15th Triennial World Congress, Barcelona, Spain

OBSERVER-BASED CONTROL DESIGN WITH ADAPTATION TO DELAY-PARAMETERS FOR TIME-DELAY SYSTEM [1]

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Abstract: Based on Lyapunov-Krasovskii functional, this paper concerns an observer-based stabilization problem for linear time-delay systems with delayed state and input. If the time-delay constants are both available for the li.near time-delay system, an observer-based controller, in which the influence of the time-delays is considered, is given. And the design of the controller and observer satisfies the separation principle. If the time-delay constants aren't precisely known for the linear time-delay system, an observer-based feedback controller with adaptation to delay parameters is first given. Then the adaptive controllers are derived by Riccati matrix inequalities. *Copyright © 2002 IFAC*

Keywords: Time-delay, Riccati equations, observers, asymptotic stability, adaptive control, Lyapunov function.

1. INTRODUCTION

Time delays in state and control input are often encountered in many industrial processes, such as chemical processes, long transmission lines in pneumatic, hydraulic, and rolling mill systems. The presence of state delay and input delay may cause instability or serious deterioration in the performance of the control systems.

An easy way of dealing with linear time-delay systems is to design a state-feedback controller based on Lyapunov-Krasovskii functional. This has attracted the attention of many researchers for the past several decades [Hao & Myung, 1995a,b; Niculescu, 1998; Jong, Eun & Hong, 1996]. Due to limited output measurement, state-feedback control laws cannot, in general, be realized. Therefore, the problem of designing an observer-based feedback controller for a linear plant to make the closed-loop system stable has been discussed in many papers during the two decades [Zhang, Cheng & Sun, 1998; Zidong, Biao & Unbehauen, 2001; Su, Wang & Chu, 1998]. At present the observer design of linear time-delay systems have mainly two methods. One is that there is no delay information in observer [Zhang, Cheng & Sun, 1998; Zidong, Biao & Unbehauen, 2001]. The design of this observer is quite simple, but this observer can't reflect the message of system itself completely and the design of the controller and observer doesn't satisfy the separation principle. Another is that there is delay information in observer [Su, Wang & Chu, 1998; Hao & Myung, 1996]. This observer can completely reflect the message of system itself and the design of the controller and observer satisfies the separation principle, but its

[1] This work was supported by NSFC (Under Grant 69604003, 69934010), Key Project (Under Grant 970211017) and Southeast University-Nanrui Fun of China.

realization has some difficulty if the delay constant can not be exactly known. In order to solve this difficulty, an adaptive control to delay parameters is presented firstly in this paper for linear time-delay system if the upper bound of delay parameters are known. Based on Riccati matrix inequalities, an observer-based feedback controller has been given in which the delay parameters of the observer are real-time estimation of delays. Thus the design of observer-based feedback controller doesn't need to know the exact value of delay constants but only need to know the upper bound of delays. It is shown that an observer-based feedback controller can be designed by a simple procedure as the solutions of the Riccati matrix inequalities are obtained. So it is very convenient to design the observer-based feedback controller which include the delay information.

2. PROBLEM STATEMENT

Consider the following linear time-delay systems

$$\begin{cases} \dot{x}(t) = Ax(t) + A_1 x(t-\tau) + Bu(t) + B_1 u(t-d) \\ y(t) = Cx(t) \\ x(t) = \phi(t),\ t \in [-\tilde{\tau}, 0], \end{cases} \tag{1}$$

where $x(t) \in R^n$ is the state, $u(t) \in R^m$ is the control input, $y(t) \in R^p$ is the measured output, A, A_1, B, B_1, C are constant matrices with appropriate dimensions. $\tau \ge 0, d \ge 0$ are the delay constants, $\tilde{\tau} = \max\{\tau, d\}$ and $\tau \le \tau^*$, $d \le d^*$, τ^* and d^* are given constants being the upper bound of τ and d respectively. ϕ is a given continuous vector-valued initial function over $[-\tilde{\tau}, 0]$ of the system (1), it is to say that $\phi \in C[-\tilde{\tau}, 0]$.

