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Research article

A new online delay estimation-based robust adaptive stabilizer for multi-input neutral systems with unknown actuator nonlinearities

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ABSTRACT

This paper studies the problem of actuator-nonlinearities compensation in the multi-input uncertain neutral systems. The neutral systems with different unknown time-varying delays, unmodeled dynamics, nonlinear perturbations and disturbances are considered. A new methodology based on the online estimation of the delays to compensate for the effects generated by dead-zone and saturation, acting in series on a system's input are presented. The online estimations of the unknown delays are accomplished by adaptive laws that guarantee the exponential stabilities of the estimated delays. In the presence of state time delay, derivative state time delay, unmodeled dynamics, nonlinear perturbations, disturbances and both input dead-zone and saturation, the asymptotic stability of the closed-loop system is ensured and the state response converge to the origin. Finally, the practicability and the efficacy of the proposed approach is demonstrated via a numerical example.

1. Introduction

Constraints are common in practical applications. These constraints can have damaging influences on the system performance unless accounted for in the controller design process. One of the major constraints that arises while controlling dynamic systems is the non-smooth nonlinearities. Non-smooth nonlinearities occur in many actuators, such as hydraulic servo-valves, piezoelectric translators, electric servomotors, mechanical connections, and other areas. The common actuator nonlinearities include saturation, backlash, hysteresis and dead-zone. They are commonly non-smooth and extremely nonlinear, and are often a source of instability and performance deterioration [1–4].

One of the actuator nonlinearities may cause through saturation. Almost real control systems have saturation nonlinearities in its actuators. The actuator saturation not only worsens the control performance producing large overshoots and large settling times, but also lead to instability since the feedback loop is broken in such situations.

Another most important non-smooth actuator nonlinearity is dead-zone. Dead-zone is a memory-less and nonlinear phenomena which can be seen in actuators such as hydraulic servo valves and electric servomotors which can threaten the system stability and performance [3–5]. Due to delays in both states and its derivatives, the control of neutral systems preceded by dead-zone is a challenging task.

In the literature, a number of examples are given where neglecting the saturation has led to crucial difficulties and threatened the overall stability of the system. In the area of flight control, actuator saturations played a vital role in the YF-22 aircraft crash in April 1992 and Gripen JAS 39 aircraft crash in August 1993 [6,7]. In the field of nuclear power, actuator saturation has also an important role in the 1986 Chernobyl nuclear power plant failure [8,9]. Hence, any active input that is generated online should meet the required control purposes while remaining within certain limits.

Although, the progress of adaptive control techniques for systems with both dead-zone and saturation in the actuator has been grown to be one of major practical interest as well as theoretical significance, the number of existing results dealing with these actuator nonlinearities in the design and analysis of adaptive controllers is still incomplete due to the inconvenience of the problem. Mainly, the considered plants should satisfy certain restrictive conditions. However, there exists some research work dealing with input saturation and/or dead-zone [1–15], and the references therein.

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The difficulty in controlling time-delay systems becomes even greater if the control is forced to be bounded. One kind of time delayed systems is the neutral systems. A neutral time delay phenomena appears in various dynamic systems, such as biological systems, economical systems, nuclear reactor, power systems, metallurgical processing systems, and transmission lines in hydraulic and pneumatic systems [16–18].

On the other hand, unmodeled dynamics and/or nonlinear perturbations and/or external disturbances may have a damaging effect on the performance of practical systems. These stumbling blocks need to be compensated as they can reduce system performance and result in system instability or even catastrophic accidents. In the past two decades, extensive attention has been paid to the research on the stability, robustness, analysis and the control of delay neutral systems, especially on the issue of stability and robustness [16–35].

In almost all the previous studies on the class of neutral system $\dot{x}(t) = A_1x(t) + A_2x(t-\tau(t)) + A_3\dot{x}(t-h(t))$, the more conservative condition $\|A_3\| < 1$ is required [16,18–28,31–33]. In [34,35], this assumption is not required but the two signals $x(t-\tau(t))$ and $\dot{x}(t-h(t))$ are assumed to be available for measurement. By making use of the adaptation process, these two assumption is not required. Using the online estimation of the time varying delays $\tau(t)$ and $h(t)$, we can generate the two signals $x(t-\tau(t))$ and $\dot{x}(t-h(t))$. In comparison to [34,35], there is no need to assume that these two signals are available for measurement. This means we can control or stabilize any neutral system with less conservative conditions.

The above studies motivate the present research, in which an adaptive control for uncertain neutral systems with input saturation and dead-zone is investigated. Based on the online estimation of the delays, an adaptive controller is designed for the neutral time-delay systems tolerant to both saturation and dead-zone that occur in the actuators. The proposed adaptive stabilizer ensures that all the signals of the controlled system are bounded, while the system states converges to the origin.

