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Delay-dependent guaranteed-cost control based on combination of Smith predictor and equivalent-input-disturbance approach

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ABSTRACT

This paper presents a new system configuration and a design method to improve control performance for a system with an input time delay and disturbances. The equivalent-input-disturbance approach is extended to handle a time-delay system. It is combined with the Smith predictor to reject disturbances. A delay-dependent stability condition is devised in terms of a matrix inequality by using the free-weighting matrix approach. The gain of the observer is designed by applying the cone complementary linearization method to the matrix inequality. A numerical example demonstrates the validity of the method.

1. Introduction

A time delay is often encountered in many practical systems, such as chemical processes, biological mechanisms, and mechanical apparatus [1–3]. Since a time delay decreases the stability margin of a closed-loop system, the design of a robust time-delay control system is a challenging problem, and has been drawing considerable attentions [4–7].

Various methods have been proposed to improve the robust performance of a closed-loop time-delay system [8–10]. The Smith predictor (SP) [11–13] among them is the one that has been widely used. It equivalently removes a time delay out of the closed control loop, and stabilizes the time-delay system. However, disturbance-rejection performance is not satisfactory for the SP. While sliding mode control (SMC) [14,15] is an effective method to solve this problem, it may cause high-frequency oscillation. This makes it difficult to implement the control law for a mechatronic system.

Some methods that actively compensate disturbances have been widely noticed. The equivalent-input-disturbance (EID) approach is one among them. It was devised to reject both matched and unmatched disturbances effectively [16–18]. An EID is a signal on the control input channel of a system that produces the same effect on the output as actual disturbances do. This approach does not require a prior information about disturbances. And since it does not use the inverse dynamics of a plant, it avoids the cancelation of unstable poles and zeros, which happens in a disturbance observer.

This paper considers a guaranteed-cost control problem for a plant with both of an input time delay and a non-stationary disturbance. The control system combines the SP with the EID approach, which is called the SP-EID control system here after, to improve control performance. Since the guaranteed-cost control method provides a control law that not only stabilizes a time-delay system but also ensures an adequate level of control performance, such a control law is presented in this paper to guarantee the upper bound of a specified linear integral-quadratic cost function. A delay-dependent sufficient stability condition is derived in terms of a matrix inequality. And the gain of the observer is obtained from the condition using the cone complementary linearization method. The validity of the method is demonstrated through simulations.

In the rest of the paper, $\begin{bmatrix} A & B \\ B^T & C \end{bmatrix}$ is indicated by $\begin{bmatrix} A & B \\ \star & C \end{bmatrix}$.

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2. Configuration of SP-EID of control system

Consider the following linear time-invariant time-delay plant:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t-\tau) + B_d d(t), \\ y(t) = Cx(t), \end{cases} \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state; $u(t) \in \mathbb{R}^m$ is the control input; $y(t) \in \mathbb{R}^q$ is the output; $d(t) \in \mathbb{R}^{n_d}$ is a disturbance; and A, B, B_d, and C are constant matrices with suitable dimensions. τ is a scalar representing the delay in the system. The initial condition is $x(t)|_{t=0} = x(0)$.

The following assumptions are made for (A, B, C). They are standard in control system design.

Assumption 1. (A, B, C) is controllable and observable.

Assumption 2. (A, B, C) has no zeros on the imaginary axis.

The configuration of the SP-EID control system is shown in Fig. 1. The system contains the plant, a controller $\overline{C}(s)$, the SP, a state observer, and an EID estimator. The EID estimator is extended from its original form in [18] to the one in the figure so as to handle the time delay in the plant. Note that

$$B^+ := (B^T B)^{-1} B^T \tag{2}$$

in the estimator.

According to the definition of the EID [18], we introduce an EID, $d_e(t)$, on the control input channel, and describe the plant as

$$\begin{cases} \dot{x}(t) = Ax(t) + B[u(t-\tau) + d_e(t)], \\ y(t) = Cx(t). \end{cases} \tag{3}$$

In the above equation, we abuse the notation a little bit, and use the same variable, $x(t)$, to indicate the state of both the original plant and that in (3). This should not cause confusion.

Let $G(s) = C(sI - A)^{-1}B$. Then, the transfer function of the plant from $u(t)$ to $y(t)$ is given by $P(s) = G(s)e^{-\tau s}$.