In order to stabilize the system (1), the state-feedback controllers have been given in general[1-4]. But in practical, the states of the system (1) aren't available and the realization of these controllers has some difficulties. One of the effective methods, which can be used to solve this problem, is to design an observer-based controller of the system (1). At present, there are mainly two methods about the observer-based controller design of the system (1).

One method is to design following observer-based feedback controller which doesn't consider the influence of state-delay and input-delay in observer

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L[y(t) - C\hat{x}(t)] \\ u(t) = F\hat{x}(t) \\ \hat{x}(t) = \psi(t), \quad t \in [-\tilde{\tau}, 0], \end{cases} \tag{2}$$

where $\hat{x}(t) \in R^n$ is the observer state vector, and $\psi \in C[-\tilde{\tau}, 0]$ is the given continuous vector-valued initial function over $[-\tilde{\tau}, 0]$ of system (2), such that the following closed-loop system is asymptotically stable.

$$\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A+BF & -BF \\ 0 & A-LC \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} A_1 & 0 \\ A_1 & 0 \end{bmatrix} \begin{bmatrix} x(t-\tau) \\ e(t-\tau) \end{bmatrix} + \begin{bmatrix} B_1F & -B_1F \\ B_1F & -B_1F \end{bmatrix} \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}, \tag{3}$$

where $e(t) = x(t) - \hat{x}(t)$. From (3) we can obviously check that the design of this observer-based feedback controller doesn't satisfy the separation principle. This brings about disadvantage when we design the system controller and observer;

Another method is to design following observer-based feedback controller which considers the influence of the delays in observer

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + A_1\hat{x}(t-\tau) + Bu(t) + B_1 u(t-d) \\ \qquad + L[y(t) - C\hat{x}(t)] \\ u(t) = F\hat{x}(t) \\ \hat{x}(t) = \psi(t), \quad t \in [-\tilde{\tau}, 0], \end{cases} \tag{4}$$

such that the following closed-loop system is asymptotically stable,

$$\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A+BF & -BF \\ 0 & A-LC \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} A_1 & 0 \\ 0 & A_1 \end{bmatrix} \begin{bmatrix} x(t-\tau) \\ e(t-\tau) \end{bmatrix} + \begin{bmatrix} B_1F & -B_1F \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x(t-d) \\ e(t-d) \end{bmatrix}. \tag{5}$$

From (5) we can obviously check that the design of this observer-based feedback controller satisfies the separation principle. This brings about advantage when we design the system controller and observer.

However, the design of the controller (4) builds on that the state-delay constant and the input-delay constant are both exactly known. In general, the time-delay constants can be hardly obtained in the engineering systems. In order to solve this problem, the design of observer-based feedback controller is given for two aspects in this paper:

① If the delay constants τ and d are both exactly available, an observer-based feedback controller (4) will be designed such that the closed-loop system (5) is asymptotically stable.

② If the delay constants τ and d aren't exactly available but their upper bound τ^* and d^* are available, the observer-based feedback controller is designed as

$$\begin{cases}\dot{\hat{x}}(t) = A\hat{x}(t) + A_1\hat{x}(t-\hat{\tau}(t)) + Bu(t) \\ \qquad + B_1u(t-\hat{d}(t)) + L[y(t) - C\hat{x}(t)] \\ u(t) = F\hat{x}(t) \\ \hat{x}(t) = \psi(t), \quad t\in[-\tilde{\tau},0],\end{cases} \tag{6}$$

where $\hat{\tau}(t)$ and $d(t)$ are the estimation value of τ and d satisfying $\hat{\tau}(t)\ge\tau, \dot{\hat{\tau}}(t)\le 0$ and $d(t)\ge d$, $\dot{d}(t)\le 0$, $\forall t\ge 0$ respectively, and the adaptive rule about delay constants τ and d are given (see Eq.(13), (14)) such that the following closed-loop systems is asymptotically stable

