Observer Based Control for Linear Cyber-physical Systems

Lidong Wang, Xinze Xue, Yingxin Wei, Tong Li and Xuebo Chen

***Abstract*—In this paper, the problem of control for a class of continuous time linear systems based on Luenberger-like state observer is investigated. A cyber-physical system is considered, which is composed of the controlled object, communication channel, filter and remote controller. A state observer is designed by using the filtered received signal, based on which two controllers are designed to stabilize the system. The stability conditions of the state observers and closed-loop system are derived by solving a linear matrix inequality. It is proved that the control methods can guarantee that all the signals of the closed-loop system are uniformly ultimately bounded. The effectiveness of the proposed methods is confirmed by simulation examples.**

***Index Terms*—cyber-physical system, time continuous linear system, stability analysis, reduced order observer.**

I. Introduction

CYBER-PHYSICAL system (CPS), which can be defined as a system by integrating physical processes, computation and networking [1], has been widely investigated by scholars. The integration means the deep interaction of physical world and the cyber components, therefore for CPSs, research objectives are complex and the scope of application is huge, such as smart power grids, smart medical devices, self-driving vehicles, and complex physical and chemical processes [2]- [6]. Various results have recently been proposed in literatures, such as system modeling [7], information acquisition [8], [9], controller design [10], [11] and security issues [12], [13].

Maintaining the stability of a system is the primary problem of system control. The problem of saturated global finite-time stabilization by state feedback for systems was studied in [14]. The authors of [15] and [16] proposed different controllers for continuous system and discrete system, respectively. The exchanging of information obtained from the smart meters on the cyber side can improve the overall performance of a CPS system. The acquisition of system state information is the premise of a system controller design. For a CPS system composed of interconnected subsystems, the communication between subsystems is an important part and the communication quality has a great influence on the stability and performance of the whole system [17]- [19]. In the process of state information transmission through the communication channel, especially the wireless channel, the state information will be contaminated due to additive noise, transmission multipath and Doppler effect [20], [21], which can reduce the performance of the state observer and controller, and even affect the stability of a CPS system. Therefore, the filter of the noised signal at the receiver is necessary for the system. Many works investigated the state estimation and system control issues with communication problems. Lu [11] proposed an input-to-state stabilizing controller for CPSs under denial of service attacks. [22] concerned with the problem of event triggered control for CPSs in the presence of actuator and sensor attacks, where an augmented matrix including states and attacks information was designed and a Luenberger observer and a controller were proposed. [23]- [27] addressed algorithms of state observing for CPS systems, which are corrupted by transmission or sensor noise inserted by malicious adversary. Authors in [28]- [33] studied the problem of control for CPS system under the deception attacks, model attacks or denial-of service attacks. [34] was concerned with the problem of multi-objective H_2/H_∞ control for uncertain nonlinear stochastic systems with state-delay and Jiao et al. [35] concerned about the problem of stability analysis of stochastic nonlinear systems with asynchronous impulses and switchings. Vorotnikov et al. [36] studied the partial stability in probability for a general class of nonlinear stochastic time-varying systems.

For all we know, most of the related works only consider

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the stability of a CPS system with transmission problems, while the stability of the whole CPS is not considered as an objective. It is also an open problem to design a state observer and controller for the whole CPS. Inspired by the above considerations, this paper addresses the observer and controller design problem for a class of linear CPSs. The main contributions of this paper are as follows.

1. The whole system composed of object to be controlled, communication channel, filter and remote control center is considered and modeled as a linear system. Due to the characteristic of subsystems, such as the filter state is known, a reduced order state observer is designed.

2. Two output feedback controllers based on the Luenberger-like reduced order state observer are constructed for the system. The stability of the CPS system is analyzed through the Lyapunov function, and the sufficient conditions of system stability are obtained by solving linear matrix inequalities (LMIs).

