Design of Unknown Input Observer for Linear Time-delay Systems

Yan-Ming Fu, Guang-Ren Duan, and Shen-Min Song

Abstract: This paper deals with the unknown input observer (UIO) design problem for a class of linear time-delay systems. A case in which the observer error can completely be decoupled from an unknown input is treated. Necessary and sufficient conditions for the existences of such observers are present. Based on Lyapunov stability theory, thedesign of the observer with internal delay is formulated in terms of linear matrix inequalities (LMI). The design of the observer without internal delay is turned into a stabilization problem in linear systems. Two design algorithms of UIO are proposed. The effect of the proposed approach is illustrated by two numerical examples.

Keywords: Linear matrix inequalities, Lyapunov stability, stabilization, time-delay systems, unknown input observer.

1. INTRODUCTION

Time delay is commonly encountered in various engineering systems, such as chemical processes, and long transmission lines in pneumatic, hydraulic, economic and rolling mill systems. It usually results in unsatisfactory performance and is frequently a source of instability, so control of time-delay systems is practically important, especially state feedback control. An unknown input observer has important applications in realization of state feedback control. A UIO is an estimator that is decoupled from the unknown input (disturbances, faults, etc.) that may be acting on the system.

Observer design theory for time-delay systems has been most widely considered in the last decade [1-7]. Various methods have been used in the observer design, for example, coordinate change approach [1], LMI method [2], reducing transformation technique [3], factorization approach [4], and polynomial approach [5]. However, little research has been focused on design of UIO for linear systems with time-varying delay.

In this paper, design of UIO for linear systems with time-varying delay is proposed. Necessary and sufficient conditions for the existence of the observer are derived. Based on Lyapunov stability theory, the design of the observer with internal delay is solved in terms of linear matrix inequality; and the design of the observer without internal delay is turned into a stabilization problem in a linear system.

This paper is divided into six sections. In Section 2, the problem to be solved in this paper is formulated. Section 3 provides the observer conditions. The design methods are proposed in Section 4. Numerical examples are presented in Section 5. Conclusions follow in Section 6.

2. PROBLEM FORMULATION

Consider the following continuous-time linear time-delay system described by

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

where $x(t) \in R^n$ is the state vector, $u(t) \in R^r$ is the input vector, $w(t) \in R^q$ is the unknown input vector, $y(t) \in R^m$ is the measured output vector, and $d(t)$ is a known time delay satisfying

$$0 \le d(t) \le d_0 , \quad 0 \le \dot{d}(t) \le d_1 < 1, \tag{2}$$

where d_0 and d_1 are known constant scalars. $\phi(t)$ is a continuous vector-valued initial function. A, A_d, B, C and E are real matrices with appropriate dimensions. Without loss of generality, it can be assumed that E has full column rank and C has full row rank.

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For the system (1), an observer that reconstructs the state $x(t)$ without the knowledge of the unknown input $w(t)$ can be constructed using measured output $y(t)$ and input $u(t)$ as

$$\begin{aligned}\dot{\hat{x}}(t) = {}& F\hat{x}(t) + G\hat{x}(t-d(t)) + Hu(t) + L_1\dot{y}(t) \\ & + L_2 y(t) + L_3 y(t-d(t)),\end{aligned} \tag{3}$$

with the initial state $\hat{x}(t)=\varphi(t), \forall t\in[-d(t),0]$, where $\hat{x}(t)\in R^n$ is the state vector. F, G, H, L_1, L_2 and L_3 are the coefficient matrices with appropriate dimensions.

With the above preparation, the problem of unknown input observer design to be solved in the paper can be stated as follows.

Problem UIO: Given the system (1) and the observer (3), design the observer parameters F, G, H, L_1, L_2 and L_3, such that

$$\lim_{t\to\infty}[\hat{x}(t)-x(t)]=0 \tag{4}$$

for any initial functions.

3. UIO CONDITIONS OF TIME-DELAY SYSTEMS

First, denote by $e(t)$ the error between $x(t)$ and its estimate $\hat{x}(t)$, that is,

$$e(t)=x(t)-\hat{x}(t), \tag{5}$$

then, we have the following theorem.

Theorem 1: The observer in the form of (3) is a UIO for system (1) if and only if the following relations are satisfied:

1) $\dot{e}(t)=Fe(t)+Ge(t-d)$ is asymptotically stable.
2) $F=(I-L_1C)A-L_2C$.
3) $G=(I-L_1C)A_d-L_3C$.
4) $H=(I-L_1C)B$.
5) $(I-L_1C)E=0$.