$$\begin{cases}\dot{x}(t) = (A+BF)x(t) + A_1x(t-\tau) - BFe(t) \\ \qquad + B_1Fx(t-d) - B_1Fe(t-d) \\ \dot{e}(t) = (A-LC)e(t) + A_1e(t-\tau) + A_1[\hat{x}(t-\tau) - \hat{x}(t-\hat{\tau})] \\ \qquad + B_1F[\hat{x}(t-d) - \hat{x}(t-\hat{d})] \\ x(t) = \phi(t), e(t) = \phi(t) - \psi(t), t\in[-\max(\tilde{\tau},\hat{\tau}(0),\hat{d}(0)), 0],\end{cases} \tag{7}$$

where F and L are gain matrices of the controller and gain matrix of observer respectively, which is taken to be determined.

3. MAIN RESULTS

(1) We assume that all the delay constants are available exactly but the state of system (1) isn't exactly available. In this case we take Lyapunov-Krasovskii functional of (5) as

$$\begin{aligned}V_1(x_t, e_t) &= x^T(t)P_cx(t) + \int_{t-\tau}^{t} x^T(\theta)S_1x(\theta)d\theta \\ &+ \int_{t-d}^{t} x^T(\theta)(B_1F)^T S_2B_1Fx(\theta)d\theta \\ &+ e^T(t)P_oe(t) + \int_{t-\tau}^{t} e^T(\theta)S_3e(\theta)d\theta \\ &+ \int_{t-d}^{t} e^T(\theta)(B_1F)^T S_4B_1Fe(\theta)d\theta,\end{aligned} \tag{8}$$

where $P_c, P_o, S_1, S_2, S_3, S_4$ are symmetry positive-definite matrices. Thus the derivative of $V_1(x_t, e_t)$ along with closed-loop system (5) is

$$\begin{aligned}\dot{V}_1 &= x^T(t)[P_c(A+BF) + (A+BF)^T P_c + S_1 \\ &+ (B_1F)^T S_2B_1F]x(t) + 2x^T(t)P_cA_1x(t-\tau) \\ &+ 2x^T(t)P_cB_1Fx(t-d) - 2x^T(t)P_cBFe(t) \\ &- 2x^T(t)P_cB_1Fe(t-d) - x^T(t-\tau)S_1x(t-\tau) \\ &- x^T(t-d)(B_1F)^T S_2B_1Fx(t-d) \\ &+ e^T(t)[P_o(A-LC) + (A-LC)^T P_o + S_3 \\ &+ (B_1F)^T S_4B_1F]e(t) + 2e^T(t)P_oA_1e(t-\tau) \\ &- e^T(t-\tau)S_3e(t-\tau) - e^T(t-d)(B_1F)^T S_4B_1Fe(t-d)\end{aligned}$$

$$\begin{aligned}&\le x^T(t)[P_c(A+BF) + (A+BF)^T P_c + P_c(A_1S_1^{-1}A_1^T \\ &+ S_2^{-1} + S_4^{-1} + S_5^{-1})P_c + S_1 + (B_1F)^T S_2B_1F]x(t) \\ &+ e^T(t)[P_o(A-LC) + (A-LC)^T P_o + (BF)^T S_5BF \\ &+ P_oA_1S_3^{-1}A_1^T P_o + S_3 + (B_1F)^T S_4B_1F]e(t)\end{aligned}$$

where S_5 is a symmetry positive-definite matrix. From the discussion above we can get following conclusion.