The rest of the paper is organized as follows. In Section II, the system is described. State observer design, controller design and stability analysis are shown in Section III. In Section IV, simulation examples are provided, and in Section V we conclude the work of the paper.

Notations: $R^{m\times n}$ denotes the set of m-by-n dimensional real matrices. P^T represents the transpose of the matrix or vector P. $\|e\|$ is Euclidean norm of a vector e. 0 represents the zero matrix with appropriate dimensions, and $P > 0$ means that P is a positive definite matrix.

II. System description

Consider a subsystem to be controlled, which can be described as a continuous linear system

$$\begin{aligned} \dot{x}_1 &= A_1x_1 + B_1u_1 + d_1 \\ y_1 &= x_1, \end{aligned} \tag{1}$$

where $x_1 \in R^{n_{x1}}$, $u_1 \in R^{n_{u1}}$, $A_1 \in R^{n_{x1}\times n_{x1}}$ and $B_1 \in R^{n_{x1}\times n_{u1}}$ are the state vector, control input vector, state transition matrix and input matrix of a controlled plant, respectively. $d_1 \in R^{n_{x1}}$ is the disturbance input, and $y_1 \in R^{n_{x1}}$ is the output of the subsystem, which can be transmitted to the control center by wireless communication channel.

At the control center, the received signal will be processed by filter, such as Kalman filter, to suppress noise and compensate the fading of wireless channel. The communication subsystem composed of channel and filter can

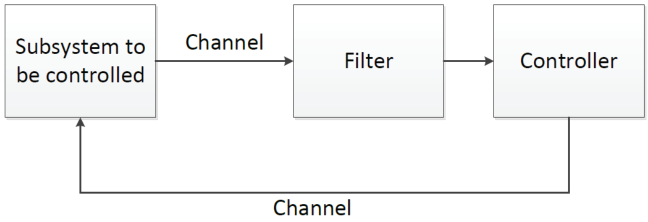

Fig. 1: A sketch map of a closed-loop system

be described as

$$\begin{aligned} \dot{x}_2 &= A_2x_2 + B_2\left(C_1x_1 + d_2\right) \\ y_2 &= x_2 \end{aligned} \tag{2}$$

where $x_2 \in R^{n_{x2}}$, $A_2 \in R^{n_{x2}\times n_{x2}}$, $B_2 \in R^{n_{x2}\times n_{c1}}$, and $C_1 \in R^{n_{c1}\times n_{x1}}$ are the state vector, state transition matrix and the transmission matrix from plant to control center, respectively. $d_2 \in R^{n_{c1}}$ is the disturbance including the residual error after filtering, and $y_2 \in R^{n_{x2}}$ is the output of the system. In order to ensure the stability of the whole system, the following assumptions are made.

Assumption 1: Matrix A_2 is Hurwitz.

Assumption 2: There exist known positive constant d, such that $\|d_i\| \leq d$, where i =1, 2.

The impulse response of wireless communication channel can be estimated at the receiver and the filter parameters can be designed in advance, hence the Hurwitz property of A_2 and the stability of the subsystem (2) can be guaranteed.

The control subsystem at the control center can be described as

$$\begin{aligned} \dot{x}_3 &= A_3x_3 + B_3u_3 \\ u_1 &= C_3x_3 \end{aligned} \tag{3}$$

where $x_3 \in R^{n_{x3}}$, $A_3 \in R^{n_{x3}\times n_{x3}}$, $B_3 \in R^{n_{x3}\times n_{u3}}$, and $C_3 \in R^{n_{u1}\times n_{x3}}$ are the state vector, state transition matrix, input matrix of the controller and the transmission matrix from control center to plant, respectively.

Combining the subsystems described above, the CPS system can be rewritten as

$$\begin{aligned} \dot{x}_1 &= A_1x_1 + B_1C_3x_3 + d_1 \\ \dot{x}_2 &= A_2x_2 + B_2\left(C_1x_1 + d_2\right) \\ \dot{x}_3 &= A_3x_3 + B_3u_3 \\ y_2 &= x_2 \end{aligned} \tag{4}$$

The closed-loop system is shown in Fig. 1.

