting value. k_1 and k_2 represent the feedback gains. The control input (δ , vehicle steering angle) is computed using the following equation.

$$\delta = k_1 e_1 + k_2 e_2 . \quad (4)$$

Based on the estimated sensitivity $\hat{C}$, the feedback gains are updated with the gradient descent method. The next equation is used to update the feedback gain.

$$\begin{aligned} \dot{k}_1 &= -\gamma_1 \left(w_1 e_1 + w_2 e_2 \right)\left(\hat{C}_{11} e_1 + \hat{C}_{21} e_2 \right) \\ \dot{k}_2 &= -\gamma_2 \left(w_1 e_1 + w_2 e_2 \right)\left(\hat{C}_{12} e_1 + \hat{C}_{22} e_2 \right) \end{aligned} . \quad (5)$$

where γ_1 and γ_2 are the adaptation gains to determine the feedback gain's change rate. The adaptation gains are self-tuned using cost values.

B. *Cost-based Gain Adaptation with Integral Action*

The change rate and tuning condition are used for self-tuning of the adaptation gain with integral action, which requires Eq. (6).

$$\gamma = \int m dt, \dot{J} \le 0 \Rightarrow m = 0.1 else\, m = -0.1, \gamma \le 0 \Rightarrow \gamma = 0 . \quad (6)$$

The adaptation gain is varied with the cost value's change rate and the positive proportional gain, m . The lower limit in Eq. (6) is applied to prevent the tuning algorithm from making the adaptation gain negative.

III. Performance Evaluation

Performance evaluations were conducted under a curved-path tracking scenario with a constant vehicle velocity (10m/s). Fig. 2 shows a model schematics for performance evaluation.

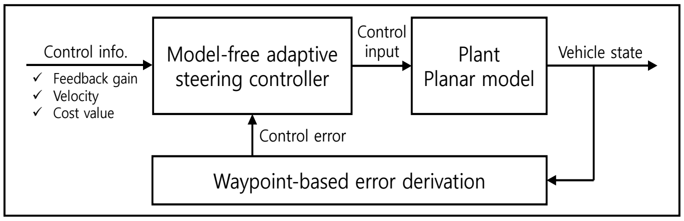

Figure 2. Model schematics for performance evaluation.

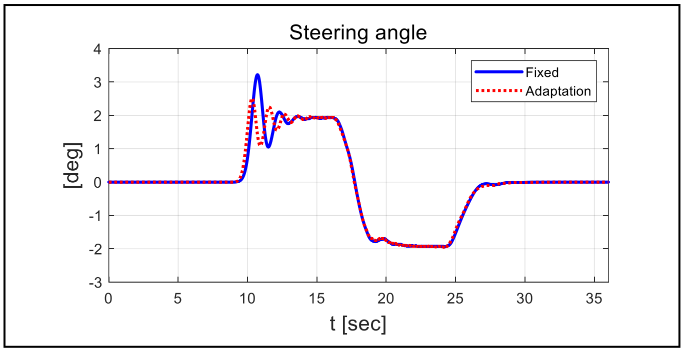

Figure 3. Steering angle.

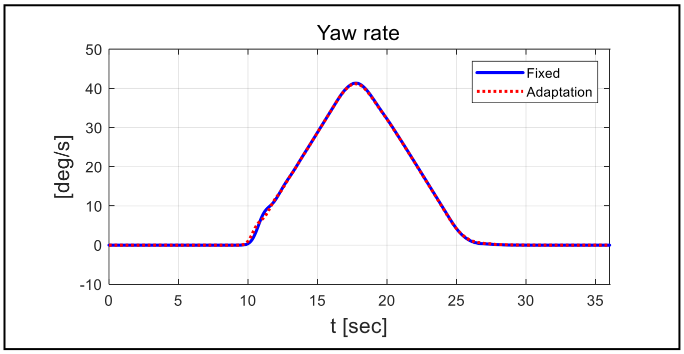

Figure 4. Yaw rate.