Theorem 1: If there exist matrices F, L, symmetric positive-definite matrices $P_c, P_o, S_1, S_2, S_3, S_4, S_5$ satisfy the following Riccati matrix inequalities:

$$\begin{aligned}&P_c(A+BF) + (A+BF)^T P_c + P_c(A_1S_1^{-1}A_1^T + S_2^{-1} \\ &\quad + S_4^{-1} + S_5^{-1})P_c + S_1 + (B_1F)^T S_2B_1F < 0\end{aligned} \tag{9}$$

$$\begin{aligned}&P_o(A-LC) + (A-LC)^T P_o + (BF)^T S_5BF \\ &\quad + P_oA_1S_3^{-1}A_1^T P_o + S_3 + (B_1F)^T S_4B_1F < 0\end{aligned} \tag{10}$$

then the closed-loop system (5) with observer-based feedback controller (4) is asymptotically stable. At this time, we can set that $F = B^T P_c$, $L = P_o^{-1}C^T$.

According to theorem 1, we can obtain the observer-based feedback controller of the system (1). But if the time-delay constants of the system (1) aren't exactly available, the realization of this controller has some difficulty in the engineering systems. This problem can be solved by an adaptive rule about delay constant τ and d in the following part.

(2) We suppose that the delay constants aren't exactly available. In this case, according to

$$\begin{aligned}\dot{\hat{x}}(t) &= A\hat{x}(t) + A_1\hat{x}(t-\hat{\tau}(t)) + Bu(t) \\ &\quad + B_1u(t-\hat{d}(t)) + LCe(t),\end{aligned}$$

$$\begin{aligned}\hat{x}(t-\tau) - \hat{x}(t-\hat{\tau}) &= \int_{t-\hat{\tau}}^{t-\tau}[A\hat{x}(\theta) + A_1\hat{x}(\theta-\hat{\tau}(\theta)) + Bu(\theta) \\ &\quad + B_1u(\theta-\hat{d}(\theta)) + LCe(\theta)]d\theta,\end{aligned}$$

the form (7) will be equivalent to

$$\begin{cases}\dot{x}(t) = (A+BF)x(t) + A_1x(t-\tau) - BFe(t) \\ \qquad + B_1Fx(t-d) - B_1Fe(t-d) \\ \dot{e}(t) = (A-LC)e(t) + A_1e(t-\tau) + A_1\int_{t-\hat{\tau}}^{t-\tau}[A\hat{x}(\theta) + A_1\hat{x}(\theta-\hat{\tau}) \\ \qquad + Bu(\theta) + B_1u(\theta-\hat{d}) + LCe(\theta)]d\theta + B_1F\int_{t-\hat{d}}^{t-d}[A\hat{x}(\theta) \\ \qquad + A_1\hat{x}(\theta-\hat{\tau}) + Bu(\theta) + B_1u(\theta-\hat{d}) + LCe(\theta)]d\theta\end{cases} \tag{11}$$

For the closed-loop system (11) we take Lyapunov-Krasovskii functional as

$$V_2(x_t,e_t)=V_1(x_t,e_t)+\gamma_1(\hat{\tau}(t)-\tau)^2+\gamma_2(\hat{d}(t)-d)^2$$
$$+2M\|P_oA_1\|\int_{-\hat{\tau}}^{-\tau}d\theta\int_{\theta}^{0}z(t+s)ds$$
$$+2M\|P_oB_1F\|\int_{-\hat{d}}^{-d}d\theta\int_{\theta}^{0}z(t+s)ds,\quad (12)$$

where $\|e(t)\|\le M,\forall t\ge 0$, $z(t)=\|A\hat{x}(t)+A_1\hat{x}(t-\hat{\tau}(t))+Bu(t)+B_1u(t-\hat{d}(t))+LCe(t))\|$, and constant M, γ_1, γ_2 can be determined later,. The derivative of $V_2(x_t,e_t)$ along with (11) is