III. Main results

The purpose of this paper is to design a control scheme for time continuous linear system (4) based on a state observer. Since only the output can be measured for subsystem (1), in order to design a controller based on the system states, a state observer should be established. Since the states of subsystems (2) and (3) can be obtained, only a reduced order observer is needed to estimate the state of the subsystem(1). Therefore, the design of reduced order state observer and controller for system (4) is discussed.

A. State observer and control design

Since the states of (1) are unknown, they should be estimated at the control center by the received signal for stable control purpose. The state observer can be developed by the output of the filter y_2. For the whole system, part of states: x_2 and x_3 are known, thus the state observer can be designed as a Luenberger-like reduced order state observer, which can be described as:

$$\dot{\hat{x}}_1 = A_1\hat{x}_1 + B_1u_1 + F(\dot{y}_2 - (A_2x_2 + B_2C_1\hat{x}_1)) \quad (5)$$

where $\hat{x}_1$ is the estimation of x_1 and $F \in R^{n_{x1}\times n_{x2}}$ is a matrix to be designed. Define the estimate error as

$$e = x_1 - \hat{x}_1 \quad (6)$$

According to (1) and (5), the time derivative of the estimate error e can be expressed as:

$$\dot{e} = A_1e - FB_2C_1e \quad (7)$$

Based on the state observer (5), two controllers of the system (4) are proposed

$$u_3 = -k_1\hat{x}_1 = -k_1(x_1 - e) \quad (8)$$

or

$$u_3' = -k_1\hat{x}_1 - k_3x_3 = -k_1(x_1 - e) - k_3x_3 \quad (9)$$

where $k_1 \in R^{n_{u3}\times n_{x1}}$ and $k_3 \in R^{n_{u3}\times n_{x3}}$ are parameters to be designed. Controller u_3 makes use of the information of state x_1, while u_3' makes use of not only the information of state x_1, but also that of x_3. Therefore, it can be predicted that the control performance of u_3' should be better than that of u_3.

B. Stability analysis

Define $X = [x_1, x_3, e, x_2]^T$ and its derivative can be obtained

$$\dot{X} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_3 \\ \dot{e} \\ \dot{x}_2 \end{bmatrix} = W \begin{bmatrix} x_1 \\ x_3 \\ e \\ x_2 \end{bmatrix} + \begin{bmatrix} d_1 \\ 0 \\ 0 \\ B_2d_2 \end{bmatrix}, \quad (10)$$

where $W = \begin{bmatrix} A_1 & B_1C_3 & 0 & 0 \\ -B_3k_1 & A_3 or (A_3 - B_3k_3) & B_3k_1 & 0 \\ 0 & 0 & A_1 - FB_2C_1 & 0 \\ B_2C_1 & 0 & 0 & A_2 \end{bmatrix}$.

One can use Lyapunov method to deduce the stability conditions of the system. Firstly, consider matrix

$$A = \begin{bmatrix} A_1 & B_1C_3 & 0 \\ -B_3k_1 & A_3 or (A_3 - B_3k_3) & B_3k_1 \\ 0 & 0 & A_1 - FB_2C_1 \end{bmatrix}. \quad (11)$$

