Proceedings of the 4th International Conference on Software Engineering and Machine Learning
DOI: 10.54254/2755-2721/2026.32318

# *Prediction-Based Compensation Method for Tracking-Deviation Delay*

**Xiaoyu Han**

*School of Mechatronic Engineering, Changchun University of Science and Technology, Changchun, China*
*1207077199@qq.com*

***Abstract.*** In tracking control systems, deviation measurements usually undergo sensor sampling, signal processing, and data transmission processes, which inevitably introduce time delay. The delayed deviation signal causes the control input to lag behind the true target state, thereby degrading system stability and tracking accuracy. To address this issue, this paper analyzes the influence of tracking-deviation delay on system dynamic performance and establishes a target motion state-space model based on the current statistical model. On this basis, an adaptive Kalman filtering method is employed to recursively estimate the target state, and the future state is extrapolated according to the delay duration to achieve prediction-based compensation. Simulation results demonstrate that the proposed method effectively reduces tracking errors under a delay of 20 ms and significantly improves system robustness and stability.

***Keywords:*** tracking deviation, delay compensation, Kalman filtering, motion prediction

## 1. Introduction

Tracking deviation is an important feedback quantity in tracking control systems, reflecting the angular difference between the system line-of-sight and the target direction. The controller drives the actuator based on the measured deviation so that the system line-of-sight gradually aligns with the target.

However, in practical systems, deviation measurements must undergo sensor sampling, data processing, and communication transmission processes, which inevitably introduce time delay.

When the target is in a dynamic motion state, delayed deviation measurements cause the control input to lag behind the true target state, resulting in slower dynamic response and increased tracking error. As the maneuverability of the target increases, the influence of delay on system performance becomes more significant.

To mitigate the influence of delay, various prediction-based compensation methods have been proposed. Kalman filtering has been widely adopted in target state estimation and prediction due to its recursive computation structure and strong real-time capability [1]. For maneuvering target tracking problems, many improved filtering algorithms have been proposed, such as adaptive Kalman filtering and unscented Kalman filtering, which enhance system adaptability to model uncertainty [2,3]. In the presence of measurement delay, introducing prediction compensation

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.32318

mechanisms can effectively reduce the influence of delay on system stability and tracking accuracy [4]. By establishing a reasonable target motion model and combining it with filtering prediction techniques, delayed measurement signals can be compensated, thereby improving system tracking performance.

## 2. Delay influence analysis

Tracking deviation is defined as the angular difference between the system line-of-sight direction and the target direction. When measurement delay exists in the system, the open-loop transfer function of the system can be expressed as

$$G(s) = \frac{K(T_1 s+1)}{s^2(T_2 s+1)} e^{-\tau s} \tag{1}$$

K — system gain
$T_1$, $T_2$ — system time constants
$\tau$ — system delay.

When delay exists in the system, the deviation signal used by the controller actually corresponds to the historical information at time $t-\tau$, while the target continues to move during the delay period. Therefore, an additional error occurs between the control input and the true target state. For dynamic targets, this error is proportional to the angular velocity and angular acceleration of the target. As the delay increases, the error will be further amplified, which leads to a decrease in system stability margin and an increase in tracking error [5].

