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# Finite-time fault-tolerant control of neutral systems against actuator saturation and nonlinear actuator faults

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ABSTRACT

This paper deals with the problem of finite-time fault-tolerant control design for a class of neutral systems subject to actuator saturation in which the time-varying delay appears in both the state and the state derivative. Specifically, this is the first attempt to consider the concept of finite-time stability for neutral systems under nonlinear fault-tolerant controller. In particular, the fault model which consists of both linear and nonlinear parts is implemented through the design of controller. By applying the Lyapunov technique and some integral inequalities, a set of sufficient conditions is derived in the form of linear matrix inequalities to ensure the finite-time stability of the addressed neutral systems. Finally, two numerical examples with simulation results are given to illustrate the effectiveness of the proposed method.

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## 1. Introduction

Faults, especially actuator faults are frequently encountered in many practical systems and often lead to poor performance and even instability of the system dynamics [1–5]. Therefore, it is necessary and important to design a fault-tolerant controller against the actuator faults. In the past decade, many valuable results on fault-tolerant control for control systems have been reported (see for instance [6–10] and the references therein). Wang and Dong [7] obtained an estimator-based fault-tolerant control design for a class of linear quantum stochastic systems subject to fault signals. Chen et al. [8] designed an adaptive fault-tolerant control scheme based on disturbance observers and radial basis function neural networks for the three degrees of freedom helicopter model subject to system uncertainties, unknown external disturbances and actuator faults. However, in most of the existing works, the controller has only linear term, which causes a deviation from most of the physical systems where nonlinear features are commonly found. Taking these facts into consideration, in this paper, a more general actuator fault model will be considered in the controller design.

It should be noted that time delay is an unavoidable factor in dynamical systems. Thus, the consideration of time delay in stability analysis of dynamical systems is more significant [11]. Moreover, in practical systems, the maximum control input is generally bounded due to the existence of physical and technological constraints which leads to the actuator saturation phenomenon [12–15]. It should be pointed out that if these factors are avoided in the controller design, it may give poor

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performance and even leads to instabilities. Since the actuator saturation has great influence on performance of control systems, it would be more practical to consider actuator saturation in neutral systems. In particular, the actuator saturation has to be taken into account during stability analysis and controller design [16–18].

Neutral dynamical control systems are often encountered in various fields of science and engineering, such as population ecology, distributed networks containing lossless transmission lines, heat exchange and steam processes, infeed grinding and continuous induction heating of a thin moving body [19,20]. More specifically, neutral systems are systems whose dynamics not only dependent on the delay of present and past states, but also on the derivatives of the states with delays [21–23]. Neutral delay systems constitute a more general class than those of the retarded type and the stability of neutral systems is a more complex issue because of the existence of derivative of the delayed state. Many important results have been reported to deal with stability analysis and controller design of neutral control systems [24–28]. It should be mentioned that most of the stability and stabilization conditions reported on neutral control systems are defined over an infinite interval. Usually for practical applications asymptotic stability is sufficient, but there are instances where large values of the state are not suitable, for instance when saturation exists. Based on this viewpoint, finite-time stabilization becomes an important research topic [29–31]. Recently, the problem of finite-time control for dynamical control systems has received much attention due to its practical applications in many areas, such as missile systems, chemical process, manufacturing systems, power systems, active and parametric networks, where the main concern is the quantitative behavior of the system state variables over a fixed finite-time interval [32–35]. A number of interesting works has been reported on finite-time boundedness, stability and filtering of various dynamical systems (see [36–39]).