Define Lyapunov function $V = X_1^TPX_1$, where $X_1 = [x_1^T, x_3^T, e]^T$ and the design parameter P is a positive definite symmetric invertible matrix with appropriate dimensions. From (10) one can deduce that

$$\dot{X}_1 = AX_1 + \begin{bmatrix} d_1 \\ 0 \end{bmatrix}. \quad (12)$$

Using Young's inequality and Assumption 2, the derivative of V can be obtained as

$$\begin{aligned} \dot{V} &= \dot{X}_1^TPX_1 + X_1^TP\dot{X}_1 + 2\left[d_1^T, 0^T\right]PX_1 \quad (13) \\ &\le X_1^T\left(A^TP + PA\right)X_1 + \eta^{-1}d^2 \\ &\quad + \eta P\left\|X_1\right\|^2, \quad (14) \end{aligned}$$

where $\eta > 0$ is a parameter to be designed. Defining $H = P^{-1}\begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{12}^T & H_{22} & H_{23} \\ H_{13}^T & H_{23}^T & H_{33} \end{bmatrix}$, one has following theorems.

Theorem 1: For the controller (8), under the Assumption 1, if there exists matrix F such that $A_1 - FB_2C_1$ is Hurwitz, and for given positive scalar α, there exists a vector k_1, such that

$$\begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{12}^T & D_{22} & D_{23} \\ D_{13}^T & D_{23}^T & D_{33} \end{bmatrix} < -(\alpha + \eta)\begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{12}^T & H_{22} & H_{23} \\ H_{13}^T & H_{23}^T & H_{33} \end{bmatrix} \quad (15)$$

where $D_{11} = H_{11}A_1^T + H_{12}C_3^TB_1^T + A_1H_{11} + B_1C_3H_{12}^T$, $D_{12} = -H_{k1}^TB_3^T + H_{12}A_3^T + H_{k2}^TB_3^T + A_1H_{12} + B_1C_3H_{22}$, $D_{13} = A_1H_{13} + B_1C_3H_{23} + H_{13}(A_1^T - C_1^TB_2^TF^T)$, $D_{22} = -H_{k3}^TB_3^T + H_{22}A_3^T + H_{k4}^TB_3^T - B_3H_{k3} + A_3H_{22} + B_3H_{k4}$, $D_{23} = H_{23}(A_1^T - C_1^TB_2^TF^T) - B_3H_{k5} + A_3H_{23} + B_3H_{k6}$, $D_{33} = H_{33}(A_1^T - C_1^TB_2^TF^T) + (A_1 - FB_2C_1)H_{33}$, and $H_{k1} = k_1H_{11}$, $H_{k2} = k_1H_{13}^T$, $H_{k3} = k_1H_{12}$, $H_{k4} = k_1H_{23}^T$, $H_{k5} = k_1H_{13}$, $H_{k6} = k_1H_{33}$, then CPS system (4) is uniformly ultimately bounded (UUB).

Proof: From the fact that P is a symmetric positive definite matrix one can know that the matrix H is also a symmetric positive definite matrix. The inequality (15) can be rewritten as $HA^T+AH < -(\alpha+\eta)H$. Both sides of the inequality multiplied left and right by P, it can be obtained

$$P\left(HA^T+AH\right)P < -(\alpha+\eta)PHP \tag{16}$$

that is

$$A^TP+PA < -(\alpha+\eta)P \tag{17}$$

Considering (14), one can get

$$\dot{V} < -\alpha V+\beta \tag{18}$$

where $\beta = \eta^{-1}d^2$. The inequality (18) means that the subsystem described by (1) and (3) is UUB, meanwhile $A_1 - FB_2C_1$ is Hurwitz, according to the properties of block matrix, it can be obtained that the CPS system (4) is UUB.

Theorem 2: For the controller (9), under the Assumption 1, if there exists matrix F such that $A_1 - FB_2C_1$ is Hurwitz, and for given positive scalar α, there exist vectors k_1 and k_3, such that

$$\begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{12}^T & D_{22} & D_{23} \\ D_{13}^T & D_{23}^T & D_{33} \end{bmatrix} < -(\alpha+\eta)\begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{12}^T & H_{22} & H_{23} \\ H_{13}^T & H_{23}^T & H_{33} \end{bmatrix} \tag{19}$$

where $D_{11} = H_{11}A_1^T + H_{12}C_3^TB_1^T + A_1H_{11} + B_1C_3H_{12}^T$, $D_{12} = -H_{k1}^TB_3^T + H_{12}A_3^T - H_{k7}^TB_3^T + H_{k2}^TB_3^T + A_1H_{12} + B_1C_3H_{22}$, $D_{13} = A_1H_{13} + B_1C_3H_{23} + H_{13}(A_1^T - C_1^TB_2^TF^T)$, $D_{22} = -H_{k3}^TB_3^T + H_{22}A_3^T + H_{k4}^TB_3^T - B_3H_{k3} + A_3H_{22} - B_3H_{k8} + B_3H_{k4}$, $D_{23} = H_{23}(A_1^T - C_1^TB_2^TF^T) - B_3H_{k5} + A_3H_{23} - B_3H_{k9} + B_3H_{k6}$, $D_{33} = H_{33}(A_1^T - C_1^TB_2^TF^T) + (A_1 - FB_2C_1)H_{33}$, and $H_{k1} = k_1H_{11}$, $H_{k2} = k_1H_{13}^T$, $H_{k3} = k_1H_{12}$, $H_{k4} = k_1H_{23}^T$, $H_{k5} = k_1H_{13}$, $H_{k6} = k_1H_{33}$, $H_{k7} = k_3H_{12}^T$, $H_{k8} = k_3H_{22}$, $H_{k9} = k_3H_{23}$, then CPS system (4) is UUB.

Proof: Similar to that of Theorem 1.

The matrix $A_1 - FB_2C_1$ can be Hurwitz by designing F using pole assignment method [37], and the inequalities (15) and (19) can be guaranteed by solving LMIs.

IV. Simulation studies

In this section, simulation examples are presented to show the effectiveness of the proposed control method.

Example 1: Consider a linear system governed by (4), where $A_1 = \begin{bmatrix} -2 & 0 \\ 0 & 1 \end{bmatrix}$, $A_2 = \begin{bmatrix} -1 & 0.5 \\ 0.5 & -1 \end{bmatrix}$, $A_3 = \begin{bmatrix} -12 & 0 \\ 0 & -1 \end{bmatrix}$, $B_1 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$, $B_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $B_3 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$, $C_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $C_3 = \begin{bmatrix} 1 & 1 \end{bmatrix}$, and $x_1 = \begin{bmatrix} x_{11} \\ x_{12} \end{bmatrix}$, $x_2 = \begin{bmatrix} x_{21} \\ x_{22} \end{bmatrix}$, $x_3 = \begin{bmatrix} x_{31} \\ x_{32} \end{bmatrix}$ are the state variables. d_1 and d_2 are external disturbances, which are set as Gaussian random noise following the distribution $N(0, 0.01)$ and subjected to the bounded condition in Assumption 2, and the noise bound $d = 1$ in Assumption 2. The F in (5) is determined using pole assignment method as $F = \begin{bmatrix} -1 & 0 \\ 0 & 2 \end{bmatrix}$. The initial conditions are selected to be $x_1(0) = [0.3, 0.2]^T$, $x_2(0) = [0.1, 0.1]^T$, $x_3(0) = [0, 0]^T$. The simulation time is set to $t \in [0, 15s]$. Two controllers (8) and (9) are adopted to stable the closed-loop system, separately. Parameters $k_1 = [7.4369, 234.2191]$ for u_3 and $k_1 = [59.6646, 577.4791]$, $k_3 = [10.0597, 8.0456]$ for u_3' are searched by LMI (15) and (19) respectively. Note that the controlled subsystem is not stable without control input u_3 or u_3' because A_1 is not Hurwitz.