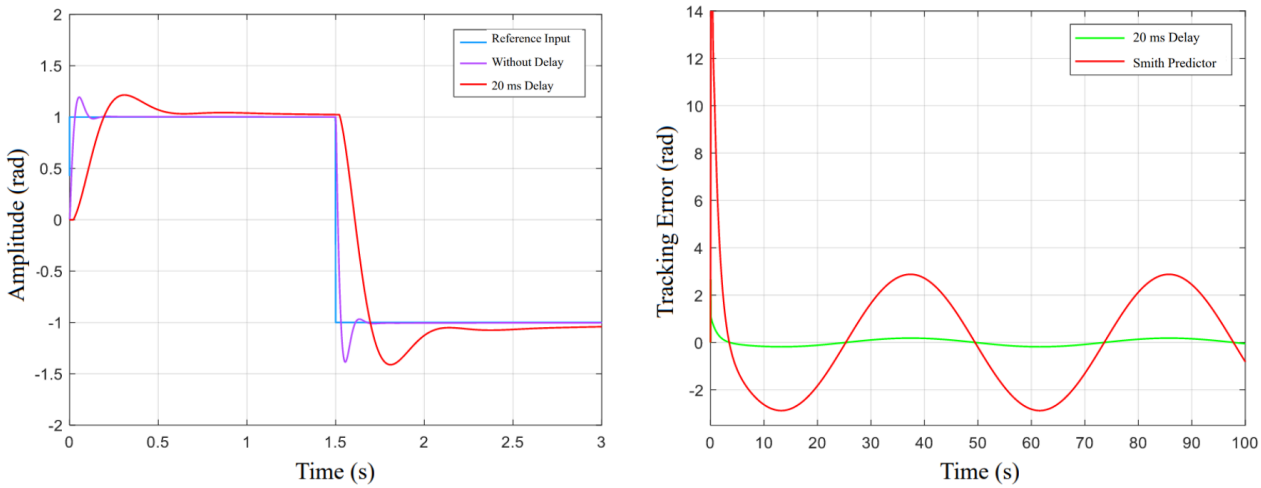



Figure 1. System response comparison with and without delay: (a) step response; (b) tracking error

It can be observed from Figure 1 that when a delay of 20 ms exists, the system response speed decreases significantly and the overshoot becomes larger. Meanwhile, the tracking error also increases obviously. This indicates that deviation delay significantly degrades the dynamic performance and tracking accuracy of the system. Therefore, an effective delay compensation method is required.

DOI: 10.54254/2755-2721/2026.32318

## 3. Conventional compensation method

The Smith predictor is a commonly used delay compensation method. Its basic idea is to establish a model of the controlled object and separate the delay element from the closed-loop system, thereby reducing the influence of delay on system stability.

However, since the system model cannot exactly match the real system, model mismatch inevitably exists. When modeling errors occur, the performance of the Smith predictor will be affected.

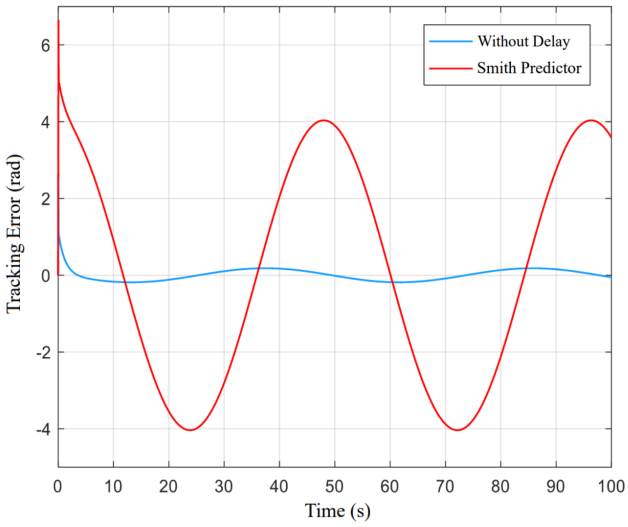



Figure 2. Tracking error of conventional prediction compensation method

It can be observed from Figure 2 that after applying the conventional prediction compensation method, the tracking error of the system is approximately 4 mrad, which is still much larger than the system requirement of 200 μrad. Therefore, the conventional prediction compensation method cannot meet the accuracy requirements of high-precision tracking systems.

## 4. Prediction-based compensation method

### 4.1. Target motion state-space model

To improve system tracking accuracy, a prediction-based compensation method using Kalman filtering is proposed. First, a target motion state-space model is established.

$$X(k) = \left[\theta(k), \dot{\theta}(k), \ddot{\theta}(k)\right]^T \tag{2}$$

$$X(k+1) = \Phi X(k) + W(k) \tag{3}$$

$$Z(k) = HX(k) + V(k) \tag{4}$$

DOI: 10.54254/2755-2721/2026.32318

where W(k) represents process noise and V(k) represents measurement noise.

Using Kalman filtering, the target state can be recursively estimated. According to the delay duration, the future state of the target can then be predicted, thereby achieving delay compensation.

To improve adaptability to maneuvering targets, a prediction filtering method based on the current statistical model is adopted. This model assumes that the target acceleration varies randomly within a short time interval and can effectively describe the maneuvering characteristics of the target. Therefore, by combining the Kalman filtering prediction mechanism, the future state of the target can be estimated and used as a feedforward compensation signal in the control loop, thereby reducing the influence of delay errors.

Assume that the system measurement contains a delay of b sampling periods. Then the measurement obtained at time k actually corresponds to the system state at time k−b:

$$Z(k) = HX(k-b) + V(k) \tag{5}$$

Therefore, the state estimate obtained by Kalman filtering is

$$\hat{X}(k-b|k-b) \tag{6}$$

To obtain the target state at the current time k, forward prediction using the state transition model is required:

$$\hat{X}(k|k-b) = \Phi^b \hat{X}(k-b|k-b) \tag{7}$$

$$\Phi^b = \Phi(T)^b \tag{8}$$

represents the b-step state transition matrix.

Through this extrapolation process, the predicted state estimate at the current moment can be obtained, thereby reducing the influence of measurement delay on system control performance.

## 4.2. Target state prediction model

According to the target motion model, the state transition matrix can be expressed as

$$\Phi(T) = \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

Therefore, when the delay is b sampling periods, the predicted state of the target can be expressed as

DOI: 10.54254/2755-2721/2026.32318

$$\widehat{X}(k+b|k) = \Phi^{b}\widehat{X}(k|k) \tag{10}$$

Expanding the above expression yields

$$\hat{\theta}(k+b) = \theta(k) + bT\dot{\theta}(k) + \frac{(bT)^2}{2}\ddot{\theta}(k) \tag{11}$$

$$\hat{\dot{\theta}}(k+b) = \dot{\theta}(k) + bT\ddot{\theta}(k) \tag{12}$$

$$\hat{\ddot{\theta}}(k+b) = \ddot{\theta}(k) \tag{13}$$

It can be seen that the future state of the target can be predicted using angular velocity and angular acceleration information, thereby compensating for measurement delay.

### 4.3. Prediction compensation control structure

After obtaining the predicted state of the target, the prediction result can be used as a feedforward compensation signal in the control system.

The control input after prediction compensation can be expressed as

$$u(k) = K_p\hat{\theta}(k+b) + K_d\hat{\dot{\theta}}(k+b) \tag{14}$$

$K_p$— position control gain

$K_d$— velocity control gain.

By using predicted future states as control feedback quantities, the control error caused by delay can be effectively reduced, thereby improving the dynamic response performance and tracking accuracy of the system.

### 4.4. Algorithm implementation procedure

Based on the above analysis, the implementation procedure of the prediction-based compensation algorithm can be summarized as follows:

1. Estimate the target state using Kalman filtering.
2. Calculate the delay sampling period b according to the system delay.
3. Perform forward prediction of the target state using the state transition matrix.
4. Use the predicted state as the feedforward compensation signal of the control system.
5. Calculate the control input and drive the actuator.

Through this prediction compensation mechanism, the degradation of system performance caused by deviation measurement delay can be effectively reduced.

DOI: 10.54254/2755-2721/2026.32318

## 5. Simulation results

### 5.1. Simulation setup

To verify the effectiveness of the proposed method, a tracking system simulation model is established.

The main simulation parameters are as follows: T=0.02s,τ=20ms, $X(0)=[0\ 0\ 0]^T$,