$$\dot{V}_2=\dot{V}_1+2\gamma_1(\hat{\tau}(t)-\tau)\dot{\hat{\tau}}(t)+2\gamma_2(\hat{d}(t)-d)\dot{\hat{d}}(t)$$
$$+2e^T(t)P_oA_1\int_{t-\hat{\tau}}^{t-\tau}[A\hat{x}(\theta)+A_1\hat{x}(\theta-\hat{\tau})+Bu(\theta)$$
$$+B_1u(\theta-\hat{d})+LCe(\theta))]d\theta+2e^T(t)P_oB_1F\int_{t-\hat{d}}^{t-d}[A\hat{x}(\theta)$$
$$+A_1\hat{x}(\theta-\hat{\tau})+Bu(\theta)+B_1u(\theta-\hat{d})+LCe(\theta))]d\theta$$
$$+2M\|P_oA_1\|\left(\dot{\hat{\tau}}(t)\int_{-\hat{\tau}}^{0}z(t+s)ds+\int_{-\hat{\tau}}^{-\tau}(z(t)-z(t+\theta))d\theta\right)$$
$$+2M\|P_oB_1F\|\left(\dot{\hat{d}}(t)\int_{-\hat{d}}^{0}z(t+s)ds+\int_{-\hat{d}}^{-d}(z(t)-z(t+\theta))d\theta\right)$$
$$\le\dot{V}_1+2\|P_oA_1\|(\|e(t)\|-M)\int_{-\hat{\tau}}^{-\tau}z(t+\theta)d\theta$$
$$+2(\hat{\tau}(t)-\tau)\left[\gamma_1\dot{\hat{\tau}}(t)+M\|P_oA_1\|z(t)\right]$$
$$+2M\|P_oB_1F\|(\|e(t)\|-M)\int_{-\hat{d}}^{-d}z(t+\theta)d\theta$$
$$+2(\hat{d}(t)-d)\left[\gamma_2\dot{\hat{d}}(t)+M\|P_oB_1F\|z(t)\right].$$

In the process above we make use of the condition of $\dot{\hat{\tau}}(t)\le 0,\dot{\hat{d}}(t)\le 0$ and $\hat{\tau}(t)\ge\tau,\hat{d}(t)\ge d,\forall t$. From above, the adaptive rule about delay constants can be taken as

$$\dot{\hat{\tau}}(t)=-\frac{1}{\gamma_1}M\|P_oA_1\|z(t).\quad (13)$$
$$\dot{\hat{d}}(t)=-\frac{1}{\gamma_2}M\|P_oB_1F\|z(t).\quad (14)$$

Since $Ce(t)=Cx(t)-C\hat{x}(t)=y(t)-C\hat{x}(t)$ is measurable, and $z(t)$ can be also measured as well.

It is very clear that there exists constant $a>0$ such that $a\|e(t)\|^2\le V_2(x_t,e_t)$ according to the expression of $V_2(x_t,e_t)$. $\varphi:=\phi-\psi\in C_k[-\widetilde{\tau},0]=\{\varphi\in C\|\varphi\|<k\},\forall k>0$. If existing the constant M satisfies the expression $aM^2\ge V_2(x_t,e_t)$, $\forall t\in[-\widetilde{\tau},0]$ and $k\le M$ at the same time, we can get that there exists $\delta>0$ such that $\|e(t)\|\le k\le M,\forall t\in[0,\delta]$. In this case $\dot{V}_2(x_t,e_t)<0$, $\forall t\in[0,\delta]$ can be gotten by Riccati matrix inequalities (9) and (10) and adaptive rules (13) and (14). According to $\dot{V}_2(x_t,e_t)<0$, $\forall t\in[0,\delta]$, we can get

$$a\|e(t)\|\le V_2(x_t,e_t)\le V_2(\phi,\varphi),\forall t\in[0,\delta].$$

If there exists $t_1>0$, $\delta_1>0$ such that $\|e(t_1)\|=M$, $\|e(t_1)\|>M$, $\dot{V}_2(x_t,e_t)<0$, $\forall t:t_1<t\le t_1+\delta_1$, and $\|e(t)\|<M$, $\forall t:0\le t<t_1$, then

$$aM^2<a\|e(t_1)\|\le V_2(x_{t_1},e_{t_1})\le V_2(\phi,\varphi)\le aM^2$$

This is a contradiction. So $\|e(t)\|\le M,\forall t\ge 0$. It is to say that $\|e(t)\|$ is bounded and its bound only has a relation with initial function φ. Therefore, Constant M is existent.