The simulation results are shown in Figs. 2-6. Figs. 2 and 3 show situations of the estimated states $\hat{x}_{11}$ and $\hat{x}_{12}$ following states x_{11} and x_{12} by controllers u_3 and u_3' respectively. It can be seen that under the control of u_3 or u_3', the system states x_{11} and x_{12} are convergent and the subsystem to be controlled is stable. Meanwhile, the output of the state observer $\hat{x}_{11}$ and $\hat{x}_{12}$ can quickly keep up with the change of x_{11} and x_{12}. Figs. 4-5 show the change of system states x_2 and x_3 with time by the proposed controllers u_3 and u_3' respectively, and the time-varying curves of u_3 and u_3' can be seen in Fig. 6. The figures confirm the stability of the closed-loop system. At the same time, it can be seen from Figs. 5-6 that the control line of u_3' is smoother than that of u_3, which is with some damping oscillation, because u_3' in (9) utilizes more observation information than u_3 in (8). One can see from the results that the proposed method results in a stable closed-loop system and the effectiveness of the proposed control method can be confirmed.

Example 2: Consider a more unstable system, which shares the same parameters as in Example 1 except for $A_3 = [-12, 0; 5, 1]$. In this system, neither A_1 nor A_3 is Hurwitz, therefore, it is a more unfavorable situation than in Example 1. The initial conditions are selected as $x_1(0) = [-0.3, -0.2]^T$, $x_2(0) = [0.1, 0.1]^T$, $x_3(0) = [0, 0]^T$. Control parameters are searched as $k_1 = [20.3961, 306.8779]$ for u_3 and $k_1 = [52.6340, 294.4861]$, $k_3 = [1.6852, -0.4692]$ for u_3', respectively. Other parameters are the same as in Example 1. Figs. 7-11 show the simulation results, which further confirm the effectiveness of the proposed controllers. It can be seen from the simulation results that u_3' has