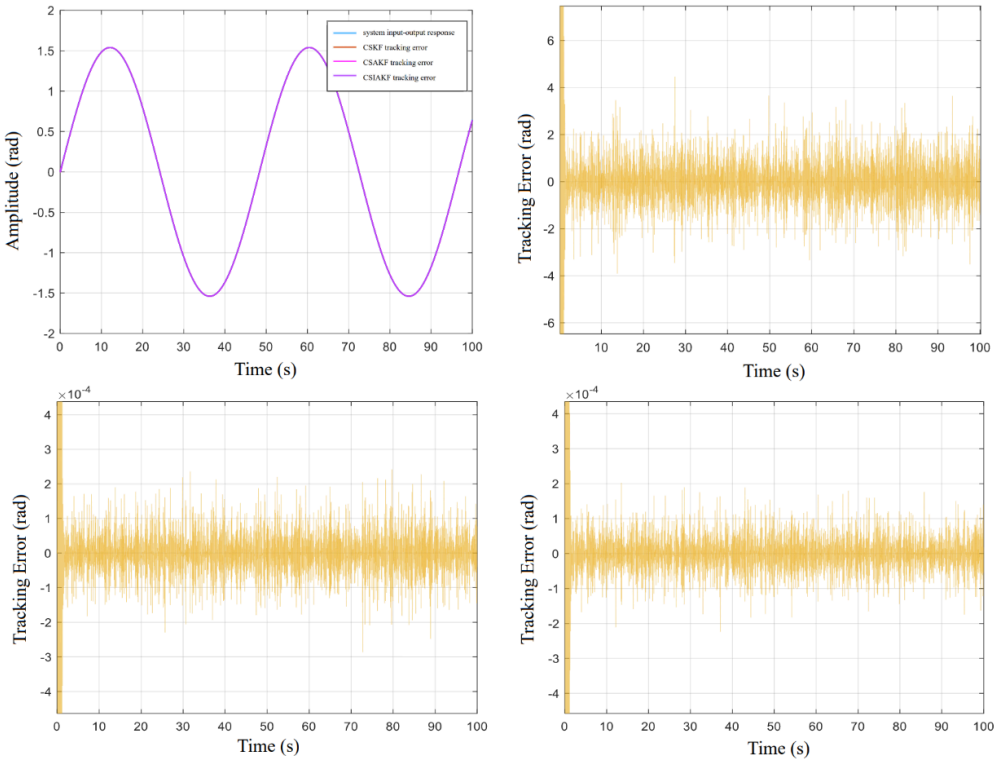



Figure 3. Simulation results of prediction-based compensation method: (a) system input-output response; (b) CSKF tracking error; (c) CSAKF tracking error; (d) CSIAKF tracking error

### 5.2. Result discussion

It can be seen from Figure 3 that when the deviation delay is 20 ms, the system input and output signals remain basically consistent.

Using the CSKF algorithm, the tracking error is approximately 265 μrad, while the CSAKF algorithm reduces the error to about 200 μrad. After applying the CSIAKF algorithm, the tracking error can be reduced to about 185 μrad.

Compared with the CSKF algorithm, the CSIAKF algorithm improves tracking accuracy by approximately 38%, and compared with the CSAKF algorithm, the tracking accuracy is further improved by about 7%.

These results demonstrate that the prediction-based feedforward compensation method can effectively reduce the influence of deviation delay on system performance.

DOI: 10.54254/2755-2721/2026.32318

## 6. Conclusion

This paper investigates the problem of deviation delay in tracking control systems and proposes a prediction-based delay compensation method based on Kalman filtering.

By establishing a target motion model and predicting the target state, feedforward compensation for delayed deviation measurements is achieved.

Simulation results show that the proposed method can effectively reduce tracking errors under delay conditions and significantly improve system stability and robustness.

## References

[1] R. E. Kalman, "A new approach to linear filtering and prediction problems, " Journal of Basic Engineering, vol. 82, no. 1, pp. 35–45, 1960.
[2] D. Simon, Optimal State Estimation: Kalman, H∞, and Nonlinear Approaches. Wiley, 2006.
[3] Y. Bar-Shalom, X. R. Li, and T. Kirubarajan, Estimation with Applications to Tracking and Navigation. Wiley, 2001.
[4] H. Liu, J. Wang, and Z. Chen, "Prediction-based delay compensation method for tracking control systems, " IEEE Transactions on Industrial Electronics, vol. 67, no. 5, pp. 4216–4225, 2020.
[5] Y. Li, Q. Zhao, and H. Sun, "Kalman filtering-based prediction compensation for time-delay systems, " Sensors, vol. 23, no. 6, 2023.