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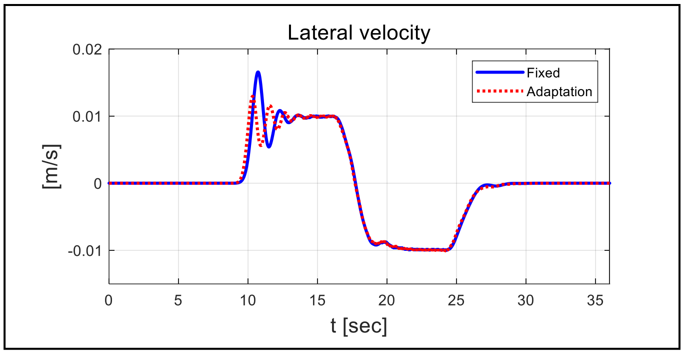

Figure 5. Lateral velocity.

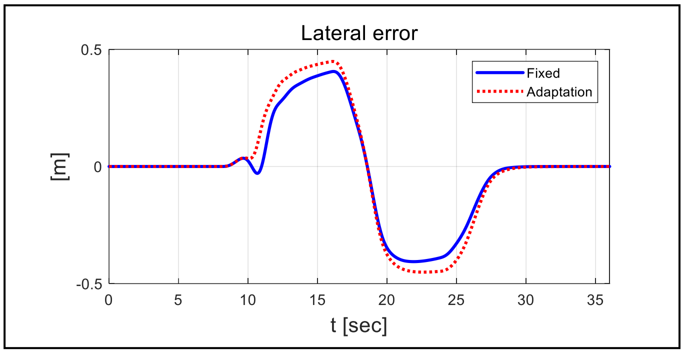

Figure 6. Control error: lateral.

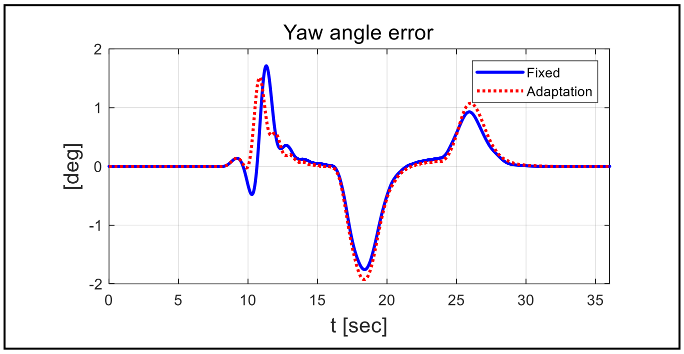

Figure 7. Control error: yaw angle.

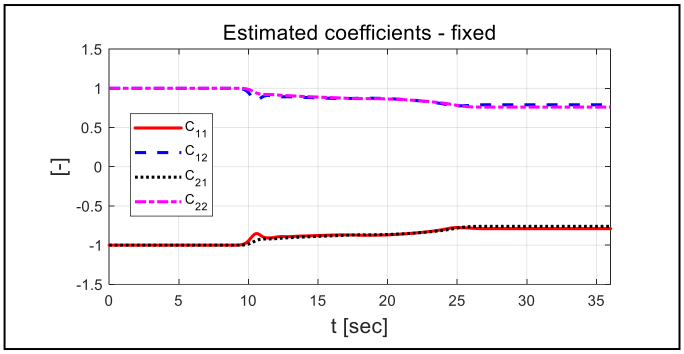

Figure 8. Estimated coefficients: fixed.

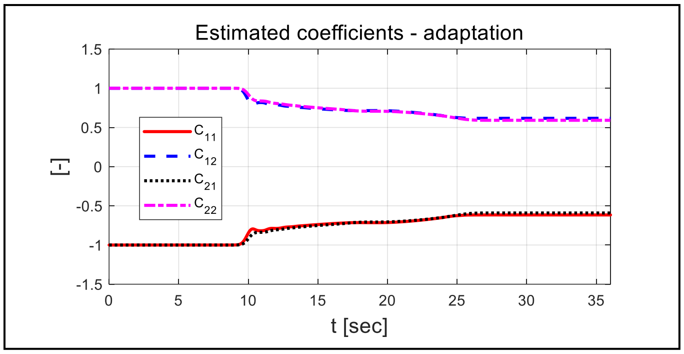

Figure 9. Estimated coefficients: adaptation.

