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Robust observer-based adaptive fuzzy sliding mode controller

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In this paper, a new observer-based adaptive fuzzy integral sliding mode controller is proposed based on the Lyapunov stability theorem. The plant is subjected to a square-integrable disturbance and is assumed to have mismatch uncertainties both in state- and input-matrices. Based on the classical sliding mode controller, the equivalent control effort is obtained to satisfy the sufficient requirement of sliding mode controller and then the control law is modified to guarantee the reachability of the system trajectory to the sliding manifold. In order to relax the norm-bounded constrains on the control law and solve the chattering problem of sliding mode controller, a fuzzy logic inference mechanism is combined with the controller. An adaptive law is then introduced to tune the parameters of the fuzzy system on-line. Finally, for evaluating the controller and the robust performance of the closed-loop system, the proposed regulator is implemented on a real-time mechanical vibrating system.

1. Introduction

The uncertainty as a perturbation of the real system model can significantly affect the dynamics of the closed-loop system and system response. As a result, it is crucial to address these uncertainties within the modeling procedure in order to increase the applicability and reliability of the model. On the other hand, the control methods mostly rely on simplified models in order to be implemented on real time configurations. These two complex modeling boundaries forced the control strategies to develop based on norm-bounded constraints of un-modeled dynamics, modeling uncertainties, and external disturbances and therefore robust controller can be considered as a general control methodology that fulfills this requirement. The sliding mode controller (SMC) is regarded as a robust technique due to the rejection of external disturbance and insensitivity with respect to bounded perturbation [1]. In addition, SMC is proven to have fast reaction with low control order [2]. An important issue of the SM technique is the sensitivity of the closed-loop system to the perturbation in the reaching initial period, during which the dynamic trajectory of the system moves toward the sliding surface [3]. An alternative approach known as integral SMC (ISMC) is contributed with aiming at solving this issue throughout elimination of the reaching phase [4]. However, even ISMC method cannot generally solve the matching problem and therefore it is used in combination with other robust techniques [5]. Recently, some researchers donated their attention toward the effects of these mismatch uncertainties in robust performance of ISMC. Cao and Xu limited their control development to the case of mismatch uncertainty only in state matrix [6]. Qu and Wang presented a SMC on a delayed system with mismatch

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perturbation in state-matrix in a linear matrix inequality (LMI) frame-work by use of a Lyapunov method [7]. Choi proposed a new ISMC in an LMI form for the systems with mismatch uncertainty in both state and input matrices. The controller is proven to be able to guaranty the asymptotic stability as well as satisfying the α-stability constraint [8]. Plestan et al. presented a new methodology for adaptive SMC without the requirement of the prior knowledge of the numerical values for the bounds of the uncertainties [9]. Their algorithms are limited to single input single output (SISO) systems with a limited order adaptive law. Ha et al. combined the fuzzy logic with SMC in order to obtain a robust disturbance rejection controller on mismatch systems. Fuzzy system is introduced to address the chattering problem of the SMC [10]. Ho et al. presented an adaptive fuzzy SMC (AFSMC) for a class of continuous time unknown nonlinear systems. Their controller guaranties the robust stability of the closed-loop system and is not subjected to chattering by the introduction of the fuzzy system [11]. Oveisi and Gudarzi used an ideal controller based on SMC and introduced a fuzzy system to mimic this controller. The robust stability is guaranteed by designing the controller based on compensation of the difference between the fuzzy controller and the ideal controller by use of Lyapunov theory [12]. In this paper a new observer-based AFISMC is introduced in order to solve the H_∞ problem for a class of systems with mismatch uncertainties in state and input matrices. The proposed controller is based on Lyapunov stability theorem and can reject the output disturbance in the presence of un-modeled/nonlinear bounded dynamics. In order to solve the mismatch and the chattering problem of SMC, the fuzzy system is introduced which is combined with an adaptive rule.

Most of the mentioned researches have limited their case study to some numerical examples. However, Wai et al. adopted an AFISMC to control the position of an electrical servo drive [13]. Gholami and Markazi introduced a new AFSM observer for a class of nonlinear MIMO systems and implemented their observer on a modular and reconfigurable robot (MRR) system [14]. Mechanical vibration control is an important application of compensator design [15]. Hasheminejad et al. implemented an AFSMC scheme to actively suppress the two-dimensional vortex-induced vibrations (VIV) of an elastically mounted circular cylinder which is free to move in in-line and cross-flow directions [16]. Gudarzi et al. designed a robust LMI-based controller to reduce the vibration magnitude of a plate by using piezoelectric actuator/sensors [17]. In this paper, the proposed controller is implemented on a piezolaminated beam which is vibrating due to the existence of undesired external disturbance. The dynamics of the system is obtained by use of a subspace system identification method. In the rest of the manuscript, I represents the identity matrix with appropriate dimension, $\|.\|$ shows the H_∞ norm of the corresponding matrix, and $\mathcal{R}$ stands for the set of real numbers.

2. Problem formulation

Consider the open loop plant of the system in uncertain state-space form of Eq. (1)

$$\dot{x} = (A+\Delta A)x + (B+\Delta B)u + Hw + f,$$
$$y = Cx, \tag{1}$$

where $x \in \mathcal{R}^n$, $u \in \mathcal{R}^m$, and $y \in \mathcal{R}^q$ are the state, input, and output vectors, respectively. In addition, $f(x,t) \in \mathcal{R}^n$ and $w \in \mathcal{R}^p$ represent the vector of un-modeled/nonlinear dynamics and square-integrable disturbance, respectively. Moreover, $A \in \mathcal{R}^{n\times n}$, $B \in \mathcal{R}^{n\times m}$, $H \in \mathcal{R}^{n\times p}$, and $C \in \mathcal{R}^{q\times n}$ are the state, control input, disturbance input, and output matrices, correspondingly. $\Delta A \in \mathcal{R}^{n\times n}$ and $\Delta B \in \mathcal{R}^{n\times m}$ are the perturbation terms that are considered as modeling source of uncertainty. It is assumed that the uncertainty matrices and un-modeled dynamics are norm-bounded as $\|\Delta A\| \le a$, $\|\Delta B\| \le b$, and $\|f(x,t)\| \le g_m\|x\|$ with a, b, and g_m being positive measurable constants. The uncertainty of disturbance input matrix can be considered as a new source of disturbance and therefore it does not appear in the model of the plant explicitly. By assuming the system to be stabilizable with nominal input matrix of full rank, the following system is introduced as the dynamics of the observer

$$\dot{\hat{x}} = (A+\Delta A)\hat{x} + (B+\Delta B)u + L(y-\hat{y}),$$
$$\hat{y} = C\hat{x}, \tag{2}$$

in which $\hat{x} \in \mathcal{R}^n$ and $\hat{y} \in \mathcal{R}^q$ are the observed state- and output-vectors, respectively. Also, L symbolizes the observer gain. An alternative representation for observer dynamics is also used later based on the full-order Luenberger observer.

2.1. Sliding mode control

2.1.1. Sliding surface and equivalent control input design

The sliding surface is defined as

$$S(t) = B^{+}\hat{x} + z, \tag{3}$$

where $B^{+} \equiv \left(B^TB\right)^{-1}B^T$. It is assumed that the initial condition is $z(0) = -B^{+}\hat{x}(0)$ in order to satisfy $S(0)=0$. In addition, z can be calculated by solving the following dynamic equation

$$\dot{z} = -\left(B^{+}A - B^{+}LC + K\right)\hat{x} - B^{+}Ly, \tag{4}$$