From this we can get following conclusion.

Theorem 2: If there exist matrices F, L, symmetric positive-define matrices $P_c,P_o,S_1,S_2,S_3,S_4,S_5$ which satisfy the Riccati matrix inequalities (9) and (10), then $\forall\varphi\in C_k$ there exists $M>0$ such that $\|e(t)\|\le M$, and the system (1) can be stabilized by observer-based feedback controller (6). In this case, the adaptive control about delay constants can be taken as (13) and (14). Where $\gamma_i>0\,(i=1,2)$ are constants to be decided such that the estimation $\hat{\tau}(t)$ of τ satisfies $\hat{\tau}(t)\ge\tau,\forall t\ge 0$ and the estimation $\hat{d}(t)$ of d satisfies $\hat{d}(t)\ge d$, $\forall t\ge 0$.

Proof: We only need to prove the existence of $\gamma_i>0\ (i=1,2)$.

When closed-loop delay system (7) is asymptotically stable, from $x(t)\to 0$, $\hat{x}(t)\to 0\ (t\to\infty)$ and (13) we can obtain $\dot{\hat{\tau}}(t)\to 0\,(t\to\infty)$. Therefore, according to the monotonous of $\hat{\tau}(t)$ and $\hat{\tau}(t)\ge 0$ we can get

$$\lim_{t\to\infty}\hat{\tau}(t)=\tau_\infty$$

and

$$\tau_\infty=\hat{\tau}(0)-\frac{1}{\gamma_1}\int_0^{+\infty}M\|P_oA_1\|z(t)dt$$
$$:=\hat{\tau}(0)-\frac{1}{\gamma_1}N(\phi,\psi).$$

Because $x(t) \to 0$, $\hat{x}(t) \to 0 (t \to \infty)$, there exist constant $\overline{M}, \lambda > 0$ such that $\|z(t)\| < \overline{M} e^{-\lambda t}$, $\forall t \geq 0$, where $\overline{M}$ is a constant which can be decided by system parameters and has a relation with initial function ϕ, ψ. So

$$N(\phi,\psi) = \int_0^{+\infty} M \|P_o A_1\| z(t) dt \leq \frac{1}{\lambda} \overline{M} M \|P_o A_1\|,$$

Thus $N(\phi,\psi)$ can be estimated. If

$$\gamma_1^{-1} \leq \max_{\varphi \in C_R[-\tau,0]} \left\{ \frac{\hat{\tau}(0) - \tau}{N(\phi,\psi)} \right\},$$

then we have $\tau_\infty \geq \tau$. This shows that the positive constant $\gamma_1 > 0$ of theorem 2 is existent and can be estimated for a given system and an initial function whose value is defined in a bounded set. We can proof the existence of $\gamma_2 > 0$ in the same way.

Remark 1 From theorem 1 and theorem 2 we can see that the observer-based feedback controllers (4) and (6) can be found if Riccati matrix inequalities (9) and (10) holds.

Remark 2 If one of the state-delay and input-delay can be exactly known but another isn't available, we can design an observer-based feedback controller with adaptation to unknown delay parameter in the same way.

Remark 3 Because the method of solving Riccati matrix inequalities has much matured (9) and (10) can be directly solved by toolbox in MATLAB software.

4. CONCLUSIONS

In this note, we have discussed the observer-based feedback controller for linear time-delay system with adaptation to delay parameter. The design of this controller satisfies the separation principle and the time-delay constants needn't be known exactly. The existence of this controller is equal to that of the controller (4) in which the time-delay constant need be known exactly. This brings us an advantage about the design of system controller.

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