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Research article

Robust passive control for a class of uncertain neutral systems based on sliding mode observer

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ABSTRACT

The passivity-based sliding mode control (SMC) problem for a class of uncertain neutral systems with unmeasured states is investigated. Firstly, a particular non-fragile state observer is designed to generate the estimations of the system states, based upon which a novel integral-type sliding surface function is established for the control process. Secondly, a new sufficient condition for robust asymptotic stability and passivity of the resultant sliding mode dynamics (SMDs) is obtained in terms of linear matrix inequalities (LMIs). Thirdly, the finite-time reachability of the predesigned sliding surface is ensured by resorting to a novel adaptive SMC law. Finally, the validity and superiority of the scheme are justified via several examples.

1. Introduction

Neutral systems, as an important type of functional differential equations of control theory, can describe many practical systems [1], e.g., lossless transmission line, distributed networks and heat exchangers. The systems are more sensitive to time-delay [2] and can be easily destabilized because the delayed state and the derivative of it exist, simultaneously. Thus, a great many reports on stability analysis and control design issues of neutral systems have sprung up, and the developments include various theoretical and practical aspects, such as stability and stabilization [3–5], reliable control [6], output-feedback control [7], guaranteed cost control [8], observer design [9, 10]. However, when subjected to some perturbations through the control channel of the system [11], which is also called as matched uncertainties in sliding mode control (SMC) theory, the aforementioned control design methods may lose their reliable effects upon many occasions.

As is known, SMC [12] is an effective robust control method for uncertain and nonlinear systems because of its various attractive features such as quick response, good transient performance, particularly, the invariance against the matched uncertainties, and it has been widely applied to various complex systems [13–18] as well in practically technical problems [19–21]. To mention a few, SMC problem for a class of uncertain neutral systems has been studied in Ref. [16]. With a novel framework of neural-network approximation, robust control problem for a type of neutral systems has been concerned via the SMC in Ref. [17]. Recently, in Ref. [18], the problem of robust exponential stabilization for uncertain neutral systems has been concerned via integral SMC. Nevertheless, in spite of the availability of SMC to tackle the systems, most of the reports are obtained upon the premise that all the system states are accessible. In many practical cases, it has been approved that the states may not be totally acquired and even generally not easily to be evaluated through output measurement, which makes the first motivation of the design.

In order to deal with these problems, by viewing the superiority and effectiveness of the SMC as well as the observer, observer-based SMC technique, also called as the sliding mode observer (SMO) strategy [22,23], has been proposed to solve the state estimation issue for a variety of complex systems as well as many realistic plants successfully, see [24–32] and the references therein. To cite a few, the SMO design for neutral systems with unmeasured states has been investigated in Ref. [29] perfectly;

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afterwards, the observer-based H_∞ control has been studied for a class of uncertain neutral systems via integral SMC in Ref. [30], and a type of neutral stochastic systems with Markovian switching parameters has been investigated by SMO in Ref. [31]. Also, robust adaptive SMC problem for a class of uncertain neutral Markovian jumped systems with unmeasured states has been studied in Ref. [32]. It is noted that in Ref. [30,31], there do not exist any perturbations through the control channels, which is quite an important issue in both theoretical and practical models. Moreover, as traditional approaches [26,28,29,32] to handle the perturbations through the control channels, two sliding surfaces or additional terms are introduced in the estimation space and the error space, respectively. In brief, the situation makes it meaningful and possible to simplify the sliding surface design (e.g., single sliding surface design) for neutral systems, which forms the second motivation of the paper. Besides, SMC law as well as its compensator are both required to maintain the sliding mode phase and suppress the effects of the matched uncertainties. This concern also makes us generate an idea automatically: How to optimize the design process of the SMO when exposed to model uncertainties such as perturbations through the control channel, structural uncertainties and external disturbance, which finally motivates us to do the study.

On the other hand, considerable attention has been paid to passivity problems (e.g., various systems may need to be passive so as to attenuate environmental disturbances) in control theory and applications [33–35]. At this point, we are intended to further study the passivity-based SMO scheme for a class of uncertain neutral systems. A new SMO strategy is presented on the basis of the state estimation and the outputs. A new sufficient condition for robust asymptotic stability and passivity of the correlated sliding mode dynamics (SMDs) is derived via the LMI technique. Then, we synthesize a novel adaptive SMC law to take charge of the finite-time reachability of predefined sliding surface. The proposed method is substantially different from the existing results. Some practical and numerical examples are adopted to verify the effectiveness and superiority of the method with computer simulations. The contribution of this paper mainly includes the following:

- A particular non-fragile observer is designed to estimate the original states, where the control input and/or its compensator for most of the existing observer design of complex time-delay systems are not involved. And a new technical route which aims to achieve the desirable performance of the system through the original system and its error system via the new SMO strategy, can be performed.
- Based on the observer, a novel single sliding surface design is presented, which leads to the SMDs and facilitates the scheme further. Then, a sufficient condition ensuring the desirable performance of the SMDs is presented under a new LMI framework.
- A novel adaptive sliding mode controller is synthesized to guarantee the finite-time reachability of the sliding surface, and the unknown bounds of the uncertainties are well estimated in such a way the method could be exhibited.
- The proposed theoretical result and its superiority are effectively justified via several examples with comparisons.

