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# Bionic fuzzy sliding mode control and robustness analysis ☆

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ABSTRACT

In this study, we propose bionic fuzzy sliding mode control based on switching control item fuzzification for a class of uncertain nonlinear systems. We introduce biological adaptation strategies into sliding mode control under uncertain boundary circumstance and disturbances. The main feature of this new method is the design of the switching-type control item in the sliding mode controller based on biological active adaptation strategies. We also analyze the robustness of the bionic fuzzy sliding mode control system and prove the stability of the closed-loop system in the Lyapunov sense. Finally, simulation results obtained for the circle of inverted-pendulum system show that it is effective and feasible. We demonstrate that bionic fuzzy sliding mode control is superior to conventional fuzzy sliding mode control. This method alleviates the chattering phenomenon that affects sliding mode control and ensures that the tracking error stabilizes at zero.



## 1. Introduction

Sliding mode control (SMC) is a robust method for controlling uncertain nonlinear systems and it has been applied successfully in many fields [1,2]. However, some chattering phenomena exist when implementing SMC, which may generate high-frequency dynamics. This type of chattering phenomenon influences the precision of control as well as increasing energy consumption. Therefore, eliminating the chattering phenomenon is the most important task in SMC [3,4]. Huang and Lin first introduced adaptive fuzzy techniques into the design of SMC [5]. They used a fuzzy controller to attenuate the chattering phenomenon in SMC and proposed a method for fuzzy SMC (FSMC). By using the adaptive FSMC algorithm, the control signal was softened and the chattering phenomenon was alleviated in a conventional SMC system [6–10]. FSMC has heuristic characteristics because of its structure and its operation is simple. Fuzzy control does not require the establishment of a precise mathematical model [11,12] and SMC is highly robust, which makes FSMC a highly promising method in control engineering [13–15].

In recent years, fuzzy control systems have made great progress in terms of the structural analysis of fuzzy controllers, as well as the universal approximation and stability analysis of fuzzy systems. However, a major constraint on these analyses is that fuzzy control cannot achieve an intelligent effect, especially in systems with changing external environments and strong external disturbance. Therefore, the chattering phenomenon has not been alleviated in FSMC systems and research is still needed to overcome this problem. Fei and Zing [16] applied a radial basis function neural network to enhance the intelligent effect of a robust adaptive SMC system in the presence of model uncertainties and external disturbance. By combining the fuzzy theory with a neural network, Wai and Muthusamy [17] proposed a fuzzy-neural network-based SMC scheme to relax

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the requirement for detailed system information and to deal with chattering control efforts in the SMC system. From an ecological viewpoint, bionic fuzzy control can be achieved by integrating individual biological properties, such as adaptation, self-organization, and self-learning, into fuzzy control systems [18]. These properties may allow fuzzy control parameters and rules to adjust automatically during the control process, thereby achieving better control.

If external disturbances occur, ecological systems can form efficient defense systems based on their anti-interference and adaptation abilities. Thus, biological agents can adapt to the environment, but they can also develop and exploit it to their own benefit, thereby allowing the overall system to achieve a state of equilibrium; thus, a fuzzy control method was proposed based on biological adaptive strategies. This method embedded biological adaptation and a strategy for responding to environmental change in the design of a conventional fuzzy system and fuzzy control. This design facilitated active biological adaptation by the system, but it also retained the characteristics of the conventional fuzzy system.

This new system was shown to be transportable and easy to design using the existing fuzzy system. Biological adaptation was introduced into fuzzy systems and a fuzzy control method was proposed with biological characteristics [19]. This method has been used successfully to produce intelligent systems for greenhouse ecological niche control. In addition, based on this niche control function, biological adaptation, self-organization, and self-learning were introduced into fuzzy systems to obtain T–S fuzzy systems with biological characteristics [20]. The universal approximation of this system was demonstrated, which was used to approximate uncertain functions. The closeness function was regarded as an ecological factor with a normal distribution and a set of fuzzy rules, and the indirect adaptive T–S fuzzy control method was established [21]. A new type of adaptive fuzzy control was described based on the biological adaptive strategy [22].

In this context, we propose the introduction of biological adaptation strategies into SMC. Using the biological self-adaptation in the design of the controller, the switching-type control item in the SMC law is approximated by bionic fuzzy systems. We use an appropriate adaptive law to adjust the system state. We also analyze the robustness of our proposed bionic FSMC system and we prove that the closed-loop system is stable in the Lyapunov sense. Finally, our simulation results obtained using the circle of inverted-pendulum system demonstrate the effectiveness and feasibility of this approach.

The remainder of this paper is organized as follows. In Section 2, we provide a brief description of SMC. Section 3 introduces fuzzy systems with biological characteristics. Section 4 presents the design of our proposed bionic FSMC. In Section 5, we analyze the robustness of our system. Computer simulation results are presents in Sections 6 and 7 gives our conclusions.

## 2. Problem statement

Consider a general nonlinear system of the form

$$\begin{cases} x^{(n)} = f(x,t) + g(x,t)u(t) + d(t), \\ y = x, \end{cases} \tag{2.1}$$

where $f$ and $g$ are unknown nonlinear functions; $x \in R^n$ is the state vector of the system, which is assumed to be available for measurement; $u \in R$ and $y \in R$ are the input and output of the system, respectively; and $d(t)$ is the unknown external disturbance. It is assumed that $|d(t)| \leqslant D$. In order to be controllable for (2.1), it is required that $g(x,t) \neq 0$. Without any loss of generality, we assume that $g(x,t) > 0$. In this system, the control objective is to be obtain the state $x$ to track a desired state $x_d$ in the presence of model uncertainties and disturbances.

We define a sliding surface in the space of the error state as

$$s(x,t) = -\left(k_1 e + k_2 \dot{e} + \cdots + k_{n-1} e^{(n-2)} + e^{(n-1)}\right) = -k^T e, \tag{2.2}$$

where $e = x_d - x = \left[e\dot{e}\ldots e^{(n-1)}\right]^T$ is the tracking error vector and $k_1, \ldots, k_{n-1}$ are the coefficients of the Hurwitzian polynomial $p(\lambda) = \lambda^{n-1} + k_{n-1}\lambda^{n-2} + \cdots + k_2\lambda + k_1$.

An SMC law can be derived as

$$u(t) = \frac{1}{g(x,t)}\left[-f(x,t) + \sum_{i=1}^{n-1} k_i e^{(i)} - d(t) + x_d^{(n)} - u_{sw}\right], \tag{2.3}$$

where $u_{sw} = \eta\, sgn(s), \eta > 0$, and

$$sgn(s) = \begin{cases} 1, & \text{for } s > 0, \\ 0, & \text{for } s = 0, \\ -1, & \text{for } s < 0, \end{cases} \tag{2.4}$$

Due to the fact that the system functions $f, g$ and the disturbance $d$ are unknown in practical systems, the control law (2.3) is usually difficult to obtain. However, the switching control term $u_{sw}$ also causes a chattering phenomena. We use fuzzy systems $\hat{f}(x|\theta_f), \hat{g}(x|\theta_g)$, and $\hat{h}(s|\theta_h)$ to approximate $f, g$, and $\eta\, sgn(s)$, respectively.

The fuzzy rules are defined as.

$R_f^l$: If $x_1$ is $A_1^l$ and $\ldots$ and $x_n$ is $A_n^l$ then $y$ is $B_f^l$.