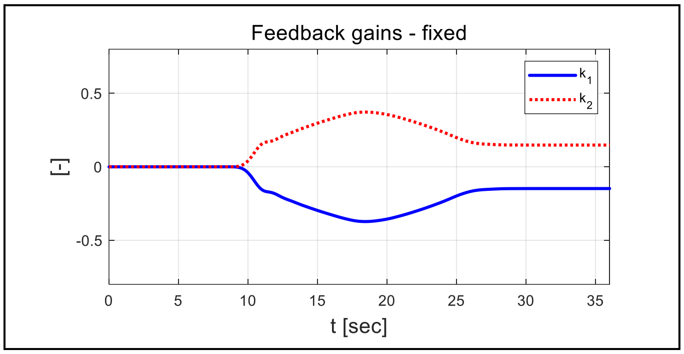

Figure 10. Feedback gains: fixed.

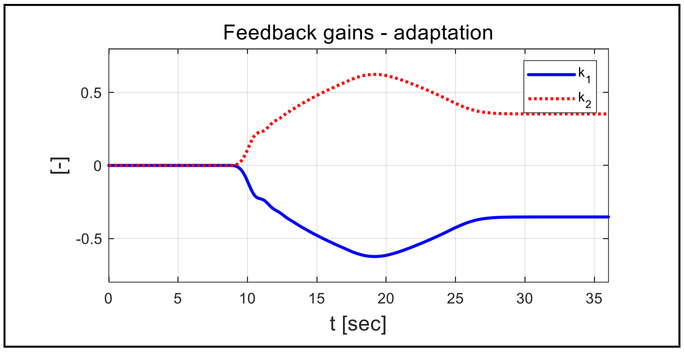

Figure 11. Feedback gains: adaptation.

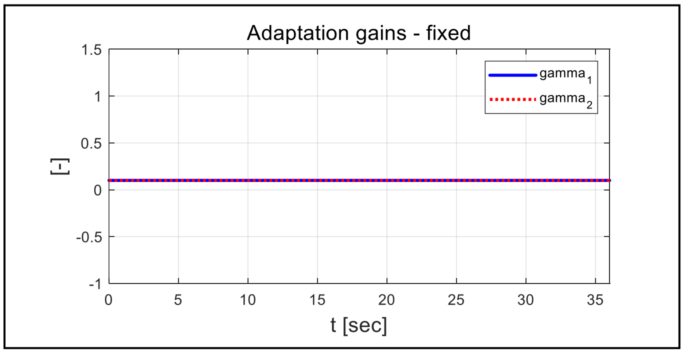

Figure 12. Adaptation gains: fixed.

Figs. 3-15 provide evaluation results. In Fig. 3, it is observed that the steering angle from the designed controller with an adaptation gain is relatively smaller than the controller with a fixed gain. Figs. 4 and 5 show the vehicle dynamics with respect to yaw rate and lateral velocity. In the case of yaw rate, there is no large difference between the two evaluation cases. However, it is observed that the lateral velocity from the designed controller with an adaptation gain is relatively smaller than the controller with a fixed gain.

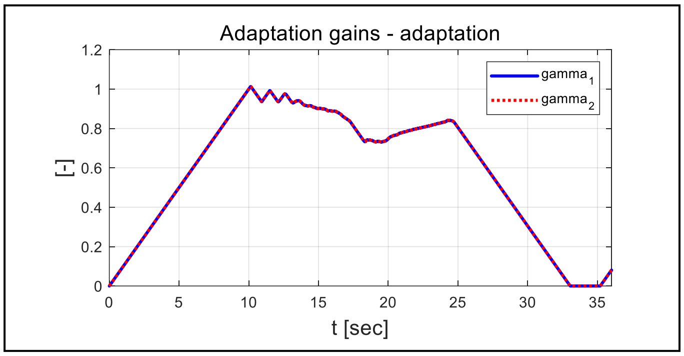

Figure 13. Adaptation gains: adaptation.

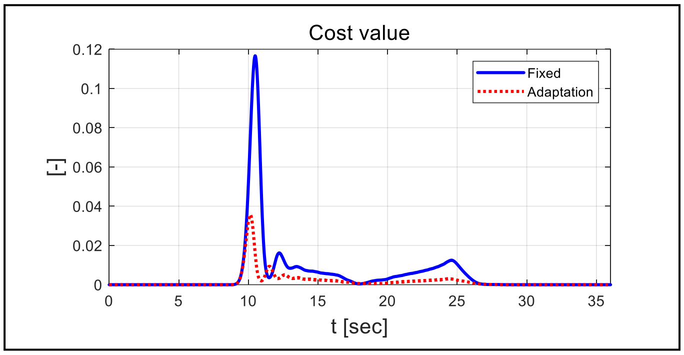

Figure 14. Cost value.