The remainder is organized as follows. System formulation is given in Section 2. In Section 3, main results of the SMO design are stated. Illustrative examples are given to show the potential and superiority in Section 4. Conclusions are given in Section 5.

Notations: The notations used in this paper are fairly standard. $P>0$ means that matrix P is positive definite; the symmetric elements of a symmetric matrix is denoted by "*"; " T " represents the transpose of a vector or matrix transposition. $\mathrm{sym}\{P\}$ is denoted as $P+P^{\mathrm{T}}$. $\mathrm{diag}\{Q\}$ represents a block-diagonal matrix Q. $L_2[0,\infty)$ is the space of square-integrable vector functions over $[0,\infty)$.

2. System description

Consider the following n-dimensional uncertain neutral system described by

$$\begin{cases} \dot{x}(t)-D\dot{x}(t-\tau)=(A+\Delta A(t))x(t)+(A_d+\Delta A_d(t))x(t-d) \\ \qquad\qquad +B[u(t)+f(t,x(t))]+Gw(t), \\ y(t)=Cx(t), \\ z(t)=Ex(t)+Fw(t), \\ x(\theta)=\phi(\theta),\ \theta\in[-h,0] \end{cases} \tag{1}$$

where $x(t)\in\mathbb{R}^n$ is the state vector, $u(t)\in\mathbb{R}^m$ is the control input, $y(t)\in\mathbb{R}^p$ is the measured output signal, $z(t)\in\mathbb{R}^q$ is the controlled output signal. $\tau>0$ is a constant neutral-term time-delay, d is the state delay, and $h=\max\{\tau,d\}$. $w(t)\in\mathbb{R}^l$ represents a set of exogenous disturbance which belongs to $L_2[0,\infty)$. $\phi(t)$ is the initial condition. A, A_d, B, C, D, E, F and G are real matrices, B is of full column rank, and the spectrum radius of the matrix D, i.e., $\rho(D)$, satisfies $\rho(D)<1$. We assume that the system Eq. (1) is detectable and stabilizable. The objective of the paper is to develop a novel SMO scheme for stabilizing the system (1) with passivity performance in which adaptive controller is synthesized such that the unmeasured system state x satisfies $\lim_{t\to\infty}x=0$ for all $t\ge 0$. To this end, the following assumptions are introduced.

Assumption 1. The structural uncertainties $\Delta A(t)$ and $\Delta A_d(t)$ are norm bounded, i.e., $[\Delta A(t)\ \Delta A_d(t)]=MF(t)[N\ N_d]$, where M, N and N_d are constant matrices, and $F(t)$ is an unknown matrix function satisfying $F^{\mathrm{T}}(t)F(t)\le I$ for all $t\ge 0$.

Assumption 2. $f(t,x(t))$ is an unknown function which represents the lumped perturbation of a physical plant through the control channel satisfying $\|f(t,x(t))\|\le\alpha\|y(t)\|$ [26,32], where $\alpha>0$ is an unknown constant.

3. Main results

In this section, we will pay important attention to stability analysis and controller synthesis of the closed-loop systems based on a particular state observer. The research framework and specific contents are shown in the following, respectively.

3.1. Non-fragile state observer and integral sliding surface design

The following state observer is designed to estimate the original system states

$$\begin{cases} \dot{\hat{x}}(t)-D\dot{\hat{x}}(t-\tau)=A\hat{x}(t)+A_d\hat{x}(t-d)+(L+\Delta L(t))(y(t)-C\hat{x}(t)), \\ \hat{y}(t)=C\hat{x}(t), \\ \hat{x}(\theta)=\hat{\phi}(\theta),\ \theta\in[-h,0] \end{cases} \tag{2}$$

where $\hat{x}(t)\in\mathbb{R}^n$ represents the estimation of $x(t)$, $\hat{y}(t)$ denotes the measured output of the observer. $L\in\mathbb{R}^{n\times p}$ is the observer gain matrix to be designed later, and $\Delta L(t)$ is an additive gain variation satisfying $\|\Delta L(t)\|\le\delta$, where $\delta>0$ is a constant, i.e., the observer may be affected by some perturbations [27,31].

Define the error variable: $e(t)=x(t)-\hat{x}(t)$. Thus, by subtracting Eq. (2) from Eq. (1), one can get the following estimation error system: