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Nonlinear time-delay anti-windup compensator synthesis for nonlinear time-delay systems: A delay-range-dependent approach

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ABSTRACT

This paper addresses the novel architectures' formulation and linear matrix inequality (LMI)-based design of dynamic nonlinear anti-windup compensator (AWC) for nonlinear time-delay systems with continuous interval time-varying delays under input saturation. An internal model control (IMC)-based AWC architecture is suggested for stable nonlinear time-delay systems and, in addition, a decoupling AWC architecture, applicable to a broader class of nonlinear time-delay systems, is proposed for compensation of the undesirable saturation effects. Further, a correspondent decoupled architecture is derived and recommended for characterizing the delayed nonlinear AWC synthesis goals. By employing Lyapunov–Krasovskii functional, local sector condition, Lipschitz condition, L_2 gain minimization, and the delay-interval information, several sufficient conditions are derived for the design of nonlinear time-delay AWC. Numerical examples for FitzHugh–Nagumo neuron and Hopfield neural network under input saturation and time-delay are presented to reveal effectiveness of the proposed anti-windup approach.

1. Introduction

Almost all physical systems are characteristically nonlinear; and linear model approximation of a nonlinear system is erroneous and unrealistic while a control system is operating over a large rang of operation. Time-delays occur in many physical systems such as industrial plants, robots, multi-faceted network control systems, power plants, communication modules, pneumatic structures, and biological and chemical processes. Delay in a system has counteracting effects on the closed-loop stability and performance; therefore, careful attention in synthesizing compensators or controllers is required when dealing with the time-delay systems. Study on time-delay systems for achieving desired closed-loop performance objectives, in addition to the stability requirement, is an interesting research area that acquired a lot of attention by researches during the last decade [1–3]. More or less in all practical control systems, an actuator cannot transport unlimited energy signal causing input saturation, which not only induces lags, performance degradation, overshoots, undershoots, oscillations, spurious limit cycles, divergence and instability but also stimulates pernicious and malicious behaviors, leading to economic losses and fatalities. Many accidents have been occurred due to the peculiar effects of saturation. Crashes of aircrafts JAS Gripen [4] and YF-22 craft [5] and meltdown of Chernobyl power plant [6] are worst examples of the saturation consequences.

Time-delay along with the input saturation constraint has more objectionable influence on performance and stability of a system [7–10]. The contemporary high speed, high accuracy and high performance technologies in aircrafts, space crafts, robots and satellites demand control systems to fulfill stringent and rigorous design performance specifications; consequently, significant attention has been dedicated to the anti-windup compensator (AWC) synthesis (see [7,10–12]). AWC-based control for systems under actuator saturation is performed into two steps (called two-step approach). A feedback controller by ignoring the saturation constraint is designed in the first step and then an AWC is augmented to compensate the undesirable saturation outcomes (see, for example, [11,13–15] etc.). There is a gigantic work on the analysis and synthesis of anti-windup for stable or unstable linear systems available in the literature [12,15–17] and, likewise, observer-based AWC formulations are addressed in [15,16,18]. Tarbouriech et al. in [19] viewed AWC design through determining and enlarging region of stability for linear systems under input delays using LMI-based delay-dependent tactics. In [20], an observer-based dynamic AWC design schema is developed for stable linear time-invariant systems by taking difference between the controller states in absence and presence of input saturation as an index of performance, and a Laplace transform oriented methodology is applied to minimize the performance index. LMI-based sufficient condition for robust AWC design is derived for Takagi-Sugeno fuzzy delayed systems with norm bounded

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uncertain parameters [7]. In a recent work [21], anti-windup synthesis problem is addressed for linear systems with delayed states, and LMI-based sufficient condition is provided to guarantee a region of stability. The previous works like [7,21] developed methods by reckoning delay-independent and delay-dependent perspectives, which are conservative for stability analysis.

It is worth noting that few exceptional works, like [11,13,22], focused on the anti-windup design of nonlinear systems. In the recent work [11], sufficient conditions are derived for designing global and local decoupling AWC for stable and unstable nonlinear systems using L_2 gain reduction of the uncertain nonlinear decoupled component by means of LMI-based optimization routines. A dynamic anti-windup scheme is developed in [13], for feedback linearizable nonlinear systems, based on minimization of the error between controller state variables with and without saturating actuators. One-step control approaches to design controller and static AWC simultaneously have been studied in [22–24] for Lipschitz and fuzzy time-delay systems. The aforementioned studies considered anti-windup synthesis either for linear systems with or without delays or for delay-free nonlinear plants. The AWC formulation for nonlinear time-delay systems with input saturation constraint is a challenging, non-trivial and unreciprocated research problem owing to fourfold difficulty of time-delays, input saturation nonlinearity, delayed and delay-free dynamical nonlinearities, and AWC incorporation into existing output feedback control system. The work on AWC design for nonlinear systems is lacking; nonetheless, the AWC synthesis approaches for the nonlinear time-delay systems are deficient to an inadequate level. To the best of authors' awareness, the dynamic nonlinear delayed full-order anti-windup compensator design for the nonlinear time-delay systems with continuous interval time-varying state delays has not been explored hitherto owing to the in-built perplexing of the nonlinear time-delay systems combined with the saturation constraint.

Motivated by AWC synthesis schemes [11,23,25], sector conditions [11,23,26], and linear delay-range-dependent stability investigation and control approaches [2,3,8,27,28], this study is devoted to the design of AWC for nonlinear time-delay systems under input saturation constraint using delay-range-dependent approach. Dynamic nonlinear delayed IMC-based AWC, decoupling AWC and equivalent decoupled AWC architectures are proposed for nonlinear time-delay systems. Further, for global and local decoupled architecture based AWC synthesis, LMI-based sufficient conditions are developed by employing Lyapunov–Krasovskii (LK) functional, local sector condition, Lipschitz continuity, L_2 gain minimization, Leibniz–Newton formula, and LMI-tools. The proposed local AWC design ensures local asymptotic convergence with a guaranteed enlargeable region of stability for all initial conditions selected from a given bounded region. Moreover, a novel delay-range-dependent AWC strategy for the linear time-delay systems and a delay-dependent AWC scheme for the nonlinear time-delay systems are deduced as specific cases of the recommended delay-range-dependent methodology. The main contribution of the paper is summarized below:

(1) Existence of a dynamic IMC-based AWC for the stable nonlinear time-delay systems is demonstrated.
(2) A novel nonlinear decoupling AWC architecture for the nonlinear time-delay systems, which is more general than the IMC-based AWC, is provided by exploiting the non-delayed and the delayed compensations.
(3) To the best of the authors' knowledge, a delay-range-dependent dynamic AWC design approach for the nonlinear time-delay systems with state delays is derived for the first time.
(4) The proposed delay-range-dependent AWC synthesis condition is based on simple LMIs that can be easily resolved for computation of the two gains for the non-delayed and the delayed compensations.

The effectiveness of the proposed method is verified for control of FitzHugh–Nagumo neuron and Hopfield neural network.

The paper is organized as follows: Section 2 provides the nonlinear time-delay system's description. Full-order AWC architectures are addressed in Section 3. Section 4 derives LMI conditions for the various types of AWC designs. Simulation results and concluding remarks are presented in Sections 5 and 6, respectively.

In this study, standard notation is used. The ith row of a matrix G is represented by $G_{(i)}$. I signifies the identity matrix and diag $\{x_1, x_2, \ldots x_n\}$ symbolizes the block diagonal matrix of suitable dimensions. $\|.\|$ represents Euclidian norm and $\|.\|_2$ signifies L_2 norm. The maximum eigenvalue of Q is denoted by $\lambda_{max}(Q)$. The symbol $*$ designates the transposed element in a symmetric matrix. $X>0$ (or $X\geq 0$) means that $X$is a positive-definite (or a semi positive-definite) matrix.

2. System description

Consider a class of nonlinear time-delay systems under input saturation, with continuous time-varying delays, given by

$$\frac{dx_p(t)}{dt} = Ax_p(t) + A_d x_p(t-\tau) + f(x_p(t)) + g(x_p(t-\tau)) + B\mathcal{N}_{sat}(u(t)),$$
$$y_p(t) = Cx_p(t) + D\mathcal{N}_{sat}(u(t)),$$
$$x_p(t) = \theta(t), \quad t \in [-\tau_2 \quad 0], \tag{1}$$

where $x_p(t)\in\Re^n$ is the plant state, $u(t)\in\Re^m$ represents the control input, and $y_p(t)\in\Re^p$ denotes the output vectors. τ indicate time-delay in the state vector. The input signal to the nonlinear time-delay system (1) is subjected to the saturation nonlinearity defined as $\mathcal{N}_{sat}(u(t)) = [\mathcal{N}_{sat1}(u_1(t)), \mathcal{N}_{sat2}(u_2(t)), \ldots, \mathcal{N}_{satm}(u_m(t))]^T$, where $\mathcal{N}_{sati}(u_i(t)) = \text{sign}(u_i(t)) \times \min\{|u_i(t)|, \overline{v}_{(i)}(t)\}, \overline{v}_{(i)}(t) > 0, \forall i \in \{1, \ldots, m\}$ and $\overline{v}_{(i)}$ is the i'th saturation limit. Matrices $A\in\Re^{n\times n}$, $A_d\in\Re^{n\times n}$, $B\in\Re^{n\times m}$, $C\in\Re^{p\times n}$ and $D\in\Re^{p\times m}$ are the real constant matrices of appropriate dimensions. The vector functions $f(x(t))\in\Re^n$ and $g(x(t-\tau))\in\Re^n$ denote nonlinear and nonlinear time-delay dynamics, respectively. The continuous-time vector function $\theta(t)$ is employed for representing the initial condition for $t\in[-\tau_2 \quad 0]$. The time-varying delay function $\tau(t)$ satisfies the bounds

$$0 \leq \tau_1 \leq \tau(t) \leq \tau_2, \tag{2}$$

$$\dot{\tau}(t) \leq d, \tag{3}$$

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

The nominal open-loop nonlinear time-delay plant under normal operating conditions without input saturation is represented as

$$\frac{dx_n(t)}{dt} = Ax_n(t) + A_d x_n(t-\tau) + f(x_n(t)) + g(x_n(t-\tau)) + Bu_n(t),$$
$$y_n(t) = Cx_n(t) + Du_n(t),$$
$$x_n(t) = \theta(t), \quad t \in [-\tau_2 \quad 0], \tag{4}$$

where $x_n(t)\in\Re^n$, $u_n(t)\in\Re^m$, and $y_n(t)\in\Re^p$ denote the state, the control input, and the measured output vectors of the nominal nonlinear time-delay system, respectively. Consider an output feedback tracking controller for the nominal open-loop plant (1), to achieve the desired nominal closed-loop performance characteristics, given by

$$\frac{dx_c(t)}{dt} = f_c(x_c, y_n, r, t),$$