Proof: From (1) and (3) we obtain the following error equation

$$\begin{aligned}\dot{e}(t) = {}& Fe(t)+Ge(t-d(t))+\big[(I-L_1C)A-L_2C-F\big]x(t) \\ & +\big[(I-L_1C)B-H\big]\ u(t)+(I-L_1C)Ew(t) \\ & +\ \big[(I-L_1C)A_d-L_3C-G\big]x(t-d(t)),\end{aligned} \tag{6}$$

with the initial condition $e(t)=x(t)-\hat{x}(t)$, $\forall t\in[-d(t),0]$.

(Sufficiency) If the last four conditions in the theorem are met, then the error (6) reduces to

$$\dot{e}(t)=Fe(t)+Ge(t-d). \tag{7}$$

Further, in view of the first condition in the theorem, we know that $e(t)\to 0$ for any initial conditions and $u(t)$. So $\hat{x}(t)$ is an estimate of $x(t)$.

(Necessity) Let (2) be a UIO for system (1). If condition 1) is not satisfied, then for $x(t)=0$, $u(t)=0$ and $w(t)=0, \forall t$, we have $e(t)\neq 0$ as $t\to\infty$. This contradicts with (4).

If conditions 2) and 3) are not satisfied, then we can find $u(t)$ such that $e(t)\neq 0$ as $t\to\infty$. This contradicts with (4).

If conditions 4) and 5) are not satisfied, there exist $u(t)$ and $w(t)$ such that $e(t)\neq 0$ as $t\to\infty$. This contradicts with (4). □

Remark 1: From the error equation (6) and Theorem 1, we know that the condition 5) in Theorem 1 guarantees that the estimate error can completely be decoupled from the unknown input.

The observer (3) is dependent of $\hat{x}(t-d(t))$. If $G=0$, the observer becomes the following observer without internal delay:

$$\dot{\hat{x}}(t) = F\hat{x}(t)+Hu(t)+L_1\dot{y}(t)+L_2y(t)+L_3y(t-d(t)), \tag{8}$$

which is independent of $\hat{x}(t-d(t))$. The initial state is again $\hat{x}(t)=\varphi(t),\forall t\in[-d(t),0]$. Based on Theorem 1, we have the following corollary.

Corollary 1: The observer in the form of (8) is a UIO for the system (1) if and only if the following relations are satisfied:

a) F is Hurwitz stable.
b) $F=(I-L_1C)A-L_2C$.
c) $(I-L_1C)A_d-L_3C=0$.
d) $H=(I-L_1C)B$.
e) $(I-L_1C)E=0$.

4. UIO DESIGN OF TIME-DELAY SYSTEMS

In this section, we study the design of a UIO for a class of time-delay systems based on the observer conditions proposed in Section 3. The following lemma is needed.

Lemma 1: [8] Condition 5) in Theorem 1 is solvable if and only if the following relation holds:

$$\text{rank}(CE)=q,\quad q\le m. \tag{9}$$

Furthermore, when $q<m$, the general solution of the

equation in condition 5) can be expressed as

$$L_1 = E(CE)^+ + K(I_m - CE(CE)^+), \tag{10}$$

where $K \subset R^{n\times m}$ is an arbitrary matrix, $(CE)^+$ denotes the generalized inverse matrix of CE.

In the following we investigate the design of a UIO. Under the condition in Lemma 1, two cases are considered.

Case 1: $q < m$

Substituting (10) into conditions 2) and 3) in Theorem 1, gives

$$F = \Phi_1 - K\Phi_2 - L_2C, \tag{11}$$

$$G = \Psi_1 - K\Psi_2 - L_3C, \tag{12}$$

where

$$\Phi_1 = A - E(CE)^+CA,\ \Phi_2 = [I_m - CE(CE)^+]CA,$$
$$\Psi_1 = A_d - E(CE)^+CA_d,\ \Psi_2 = [I_m - CE(CE)^+]CA_d.$$

Using Theorem 1, relations (11) and (12), we can obtain the observer error equation as

$$\begin{aligned}\dot e(t) &= (\Phi_1 - K\Phi_2 - L_2C)e(t)\\ &\quad + (\Psi_1 - K\Psi_2 - L_3C)e(t-d(t)).\end{aligned} \tag{13}$$

From the above equation, we know that the problem of the observer design is reduced to the determination of the observer parameters L_2, L_3 and the free parameter K such that condition 1) of Theorem 1 is satisfied. Based on Theorem 1 and Lyapunov stability theory, we can give the independent of delay conditions for the stability of the observer in the form of (3).

Theorem 2: The observer in the form of (3) is a UIO for the system (1) if there exist matrices $P = P^T > 0$, $Q = Q^T > 0$, X, Y and Z satisfying the following LMI:

$$\begin{bmatrix} M_1 & M_2 \\ M_2^T & -(1-d_1)Q \end{bmatrix} < 0, \tag{14}$$

where
$$M_1 = \Phi_1^T P + P\Phi_1 - \Phi_2^T X^T - X\Phi_2 - C^TY^T - YC + Q,$$
$$M_2 = P\Psi_1 - X\Psi_2 - ZC.$$

In this case, the free parameter K and the observer parameters L_2, L_3 are given by

$$K = P^{-1}X, \tag{15}$$

$$L_2 = P^{-1}Y, \tag{16}$$

$$L_3 = P^{-1}Z. \tag{17}$$

Proof: Consider the following Lyapunov function:

$$V(e,t) = e^T(t)Pe(t) + \int_{t-d(t)}^{t} e^T(s)Qe(s)ds, \tag{18}$$

where $P = P^T > 0$, $Q = Q^T > 0$. By differentiating $V(e,t)$ along the solution of 1) of Theorem 1, we can obtain

$$\begin{aligned}\dot V(e,t) &= e^T(t)[F^TP + PF + Q]e(t)\\ &\quad - (1-\dot d(t))e^T(t-d(t))Qe(t-d(t))\\ &\quad + e^T(t-d(t))G^TPe(t) + e^T(t)PGe(t-d(t)).\end{aligned} \tag{19}$$

Letting $Q_d = (1-d_1)Q$ and using $0 \le \dot d(t) \le d_1 < 1$, we get

$$\dot V(e,t) \le \hat e^T(t)\begin{bmatrix} F^TP + PF + Q & PG \\ G^TP & -Q_d \end{bmatrix}\hat e(t), \tag{20}$$

where $\hat e^T(t) = \begin{bmatrix} e^T(t) & e^T(t-d(t)) \end{bmatrix}$, if $\dot V(e,t) < 0$, when $\hat e(t) \ne 0$ then $e(t) \to 0$ as $t \to \infty$ and 1) of Theorem 1 is globally asymptotically stable independent of delay. From (20), $\dot V(e,t) < 0$ if

$$\begin{bmatrix} F^TP + PF + Q & PG \\ G^TP & -Q_d \end{bmatrix} < 0. \tag{21}$$

Substituting the conditions 2)-4) in Theorem 1 into (21) and replacing X, Y and Z by (15)-(17), it can be easily obtained that (21) is equivalent to the LMI (14). □

If the delay d is a constant, we obtain the following corollary.

Corollary 2: The observer in the form of (3) is a UIO for the system (1) if there exist matrices $P = P^T > 0$, $Q = Q^T > 0$, X, Y and Z satisfying the following LMI:

$$\begin{bmatrix} M_1 & M_2 \\ M_2^T & -Q \end{bmatrix} < 0. \tag{22}$$

Under this condition, the free parameter K and the observer parameters L_2, L_3 are given by

$$K = P^{-1}X, \tag{23}$$

$$L_2 = P^{-1}Y, \quad (24)$$

$$L_3 = P^{-1}Z. \quad (25)$$

Now, we consider the design of the observer without internal delay. Corollary 1 provides us not only with the existence conditions for UIO in the form of (8) but also an approach to the selection of the observer parameters.

First we provide the following theorem about the existence condition for solution to condition c).

Theorem 3: Condition c) in Corollary 1 is solvable if and only if the following relation holds

$$\text{rank}\begin{bmatrix}\Psi_2 \\ C\end{bmatrix} = \text{rank}\begin{bmatrix}\Psi_2 \\ \text{C} \\ \Psi_1\end{bmatrix}. \quad (26)$$

Proof: Substituting equation (10) into the condition c), we obtain

$$\begin{bmatrix}-K & L_3\end{bmatrix}\begin{bmatrix}\Psi_2 \\ C\end{bmatrix} = \Psi_1. \quad (27)$$

Using the result of linear algebra, matrix equation (27)is solvable if and only if (26) holds. □

Now let us consider the condition a) in Corollary 1. Based on the observer knowledge in linear systems theory, the condition a) in Corollary 1 can be satisfied if and only if the matrix pair $\left((I - L_1C)A, \ C\right)$ is detectable.

Based on the above analysis, an algorithm for UIO design can be given as follows.

Algorithm UIO: ($q < m$)

Step 1: Calculate matrix L_1 by (10).

Step 2: Check the rank condition (26). If (26) holds, calculate L_3 and K by solving (27). Otherwise go to Step 4.

Step 3: If the matrix pair $\left((I - L_1C)A, \ C\right)$ is detectable, obtain L_2 by using any stabilization approach in linear systems theory such that the matrix F given in condition b) in Corollary 1 is stable, and then go to Step 5. Otherwise proceed to Step 4.

Step 4: Solve LMI (14). If LMI (14) is insolvable, the problem has no solution, or the algorithm fails. Otherwise, we can obtain matrices P, X, Y and Z, and can further calculate L_1, L_2 and L_3 according to (10) and (15)-(17).

Step 5: Calculate F, G, H by their expressions in the conditions 2), 3) and 4) in Theorem 1.

Case 2: $q = m$

If $q = m$, based on condition 5) in Theorem 1, we can obtain

$$L_1 = E(CE)^{-1}. \quad (28)$$

Substituting (28) into conditions 2) and 3) in Theorem 1, yields

$$F = \Xi_1 - L_2C, \quad (29)$$

$$G = \Xi_2 - L_3C, \quad (30)$$

where

$$\Xi_1 = A - E(CE)^{-1}CA, \ \Xi_2 = A_d - E(CE)^{-1}CA_d.$$

By using Theorem 1 and relations (29) and (30), the observer error equation can be derived as

$$\dot{e}(t) = (\Xi_1 - L_2C)e(t) + (\Xi_2 - L_3C)e(t - d(t)). \quad (31)$$

From (31), we know that the problem of the observer is reduced to the determination of the observer parameters L_2, L_3 such that the condition 1) in Theorem 1 is satisfied. Based on Theorem 2, we can give the independent of delay conditions for the stability of the observer in the form of (3) in this case.

Corollary 3: The observer in the form of (3) is a UIO for the system (1) if there exist matrices $P = P^T > 0$, $Q = Q^T > 0$, Y and Z satisfying the following LMI:

$$\begin{bmatrix}N_1 & N_2 \\ N_2^T & -(1-d_1)Q\end{bmatrix} < 0, \quad (32)$$

where

$$N_1 = \Xi_1^T P + P\Xi_1 - C^T Y^T - YC + Q, \ N_2 = P\Xi_2 - ZC.$$

In this case, the observer parameters L_2 and L_3 are given by

$$L_2 = P^{-1}Y, \quad (33)$$

$$L_3 = P^{-1}Z. \quad (34)$$

Similar to Theorem 3, we present the following corollary concerning the existence condition for solution to condition c) in Corollary 1.

Corollary 4: The condition c) in Corollary 1 is solvable if and only if the following relation holds:

$$\text{rank} \ C = \text{rank}\begin{bmatrix}C \\ \Xi_1\end{bmatrix}. \quad (35)$$

Based on Corollaries 3 and 4, an algorithm for UIO design can be given as follows.

Algorithm UIO: ($q = m$)

Step 1: Calculate matrix L_1 by (28).

Step 2: Check the rank condition (35), if (35) holds, calculate L_3 by solving equation c) in Corollary 1. Otherwise go to Step 4.

Step 3: Based on L_1, if the matrix pair $((I-L_1C)A\ ,\ C)$ is detectable, obtain L_2 by any stabilization approach in linear systems theory such that matrix F given in condition b) in Corollary 1 is stable, and then go to Step 5. Otherwise proceed to Step 4.

Step 4: Solve LMI (32). If LMI (32) is insolvable, the problem has no solution, or the algorithm fails. Otherwise, we can obtain matrices P, X, Y and Z, and can further calculate L_2 and L_3 according to (33) and (34).

Step 5: Calculate F, G, H by their expressions in the conditions 2), 3) and 4) in Theorem 1.

5. NUMERICAL EXAMPLES

To illustrate the design methods for UIO, in this section we present two examples.

Example 1: ($q<m$)

Consider the following system:

$$\dot{x}(t)=\begin{bmatrix}-1 & 0\\ 0 & -2\end{bmatrix}x(t)+\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}x(t-d(t))$$
$$+\begin{bmatrix}1\\ 0\end{bmatrix}u(t)+\begin{bmatrix}1\\ 2\end{bmatrix}w(t),$$
$$y(t)=\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}x(t),$$

where $d(t)$ satisfies $0\le \dot{d}(t)\le 0.2$.

It is clear that $q<m$. So we can design the observer for this example system using algorithm UIO ($q<m$).

Step 1: Calculate L_1 by (10).

$$L_1=\begin{bmatrix}0.4 & 0.2\\ 0.8 & 0.4\end{bmatrix}+K\begin{bmatrix}0.2 & -0.4\\ -0.4 & 0.8\end{bmatrix}.$$

Step 2: Note that

$$\text{rank}\begin{bmatrix}\Psi_2\\ C\end{bmatrix}=\text{rank}\begin{bmatrix}\Psi_2\\ \text{C}\\ \Psi_1\end{bmatrix}=2,$$

and the rank condition (26) holds. Following from (27), we have

$$K=\begin{bmatrix}0.2 & -0.4\\ -0.06 & 0.12\end{bmatrix},\ L_3=\begin{bmatrix}-0.2 & 0.4\\ 0.14 & -0.08\end{bmatrix}.$$

Step 3: It is easy to check that $[(I-L_1C)A\ ,\ C]$ is detectable. So we can design the observer in the form of (8). Based on some stabilization approach in linear systems theory, we obtain

$$L_2=\begin{bmatrix}1.2 & -0.2\\ 1.48 & 0.32\end{bmatrix}.$$

Step 4: Using the equations in conditions 2), 3) and 4) in Theorem 1, we can derive

$$L_1=\begin{bmatrix}0.6 & -0.2\\ 0.74 & 0.32\end{bmatrix},\ F=\begin{bmatrix}-1 & 0\\ 0 & -2\end{bmatrix},\ H=\begin{bmatrix}1.2\\ -0.32\end{bmatrix}.$$

Example 2: ($q=m$)

Consider the following system:

$$\dot{x}(t)=\begin{bmatrix}-1 & 0\\ 0 & -2\end{bmatrix}x(t)+\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}x(t-d(t))$$
$$+\begin{bmatrix}1\\ 0\end{bmatrix}u(t)+\begin{bmatrix}1\\ 2\end{bmatrix}w(t),$$
$$y(t)=\begin{bmatrix}1 & 0\end{bmatrix}x(t),$$

where $d(t)$ satisfies $0\le \dot{d}(t)\le 0.2$.

It is clear that $q=m$. So we can design the observer for this example system using algorithm UIO ($q=m$).

Step 1: From (28), we can obtain

$$L_1=\begin{bmatrix}1 & 2\end{bmatrix}^T.$$

Step 2: Check the rank condition (35). We can obtain

$$\text{rank } C\ne \text{rank}\begin{bmatrix}C\\ \Xi_1\end{bmatrix}.$$

So we can't design the observer in the form of (8).

Step 3: Solve LMI (32) by the LMI toolbox in MATLAB.

$$P=\begin{bmatrix}55.3031 & -0.0000\\ -0.0000 & 26.9949\end{bmatrix},\ Q=\begin{bmatrix}69.1288 & -0.0000\\ -0.0000 & 59.0970\end{bmatrix},$$
$$Y=\begin{bmatrix}62.2160\\ 59.9889\end{bmatrix},\ Z=\begin{bmatrix}-0.0000\\ -53.9898\end{bmatrix}.$$

According to (33)-(34), we have

$$L_2=\begin{bmatrix}1.1250\\ 2.0000\end{bmatrix},\ L_3=\begin{bmatrix}0.0000\\ -2.0000\end{bmatrix}.$$

Step 4: Using the equations in conditions 2), 3) and 4) in Theorem 1, we can derive

$$F=\begin{bmatrix}-1.1250 & 0\\ -0.0000 & -2.0000\end{bmatrix},\ G=\begin{bmatrix}0 & 0\\ 0 & 1.0\end{bmatrix},\ H=\begin{bmatrix}0\\ 2\end{bmatrix}.$$

6. CONCLUSIONS

In this paper, the design problem of UIO for a class of linear time-delay systems is studied. Necessary and sufficient conditions to its existence are presented. Based on these conditions and Lyapunov stability theory, two design algorithms are proposed. Demonstrative examples show the effect of the proposed algorithms.

Future research will focus on the design problem of UIO when the estimate error can't completely be decoupled from unknown inputs.

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