A full-order observer is used to estimate the EID. The state-space representation of the observer is

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu_f(t-\tau) + L[y(t) - \hat{y}(t)], \\ \hat{y}(t) = C\hat{x}(t), \end{cases} . \tag{4}$$

where $\hat{x}(t)$ is a reconstruction state of $x(t)$.

Following the same line as that in [18], it is easy to show that an estimate of the EID is given by

$$\hat{d}_e(t) = B^+ LC\tilde{x}(t) + u_f(t-\tau) - u(t-\tau), \tag{5}$$

where

$$\tilde{x}(t) = x(t) - \hat{x}(t). \tag{6}$$

A low-pass filter, $F(s)$,

$$\begin{cases} \dot{x}_F(t) = A_F x_F(t) + B_F \hat{d}_e(t), \\ \tilde{d}_e(t) = C_F x_F(t), \end{cases} \tag{7}$$

is used to select the angular-frequency band width for the EID estimation. It satisfies

$$|F(j\omega)| \approx 1, \quad \forall \omega \in [0, \omega_r], \tag{8}$$

where ω_r is the highest angular frequency of the disturbance. A suitable filter has its cutoff angular frequency being more than 5–10 times larger than ω_r. The filtered disturbance, $\tilde{d}_e(t)$, is given by

$$\tilde{D}_e(s) = F(s)\hat{D}_e(s), \tag{9}$$

where $\tilde{D}_e(s)$ and $\hat{D}_e(s)$ are the Laplace transformations of $\tilde{d}_e(t)$ and $\hat{d}_e(t)$ respectively.

A new control law of the control system is

$$u(t) = u_f(t) - \tilde{d}_e(t). \tag{10}$$

3. Stability analysis and system design of SP-EID control system

This section first analyzes the stability of the SP-EID control system, then presents a design method based on the analysis result.

3.1. Stability analysis

Let the reference input and the disturbance be zero, that is,

$$r(t) = 0, \quad d(t) = 0. \tag{11}$$

The plant is described by

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t-\tau), \\ y(t) = Cx(t). \end{cases} \tag{12}$$

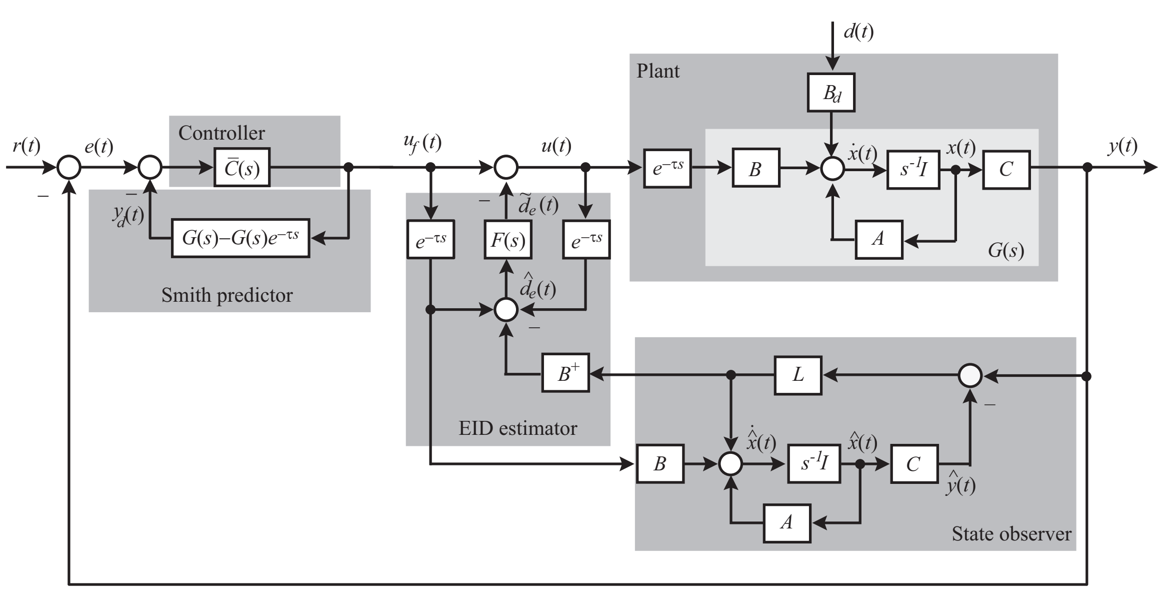

Fig. 1. Configuration of SP-EID control system.