The contribution of this paper has the following advantages over the earlier ones in the literature such as [16,18–28,31–33];

1) The more conservative condition $\|A_3\| < 1$ is relaxed.
2) By the online estimation of the time varying delays $\tau(t)$ and $h(t)$, the system delayed states $x(t-\tau(t))$ and the delayed derivative states $\dot{x}(t-h(t))$ is not required to be available for measurement.
3) The input saturation is unknown.
4) The unsymmetrical dead-zone is unknown.
5) The system parameters matrices are assumed to be unknown.
6) The unmodeled dynamics, nonlinear perturbations and disturbances are unknown.

The paper is organized as follows. The main problem in this paper is formulated in Section 2. The modeling of the actuator saturation and dead-zone is given in Section 3. The controller design is proposed in Section 4. The main result of this paper is augmented in Section 5. Simulations on controlling neutral systems via adaptive control will be presented in Section 6. Finally, Section 7 concludes this paper.

2. Formulation of the problem

We consider a class of neutral system with different time-varying delays, unmodeled dynamics, disturbances and saturated input with dead-zone nonlinearity given as follows:

$$\begin{aligned} \dot{x}(t) - A_3\dot{x}(t-h(t)) &= (A_1 + \Delta A_1)x(t) + (A_2 + \Delta A_2)x(t-\tau(t)) \\ &\quad + f_1(x) + f_2(x(t-\tau(t))) + dz(\sigma(u(t))) + d(t), \quad t \geq 0 \\ x(t) &= \phi(t), \quad t \in [-H, 0] \end{aligned} \tag{1}$$

where $x(t) \in \Re^n$ are the system states, $A_1, A_2, A_3 \in \Re^{n\times n}$ are unknown constant system matrices, $u(t) \in \Re^n$ is the controller output to be designed, $dz(\sigma(u(t)))$ denotes the actuator output with dead-zone and saturation type nonlinearities, $H \in \max\{\tau(t), h(t)\}$. The time delays $\tau(t)$ and $h(t)$ are time varying and unknown, satisfying $\dot{\tau}(t) \leq \eta_\tau < 1$, $\dot{h}(t) \leq \eta_h < 1$ for some known constants η_τ and $\eta_h > 0$. ΔA_i are unknown unmodeled dynamics, $i = 1, 2$, and $d(t) \in \Re^n$ is a bounded disturbance vector with unknown bound; $\|d(t)\| \leq d^*$. $f_i(x)$ are unknown nonlinear function vectors with $f_i(0) = 0$, $i = 1, 2$.

***Assumption* 1:** We assume that there always exist unknown positive scalars L_i^*, $i = 1, 2$ satisfying the following inequality

$$\|f_1(x)\| \leq L_1^*\|x\|$$
$$\|f_2(x(t-\tau))\| \leq L_2^*\|x(t-\tau)\|$$

***Assumption* 2:** The parameter uncertainties of the uncertain neutral system (1) are assumed to be of the form $\Delta A_i = D_iG_i(t)$, $i = 1, 2$, where $D_i \in \Re^{n\times n}$ are constant matrices which denote the system structure uncertainty and satisfying, $\|D_i\| \leq \mu_i^*$, where μ_i^* are positive constants with unknown values. $G_i(t)$ are unknown, real and possibly time-varying matrices satisfying, $\|G_i(t)\| \leq 1$, $\forall t$.

The objective is to generate a bounded controller $u(t)$ such that the plant input $dz(\sigma(u(t)))$ guarantees that all signals in the system remain bounded, and $x(t)$ goes to zero asymptotically.

3. Modeling of actuator nonlinearities

In this section, a model of the actuator nonlinearities is proposed.

3.1. Modeling of the actuator saturation

The saturation function $\sigma(u(t))$, generated by the actuators limited magnitude, is represented as; see Fig. 1.

$$\sigma(u(t)) = sat(u(t)) = \begin{cases} u_{\max} & u(t) \geq u_{\max} \\ u(t) & -u_{\min} < u(t) < u_{\max} \\ -u_{\min} & u(t) \leq -u_{\min} \end{cases} \tag{2}$$

where u_{max} and u_{min} are unknown positive constants defined as maximum and minimum plant actuator saturation amplitudes, respectively.

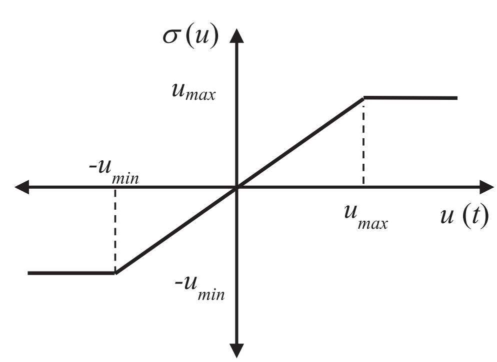

Fig. 1. Saturation function.