To the best of our knowledge, no work has been reported on the finite-time stabilization for neutral-type control systems with actuator saturation and time-varying delays via fault-tolerant control with nonlinear actuator faults which motivates this study. Thus, in this paper, we utilize the nonlinear fault-tolerant control to study the problem of finite-time stability of neutral dynamical systems. Due to great potential applications of neutral type systems in different practical domains, the significance of this work is that it characterizes finite-time stability of the system, where the control issues, namely, actuator saturation and actuator faults are dealt simultaneously. The main contributions of this paper are summarized as follows:

(i) This is the first attempt to resolve the problem of finite-time stabilization for a class of neutral systems with actuator saturations via fault-tolerant controller with nonlinear actuator faults.
(ii) A new design method of nonlinear fault-tolerant feedback controller is proposed to achieve the finite-time stability for neutral systems with actuator saturations.
(iii) By constructing a proper Lyapunov functional and using Jensen's integral inequality, sufficient conditions are derived in the form of linear matrix inequalities (LMIs) to obtain the required result.

The remaining part of the paper is organized as follows: Section 2 describes the problem formulation and some relevant preliminary results. In Section 3, the main results are given which include finite-time stabilization criteria and control design for the formulated neutral control system. Numerical examples are given in Section 4 followed with conclusion in Section 5.

**Notations:** The superscripts $T$ and $(-1)$ stand for matrix transposition and matrix inverse, respectively; $\mathcal{R}^{n\times n}$ denotes the $n\times n$-dimensional Euclidean space; $P>0$ means that $P$ is real, symmetric and positive definite; $I$ and 0 denote the identity and zero matrices with compatible dimensions, respectively. $\lambda_{max}(A)$ and $\lambda_{min}(A)$, respectively, denote the maximal and minimal eigenvalues of a real matrix $A$; $sym(X)$ represents the term $X+X^T$. We use an asterisk $(*)$ to represent a term that is induced by symmetry. Matrices which are not explicitly stated are assumed to be compatible for matrix multiplications.

## 2. Problem formulation and preliminaries

Consider a neutral time-delay system with saturation in control input in the following form:

$$\begin{aligned} &\dot{x}(t) - C\dot{x}(t-h(t)) = Ax(t) + A_d x(t-h(t)) + Bsat(u^F(t)), \\ &x(t) = \phi(t), \forall t \in [-h, 0], \end{aligned} \tag{1}$$

where $x(t)\in\mathcal{R}^n$ represents the state vector, $u^F(t)\in\mathcal{R}^m$ denotes the control input, $A$, $A_d$, $B$ and $C$ are known real constant matrices with appropriate dimensions. $h(t)$ is a time-varying function that satisfies $0\le h(t)\le h$ and $\dot{h}(t)\le\mu<1$, where $h$ and $\mu$ are constants. Further, $sat:\mathcal{R}^m\to\mathcal{R}^m$ is the saturation function defined by $sat(u^F(t))=[sat(u_1^F(t))\ sat(u_2^F(t))\ \cdots\ sat(u_m^F(t))]^T$, where $sat(u_j^F(t))=sign(u_j^F(t))min\{1,|u_j^F(t)|\},\ j=1,2,\ldots,m$. Now, we consider a reliable controller which contains both linear and nonlinear terms in the form

$$u^F(t) = Gu(t) + f(u(t)), \tag{2}$$

where $G$ is the actuator fault matrix, $u(t)=Kx(t)$ in which $K$ is the control gain matrix and the function $f(\cdot)$ represents the nonlinear characteristic of actuators which inevitably occurs in many number of practical systems. The actuator fault matrix $G$ is defined as $G=\text{diag}\{g_1,g_2,\ldots,g_m\},\ 0\le\underline{g}_j\le g_j\le\overline{g}_j\le1,\ j=1,2,\ldots,m,$ where $g_j=0$ means that $j$th actuator completely fails, $g_j=1$ means that $j$th actuator is normal. Define $\overline{G}=\text{diag}\{\overline{g}_1,\overline{g}_2,\ldots,\overline{g}_m\}$, $\underline{G}=\text{diag}\{\underline{g}_1,\underline{g}_2,\ldots,\underline{g}_m\}$, $G_0=\frac{\overline{G}+\underline{G}}{2}$ and $G_1=\frac{\overline{G}-\underline{G}}{2}$. Then, the matrix $G$ can be written as

$$G = G_0 + G_1\Sigma, \tag{3}$$

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