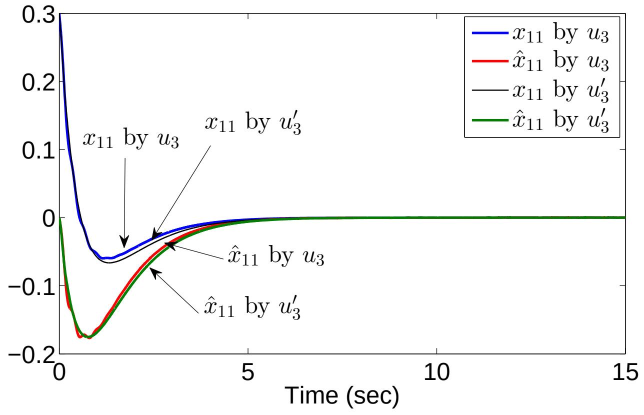

Fig. 2: State estimation $\hat{x}_{11}$ follows state x_{11}

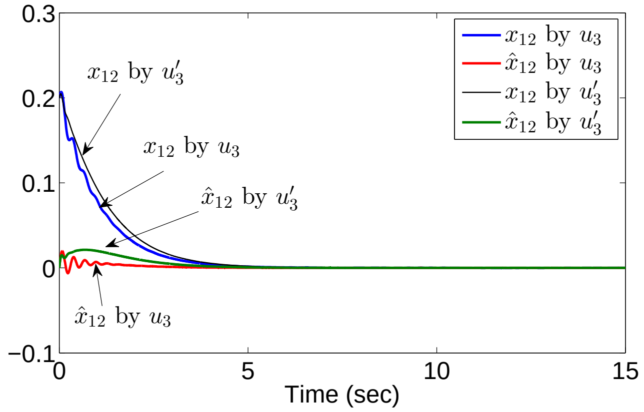

Fig. 3: State estimation $\hat{x}_{12}$ follows state x_{12}

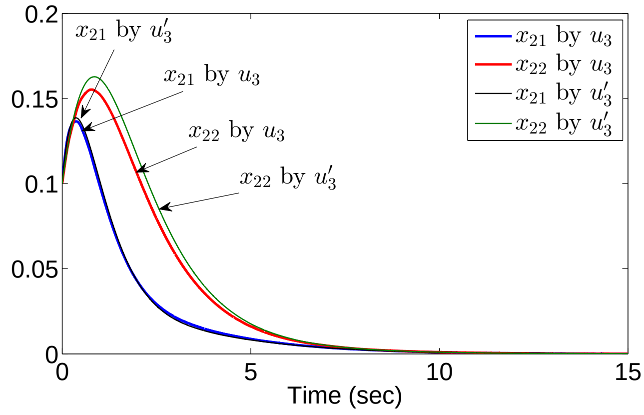

Fig. 4: Change of state x_2

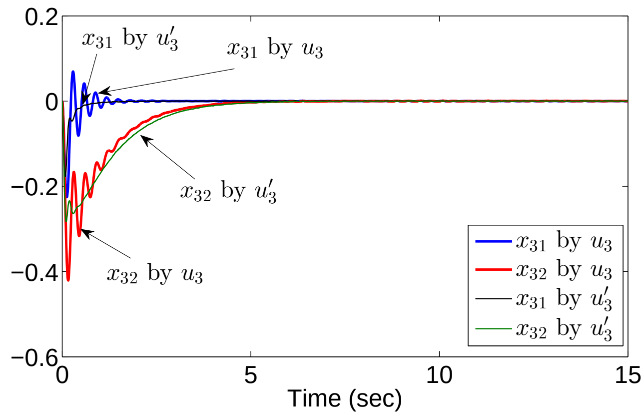

Fig. 5: Change of state x_{31}

better control performance because of utilizing more system information.

V. Conclusion

In this paper, the state observer based control problem was investigated for a class of time continuous linear CPS, which is composed of the controlled object, communication channel, filter and remote controller. A Luenberger-like reduced order state observer was constructed to obtain the system states, based on which two controllers were designed. The stability of the closed-loop system was analyzed based on the Lyapunov theory, and the stability sufficient conditions of the system were obtained by solving LMIs. Simulation results confirmed the effectiveness of the proposed scheme. While the considered system was linear systems, and the future research will take nonlinear systems into account.

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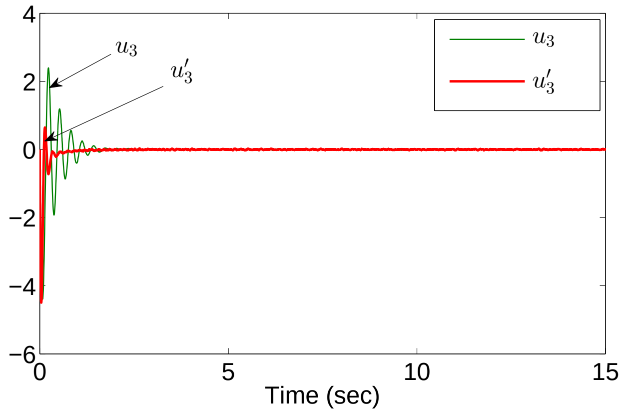

