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Enhanced adaptive fuzzy sliding mode control for uncertain nonlinear systems

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ABSTRACT

In this article, a novel Adaptive Fuzzy Sliding Mode Control (AFSMC) methodology is proposed based on the integration of Sliding Mode Control (SMC) and Adaptive Fuzzy Control (AFC). Making use of the SMC design framework, we propose two fuzzy systems to be used as reaching and equivalent parts of the SMC. In this way, we make use of the fuzzy logic to handle uncertainty/disturbance in the design of the equivalent part and provide a chattering free control for the design of the reaching part. To construct the equivalent control law, an adaptive fuzzy inference engine is used to approximate the unknown parts of the system. To get rid of the chattering, a fuzzy logic model is assigned for reaching control law, which acting like the saturation function technique. The main advantage of our proposed methodology is that the structure of the system is unknown and no knowledge of the bounds of parameters, uncertainties and external disturbance are required in advance. Using Lyapunov stability theory and Barbalat's lemma, the closed-loop system is proved to be stable and convergence properties of the system is assured. Simulation examples are presented to verify the effectiveness of the method. Results are compared with some other methods proposed in the past research.

1. Introduction

The Variable Structure System (VSS) research was originated in early 1950s for single input systems with high order differential equations [1–3]. VSS was not very popular among control engineers prior to 1970s due to the absence of a systematic design procedure and high oscillation chattering in the control input. Although many scientists had conducted much research in the area of VSS, it was not until 1977 that the VSS concept was fully appreciated.

The variable structure control with sliding mode was introduced to control engineers by Utkin [4]. The Sliding Mode Control (SMC) was originally developed for variable structure systems in the continuous domain. In his survey paper, Utkin presented a thorough description of the SMC theory in continuous time. Later, Slotine and Li [5] discussed continuous SMC in more detail. More recently, the research in the field of discrete time SMC has attracted many researchers [6]. SMC is an efficient tool to control complex high-order dynamic plants operating under uncertainty conditions due to its order reduction property and low sensitivity to disturbances and plant parameter variations.

In SMC, the states of the controlled system are first guided to reside on a designed surface (i.e., the sliding surface) in state space and then keeping them there with a shifting law (based on the system states).

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There has been a wide variety of applications of SMC in areas such as robotics, power control, aerospace, and process control [7–11]. The most prominent property of the SMC is its insensitivity to parameter variations and external disturbances. However, its major drawback in practical applications is the chattering problem. Numerous techniques have been proposed to eliminate this phenomenon in SMC [12,13].

Conventional methods used to eliminate the chattering are to replace the relay control by a saturating approximation [14], integral sliding control [15–17] and Boundary Layer technique [5]. The boundary layer approach was introduced to eliminate the chattering around the switching surface and the control discontinuity within this thin boundary layer. If systems uncertainties are large, the sliding-mode controller would require a high switching gain with a thicker boundary layer to eliminate the higher resulting chattering effect. However, if we continuously increase the boundary layer thickness, we are actually reducing the feedback system to a system without sliding mode.

To tackle these difficulties, fuzzy logic controllers are often used to deal with the discontinuous sign function in the reaching phase of SMC [18–33]. Recently, AFSMC methods are also used for this purpose, which is shown to be quite effective [34–36].

Fuzzy Logic Control (FLC) has been an active research topic in automation and control theory since the work of Mamdani [37] based on the fuzzy sets theory of Zadeh [38]. The basic concept of FLC is to utilize the qualitative knowledge of a system for designing a practical controller. Generally, FLC is applicable to plants that are ill-modeled, but qualitative knowledge of an experienced operator is available. It is particularly suitable for those systems which have uncertain or complex dynamics.

