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Stabilization for networked control systems subject to actuator saturation and network-induced delays

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ABSTRACT

In this paper, stabilization is presented for a networked control system with actuator saturation and network-induced delays. A method is exploited at updating steps of control signal rather than sampling steps in the networked control system under actuator saturation. A network-based controller is designed under the limitation of actuator saturation. With a cone complementary linearization approach, a presented scheme is also used to estimate the domain of attraction for the networked control system. A numerical simulation is provided to show the effectiveness and correctness of the method in this paper.

1. Introduction

In recent years, actuator saturation has been discussed for control systems in large quantities of literatures [1,2]. Owing to input limitations, physical actuators are subject to input saturation in control systems [3]. Note that actuator saturation readily leads to plant's starting with less energy, which can cause systems to be unstable [4]. In order to avoid getting worsen and even lost of stability for a system, actuator saturation has to be considered in the process of designing the close-loop system [5]. To deal with actuator saturation, some measures for estimating the domain of admissible initial states for control systems have been investigated in monograph [6]. In [7], a method based on linear matrix inequalities is derived to estimate the domain of attraction for a saturated linear feedback system. Note that network-induced delays are main problems in NCSs [8–10]. Output feedback delay compensation control has been investigated for NCSs with random delays [11]. Fuzzy delay compensation control has also been considered for T–S fuzzy systems over networks in [12]. Considering time-varying delays in control systems with actuator saturation, an advanced and less conservative delay-range-dependent method is presented in [13]. With nested actuator saturation, discrete-time linear systems are discussed in terms of stability conditions and the estimate of the domain of attraction in [14]. Recently, an auxiliary time-delay feedback technique is introduced to cope with stabilization of neutral time-delay systems with actuator saturation [15]. Furthermore, actuator saturation also appears in NCSs, which is very interesting for stability of NCSs with actuator saturation and remains challenging up to the present.

There are considerable benefits and advantages for NCSs than traditional point-to-point control systems, such as cost-saving [16], resource-sharing [17], flexibility-improving [18]. With introduction of networks, issues and challenges emerge in forms of time delays [19–21], data-packet losses [22,23], communication noise [24,25], bandwidth scheduling and signal quantization [26–28]. Note that time delays and data-packet losses are the two most important ones, and many attentions have been devoted to solve them in both continuous-time systems [29,30] and discrete-time systems [31–34], for several years. Mainly for discrete-time systems, two kinds of methods on time delays appear in related works. The one kind is a deterministic bound method which places bounds on delay-time and lost-data-packets [35,36]. The other one is a stochastic method in which network-induced delays are modeled as certain probability distributions [37–40]. Stabilization analysis of NCSs with time delays and data-packet losses is presented in [41]. In [41], a method guarantees debasement of Lyapunov functions at each control signal updating step, which is less conservative then traditional methods which guarantee the debasement of Lyapunov

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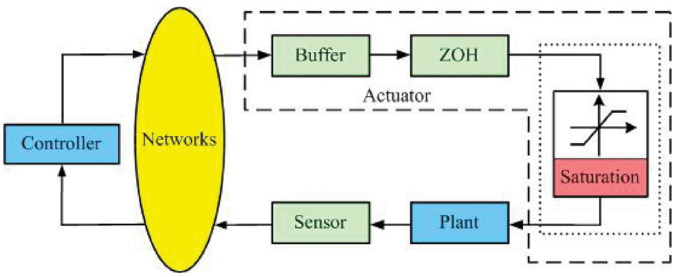

Fig. 1. Networked control system with actuator saturation.

functions at sampling steps. Actuator saturation has not been fully investigated for NCSs in [41], the main goal of this work is to fill this gap, i.e., to extend the results in NCSs subject to actuator saturation.

Considering actuator saturation in a NCS with network-induced delays, the domain of attraction is estimated in this paper. By guaranteeing debasement of Lyapunov functions at each control signal updating step, an improved stability criterion is derived for the NCS with actuator saturation. Thereby, a corresponding stabilization controller design technique is proposed for the NCS subject to actuator saturation. A cone complementary linearization (CCL) approach is utilized to cope with nonlinear matrix equalities, and the domain of attraction for NCSs is also obtained subsequently. The effectiveness and merit of the proposed method are demonstrated by a numerical example. Specifically, main contributions of this paper are summarized as follows:

(i) Stabilization conditions of NCSs subject to actuator saturation and time delays are proposed by fully analysis in this paper.
(ii) A less conservative method is exploited to analyze the problems on NCSs under actuator saturation at updating steps of control signal.
(iii) An effective scheme is used to estimate the domain of attraction for NCSs with a cone complementary linearization approach.

Notation: Notations appeared in this paper are normally standard. In the sequel, if not explicitly stated, matrices are assumed to have compatible dimensions. $\mathbf{I}[i, j]$ represents the integer set $\{i,\ i+1,\ \ldots,\ j\}$, and $\mathbf{Z}^+$ is defined as a positive integer set. $\mathbf{R}^n$ (or $\mathbf{R}^m$) denotes n (or m) dimensional Euclidean space. Notation $X > Y (X \geq Y)$ means that matrix $X - Y$ is positive definite ($X - Y$ is semi-positive definite). For any matrix A, A^T and A^{-1} mean the transpose of matrix A and the inverse of matrix A, respectively. $diag\{M_1\ M_2\ \ldots\ M_r\}$ is the shorthand of a block diagonal matrix with diagonal blocks being the matrices $M_1,\ M_2,\ \ldots,\ M_r$. $*$ is used as an ellipsis of symmetric block matrices.

2. Problem formulation

In this paper, the plant of NCSs is described as the following discrete-time system:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k), & k > 0, \\ u(k) = Fx(k), \end{cases} \tag{1}$$

where A, B and F are system matrices with compatible dimensions, $x(k) \in \mathbf{R}^n$ represents the state vector, $u(k) \in \mathbf{R}^m$ denotes the control input. The structure of NCSs with actuator saturation is shown in Fig. 1.

The dash line area represents actuator, and it consists of a buffer, a zero order holder (ZOH) and a saturation function. In order to analyze the actuator with saturation function conveniently, a function "sat" is appeared with appropriate dimensions in our subsequent deduction. Thereby, the function "sat" is defined as follows:

$$sat(u) = \left[sat(u_1), sat(u_2), \ldots, sat(u_m) \right]^T,$$

where

$$sat(u_i) = sgn(u_i) \min\{1, |u_i|\}.$$

Considering both actuator saturation and network-induced delays in the NCS framework, system (1) is established as follows:

$$\begin{cases} x(k+1) = Ax(k) + Bsat(u(k-\tau_k)), & k > 0, \\ x(s) = \varphi(s), & s \in [-\tau_2, 0], \end{cases} \tag{2}$$

where $x(k) \in \mathbf{R}^n$ is the state vector, $u(k-\tau_k) \in \mathbf{R}^m$ is the control input with time-varying delay τ_k, A and B are constant matrices, $\varphi(s)$ is the initial state in $[-\tau_2, 0]$. Note that τ_k in system (2) is a time-varying input delay in NCSs. The following two assumptions are given as

$$\tau_1 \leq \tau_k \leq \tau_2, \ \ \tau_{k+1} - \tau_k \leq \mu, \tag{3}$$

where τ_1 and τ_2 are the lower and upper bounds for τ_k, respectively, and μ is the delay variation rate.

If a new control signal arrives at the ZOH at time step k, then the time step k is called an updating step, and a holding step is defined as that the control signal does not reach correspondingly. When data packets are lost or in wrong orders, the ZOH used in NCSs chooses the newest available control signal in terms of controlling the plant. If a time step $k+1$ is a holding step, then the last control signal will be applied into systems, and equality $\tau_{k+1} = \tau_k + 1$ holds in this situation. Correspondingly, if a time step $k+1$ is an updating step, a new control signal time stamp $k+1-\tau_{k+1}$ must be newer than the last one $k - \tau_k$. Thereby, inequality $k+1-\tau_{k+1} \geq k - \tau_k + 1$ is achieved, i.e., $\tau_{k+1} \leq \tau_k$ holds. Moreover, two propositions are described in the following.

Proposition 1. *For time-varying delay τ_k, the following property is given as*

$$\begin{cases} \tau_{k+1} \leq \tau_k, & k+1 \text{ is an updating step}, \\ \tau_{k+1} = \tau_k + 1, & k+1 \text{ is a holding step}. \end{cases}$$

Note that let $\mathcal{K} := \{k_1, k_2, \ldots\}$ ($\mathcal{K} \subset \mathbf{Z}^+$) denote a time-index sequence of updating steps, and $\delta_{k_s} \triangleq k_{s+1} - k_s$ denotes the holding step number until time step k_s.

Proposition 2. *Variable δ_{k_s} complies to the following limitation:*

$$0 \leq \delta_{k_s} \leq \hat{\delta} \triangleq \max_{k_s \in \mathcal{K}} (\delta_{k_s}),$$

which implies that one step is updating step for every $\hat{\delta}$ time steps at least. Note that $\hat{\delta}$ makes a reflection on comprehensive effect of the time-varying delays, maximum consecutive packet losses and packet in-wrong-order.

The following networked controller is taken as

$$u(k-\tau_k) = Fx(k-\tau_k). \tag{4}$$

Then system (2) is rewritten as follows:

$$x(k+1) = Ax(k) + Bsat(Fx(k-\tau_k)), \tag{5}$$

where $F \in \mathbf{R}^{m \times n}$ is the feedback gain. Let f_i denote the ith row of F, and

$$\mathcal{L}(F) := \left\{ x \in \mathbf{R}^n : |f_i x| \leq 1, i = 1, 2, \ldots, m \right\}, \tag{6}$$

where $\mathcal{L}(F)$ is the region in which the state of system (5) abides by linear variation, i.e., the linear region of saturation, as F is the feedback matrix.

The following definition on the domain of attraction is shown.