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Chattering-free fuzzy sliding mode control in MIMO uncertain systems

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ABSTRACT

Control of nonlinear multivariable systems is very challenging in the area of systems and control. This paper is concerned with a framework that unifies sliding mode control (SMC) and fuzzy logic control (FLC). Based on the combination of the SMC with fuzzy control, this paper presents a new and feasible design algorithm to synthesize a robust fuzzy sliding mode controller which can easily tackle the stabilizing and tracking problem of a class of MIMO nonlinear systems in the presence of uncertainties and external disturbance. A practical design that combines a fuzzy technique with SMC to enhance robustness and sliding performance in a class of uncertain MIMO nonlinear systems is proposed. Using a fuzzy scheme, a Fuzzy Sliding Mode Controller (FSMC) is used to approximate the hitting control in the neighborhood of the sliding manifold. The main contribution of the proposed method is that the structure of the controlled system is partially unknown and does not require the bounds of uncertainty and disturbance of the system to be known; meanwhile, the chattering phenomenon that frequently appears in the conventional variable structure systems is also eliminated without deteriorating the system robustness. A series of computer simulations are included to verify the effectiveness of the proposed design algorithm.

1. Introduction

The variable structure control (VSC) is characterized by a discontinuous controller which can change its structure automatically on reaching a switching surface in order to obtain a desired dynamic performance. It has been shown that the VSC possesses several advantages, such as fast response, robustness of stability, insensitivity to the matching parameters' variations, and external disturbances [1–4]. The Sliding Mode Control (SMC) method that originated from the theory of VSS was considered as an effective method for the control of systems with uncertainties in the past several decades. SMC was introduced to control engineers by Utkin [5]. In his survey paper, Utkin presented a thorough description of the SMC theory in continuous time.

SMC is one of the effective nonlinear robust control approaches since it provides system dynamics with an invariance property to uncertainties, once the system dynamics are controlled in the sliding mode [6,7]. The insensitivity of the controlled system to uncertainties exists in the sliding mode, but not during the reaching phase. Thus the system dynamics in the reaching phase is still influenced by uncertainties.

However, its major drawback in practical applications is the chattering problem. Numerous techniques have been proposed to eliminate this phenomenon in SMC [8,9].

Commonly used methods to eliminate the chattering, are to replace the relay control by a saturating approximation [10], integral sliding control [11], and boundary layer technique [12]. The boundary layer approach was introduced to eliminate the chattering around the switching surface and the control discontinuity within this thin boundary layer.

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If system uncertainties are large, the sliding-mode controller would require a high switching gain with a thicker boundary layer to eliminate the resulting higher chattering effect. However, if we continuously increase the boundary layer thickness, we are actually reducing the feedback system to a system without a sliding mode. To tackle these difficulties, recently, Fuzzy SMC (FSMC) has also been used for this purpose, which is shown to be quite effective [13–15].

Fuzzy Control (FC) has been an active research topic in automation and control theory since the work of Mamdani [16] based on the fuzzy sets theory of Zadeh [17]. The basic concept of FC is to utilize the qualitative knowledge of a system for designing a practical controller.

Generally, FC is applicable to plants that are ill-modeled, but qualitative knowledge of an experienced operator is available. It is particularly suitable for those systems with uncertain or complex dynamics.

Generally, in contrast to a conventional control algorithm, there is a fuzzy control algorithm consisting 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 stability. This combination (i.e., FSMC) provides the mechanism for designing robust controllers for nonlinear systems with uncertainty [18–22]. Considering the above-mentioned issues, in this paper, we investigate the control of a class of nonlinear systems using FSMC for constructing a simple controller.

In this paper, in order to eliminate the chattering problem, fuzzy inference engine is used for reaching phase and fuzzy sliding mode control methodology is proposed. The main advantage of this method is that the robust behavior of the system is guaranteed. The second advantage of the proposed scheme is that the performance of the system is improved in the sense of removing the chattering in comparison with the same SMC technique without using Fuzzy Logic Controller (FLC). The rest of this paper is organized as follows. Section 2 presents the system description. The design of the proposed controller is introduced in Section 3. Simulation results are given in Section 4. Finally, conclusions are given in Section 5.

2. System description and traditional SMC

In this section, the MIMO nonlinear system with the presence of uncertainties and external disturbance is described. The state equation of the MIMO nonlinear system is a first-order differential equation as follows:

$$\dot{X} = f(X,t) + \Delta f(X,t) + d(t) + u, \quad X = [x_1\ x_2\ \dots\ x_n]^{\mathrm{T}} \in R^n \text{ and } u \in R^n \tag{1}$$

where $X(t) = [x_1(t)\ x_2(t)\ \dots\ x_n(t)]^{\mathrm{T}} \in R^n$ is the state vector and $u(t) \in R^n$ is the control input of system (1). $\Delta f(X,t)$ is an uncertain term representing the unmodeled dynamics or structural variation of system (1) and $d(t)$is the disturbance of system (1).

In general, the uncertain term $\Delta f(X,t)$ and the disturbance term $d(t)$ are assumed to be bounded, i.e.

$$\|\Delta f(X,t)\|_\infty \le \alpha \quad \text{and} \quad \|d(t)\|_\infty \le \beta, \tag{2}$$

where $\alpha,\ \beta$ are two positive and known constants.

The control problem is to get the system to track an n-dimensional desired vector $X_d(t)$ (i.e. the original nth-order tracking problem of state $X_d(t)$ as discussed in [12]), $X_d(t) = [x_{d1}(t)\ x_{d2}(t)\ \dots\ x_{dn}(t)]^{\mathrm{T}} \in R^n$, which belongs to a class of continuous functions on $[t_0, \infty]$. Let the tracking error be

$$E(t) = X(t) - X_d(t) = [x_1(t) - x_{d1}(t)\ x_2(t) - x_{d2}(t)\ \dots\ x_n(t) - x_{dn}(t)]^{\mathrm{T}} = [e_1(t)\ e_2(t)\ \dots\ e_n(t)]^{\mathrm{T}}. \tag{3}$$

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

$$\lim_{t\to\infty} \|E(t)\| = \lim_{t\to\infty} \|X(t) - X_d(t)\| \to 0 \tag{4}$$

where $\|\ .\ \|$ denotes the Euclidean norm of a vector.

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 confined there with a shifting law (based on the system states). A time varying surface $s(t)$ is defined in the state space $\Re^{(n)}$ by equating the variable $s(X,t)$, defined below, to zero.

$$s(X,t) = \left(\frac{\mathrm{d}}{\mathrm{d}t} + \lambda\right)^{n-1} E(t). \tag{5}$$

Here, λ is a strict positive constant, taken to be the bandwidth of the system [12]. As our problem formulation is a first-order differential equation then $n = 1$ and the relation (5) can be rewritten as follows,

$$s = E(t). \tag{6}$$

When the closed loop system is in the sliding mode, it satisfies $\dot{s} = 0$ and then the equivalent control law is obtained by:

$$u_{eq} = -f(X,t) - \Delta f(X,t) - d(t) + \dot{X}_d(t). \tag{7}$$