Fig. 6: Control law u_3 and u'_3

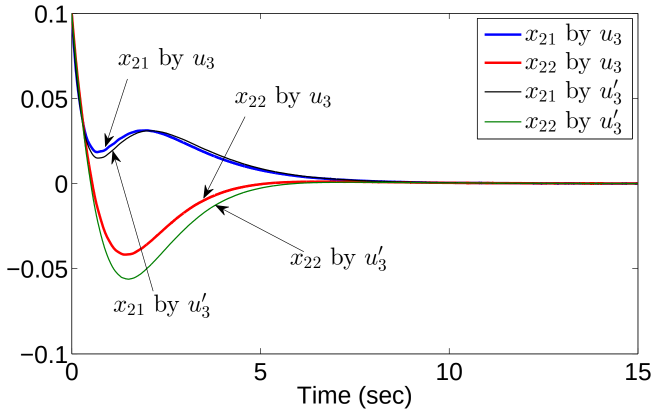

Fig. 9: Change of state x_2

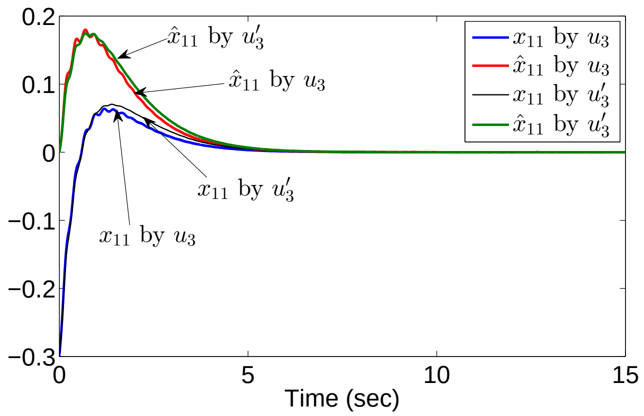

Fig. 7: State estimation $\hat{x}_{11}$ follows state x_{11}

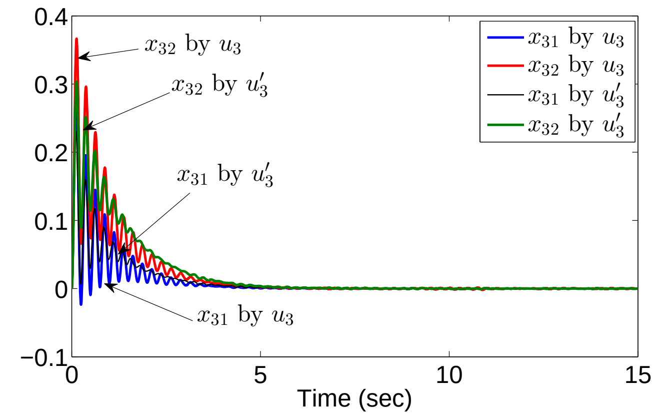

Fig. 10: Change of state x_{31}

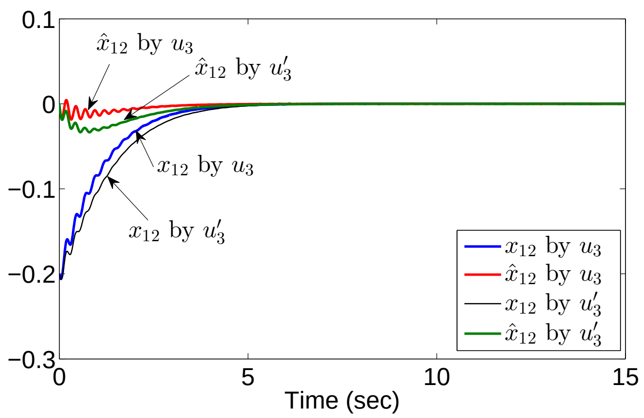

Fig. 8: State estimation $\hat{x}_{12}$ follows state x_{12}

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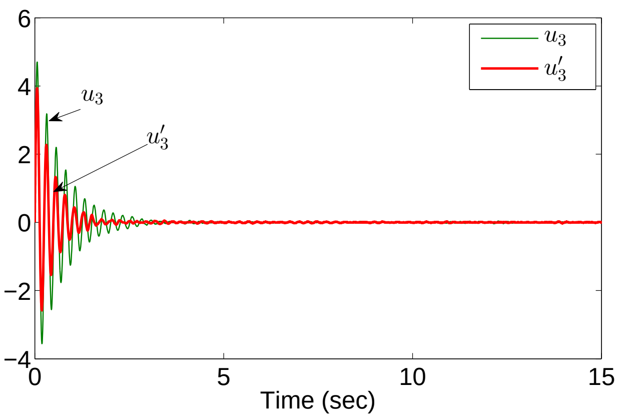

Fig. 11: Control law u_3 and u_3'

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