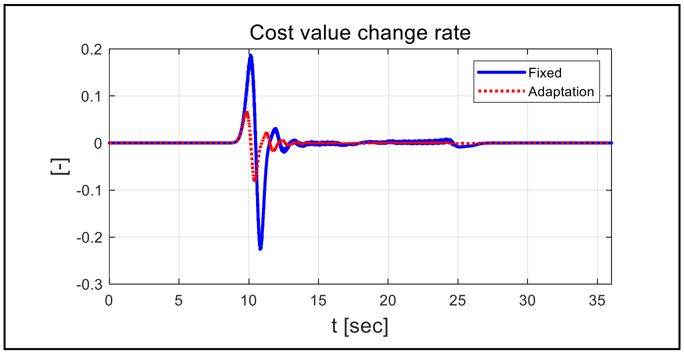

Figure 15. Cost value change rate.

Figs. 6 and 7 show the control errors, lateral error at preview point and yaw angle error at mass center, respectively. It is observed that there is no large difference between the two cases. Figs. 8 and 9 present the estimated sensitivity (coefficient) with a fixed gain and an adaptation gain. It is noted that estimated coefficients with an adaptation gain are changed more than the other case. Also, it is noted in Figs. 10 and 11 that the magnitude values of maximum and minimum feedback gains in the case of adaptation are larger than the other case (adaptation: max-about 0.624, min-about -0.624 vs fixed: max-about 0.3725, min-about -0.3725). The magnitude values of steady-state feedback gains with adaptation are also larger than the other case (adaptation: about 0.3529/-0.3529 vs fixed: about 0.148/-0.148).

Fig. 13 depicts the adaptation gain while Figs. 14 and 15 show the cost value and its change rate. We can find that the cost and its change rate values with an adaptation gain are relatively smaller than ones with a fixed gain. Fig. 16 shows the vehicle path tracking trajectory. There is an ignorable difference in tracking position between the two cases. This is because appropriate fixed adaptation gains were selected to satisfy reasonable path tracking performance with the model-free controller.

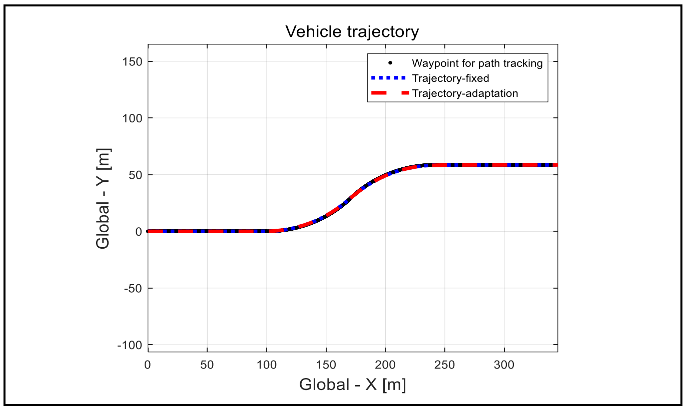

Figure 16. Path tracking trajectory.

The above evaluation results denote that increasing adaptation gains can improve the tracking control performance when a change rate of the cost value is positive. It also leads to a decrease in the cost value and its change rate (magnitude). Therefore, the proposed adaptation method with cost-based integral action allows the path tracking to be improved for the considered scenario through self-tuning.

IV. CONCLUSION

This study proposed the model-free adaptive steering control algorithm for autonomous vehicle path tracking that does not require a mathematical system model. For the design of the proposed controller, a feedback control scheme was applied and its feedback gains adaptation algorithm was developed with sensitivity estimation. The sensitivity was estimated using recursive least squares with a forgetting factor and feedback gains were adjusted based on the gradient descent method. In addition, the self-tuning algorithm for adaptation gains was proposed using the cost value with integral action. Performance evaluations were carried out under a curved-path tracking scenario and show that the path tracking performance could be enhanced by the designed controller with the application of an adaptation gain.

As a theme for future extension, the improvement of the weighting value determination method and the optimization of adaptation gains are considered to deal with path tracking performance. It is expected that the proposed model-free adaptive steering controller can be used for the vehicle path tracking control algorithm of autonomous vehicles.

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