Generally, in contrast to a conventional feedback control algorithm, there is a fuzzy control algorithm consists of a set of heuristic decision rules that can be represented as a non-mathematical control algorithm. This algorithm proves to be very effective especially when the precise model of the system under control is not available or expensive to prepare. The principle of SMC has been introduced in designing fuzzy logic controllers to guarantee the stability. This combination (i.e., FSMC) provides the mechanism to design robust controllers for nonlinear systems with uncertainty [39–41].

Designing adaptive fuzzy controllers by the integration of fuzzy logic and the SMC [42–44] for ensuring stability and consistent performance is a well known research topic. Many new algorithms have been proposed based on the integration of these control methods [45,46]. These approaches are similar in the aspect that they directly approximate the sliding mode control law by fuzzy approximators. One main advantage of this control scheme is its insensitivity to modeling uncertainty and external disturbances. Many AFSMC schemes have been proposed to eliminate the chattering using a fuzzy sliding surface in the reaching condition of the SMC [45–49].

In this article, a novel AFSMC algorithm is proposed for a class of continuous time unknown nonlinear systems. To design the hitting part of the SMC, a fuzzy controller is used. This will reduce the chattering and improve the robustness. An AFSMC is used (as equivalent control part of SMC) to approximate the unknown parts of the uncertain system. We provide the proof that closed-loop system is globally stable in the Lyapunov sense and the system output can track the reference signal in the presence of modeling uncertainties and external disturbances.

The rest of this paper is organized as follows. Section 2 presents the system definitions and introduces the classical SMC design method. Sections 3 and 4 present the design method for the reaching and equivalent control parts, respectively. Section 5 presents the proof of asymptotic stability for the proposed method. Section 4 provides the simulation results and finally, conclusions are given in section 7.

2. System description and traditional SMC

Consider nonlinear systems whose dynamical equations can be expressed in the canonical form [50]

$$\begin{cases} \dot{x}_i = x_{i+1}, & 1 \leqslant i \leqslant n-1, \\ \dot{x}_n = f(x,t) + d(t) + g(x,t)u(t), \end{cases} \tag{1}$$

where $x(t) = [x_1(t)x_2(t)\cdots x_n(t)]^T \in \Re^n$ is the state vector, $f(x,t)$ and $g(x,t)$ are two unknown functions belong to $\Re^n \to \Re$ space. $u(t)$, and $d(t) \in \Re$ are the control input and the external disturbance, respectively.

Assumption 1 ([5,51,52]). The unknown functions $f(x,t)$, $g(x,t)$ and $d(t)$ satisfy the following conditions:

$$|f(X,t)| \leqslant F < \infty, \;\; 0 < g_{\min} \leqslant g(X,t) \leqslant g_{\max} < \infty \quad \text{and} \quad |d(t)| \leqslant \beta, \tag{2}$$

where $X \in U_X \subset \Re^n$, U_X is a compact set defined as: $U_X = \{X \in \Re^n : \|X\| \leqslant m_x < \infty\}$ and F, β, $g_{\min}$ and $g_{\max}$ are unknown constants.

The control problem is to force the system to track an n-dimensional desired vector $X_d(t)$ (i.e. the nth-order tracking problem of state $x_d(t)$ as discussed in [50]), $X_d(t) = [x_{d1}(t)x_{d2}(t)\cdots x_{dn}(t)] = [x_d(t)\dot{x}_d(t)\cdots x_d^{(n-1)}(t)] \in R^n$, which belong to a class of continuous functions in the interval $[t_0,\infty]$. The tracking error is defined as

$$E(t) = X(t) - X_d(t) = [x(t) - x_d(t)\dot{x}(t) - \dot{x}_d(t)\cdots x^{(n-1)}(t) - x_d^{(n-1)}(t)] = [e(t)\dot{e}(t)\cdots e^{(n-1)}(t)] = [e_1(t)e_2(t)\cdots e_n(t)]. \tag{3}$$

The control goal considered in this paper is that for any given target $X_d(t)$, a SMC is designed such that the resulting state response of the tracking error vector satisfies the following condition: