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A new method for control of nonlinear networked systems

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ABSTRACT

Networked control of a class of nonlinear systems is considered. For this purpose, the previously proposed variable selective control (VSC) methodology is extended to the nonlinear systems. This extension is based upon the decomposition of the nonlinear system to a set fuzzy-blended locally linearized subsystems, and further application of the VSC methodology to each subsystem. Using the idea of parallel distributed compensation (PDC) method, the closed-loop stability of the overall networked system is guaranteed, using new linear matrix inequalities (*LMIs*). For the real-time implementation, real-time control signals are constructed for every entry of pre-specified vector of time delays, which is selected based on the presumed upper-bound of the network time delay. Similar to the traditional packet-base control methodology, such control signals are then packed as a control-side packet and transmitted back to a time delay compensator (*TDC*) located on the plant-side of the network. According to the most recent network time delay, the *TDC* selects just one entry of the control vector and applies it to the actuator through a zero order hold element. A sufficient condition for closed-loop asymptotic stability is determined. Simulation studies on nonlinear benchmark problems demonstrate the effectiveness of the proposed method.

1. Introduction

Due to the expansion of physical setups, the traditional point-to-point communication architecture of control systems in which the sensors, actuators and controllers communicate through wires is no longer able to meet new requirements, such as less modularity and integrated diagnostics, quicker and easier maintenance, and lower cost. On the other hand, recently, network technologies have dramatically been developed with the special properties of reduced wiring and increased flexibility. Therefore, network technologies have been more and more applied to control systems [1–4], which are usually referred as networked control systems (*NCSs*) or particularly, Internet-based control systems. In this way, the geographically separated sensors, actuators and controllers are interconnected into closed-loop systems through wired or wireless communication channels, e.g., the Internet. These permit an economic, and flexible, remote monitoring and adjustment of plants over the Internet, which provide the benefit of reacting to plant fluctuations from anywhere around the world at any time. Moreover, NCSs are implemented in a broad range of systems, such as tele-manufacturing, tele-surgery, automated traffic control, space exploration, disaster rescue, health care, museum guidance, and military systems [5,6].

However, due to the complex working conditions and limited bandwidth, the insertion of a communication network into a closed-loop control system has also given rise to some interesting and challenging problems such as Network-induced, random, time delay, packet loss, and packet-disordering; that is out-of-order arrival of packets at the destination. As a result, direct usage of many traditional control methodologies to NCSs may lead to performance degradation and/or instability. How to compensate the negative effects of these factors on the control performance and stability of an NCS has therefore received remarkable attentions in the recent years. In this way, most of the researches have been concentrated on the linear NCSs, for example in [7,8]. For this purpose, Rahmani and Markazi proposed a *variable selective control* (*VSC*) strategy by combining the variable sampling period and packet based control methods [9,2]. This method could guarantee the closed-loop stability, even for the large network delay and/or packet loss rate.

All aforementioned researches have been extended for the linear plants, but, most physical systems are difficult to be modeled linearly. Therefore, nonlinear networked control systems have been an ever hot research issue over the past few years. On one hand, some previous methods were developed based on the nonlinear control theories. Ma et al. [10] designed a state feedback

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controller, using the discrete-time (*DT*) sliding mode concept and guaranteed the robustly exponential stability of the closed-loop system. Mirkin et al. [11] proposed the sliding mode coordinated decentralized model reference problem for multi-agent systems with communication delays. Wouw et al. [5] proposed a prescriptive framework for designing the stabilizing controllers based on approximate DT models for nonlinear NCSs. Guan [12] studied the adaptive output feedback control methodology for uncertain, nonlinear, time-delayed systems. Yoo [13] proposed an adaptive output-feedback control approach using the observer dynamic surface design technique for uncertain nonlinear time-delayed systems.

On the other hand, in order to implement the previously developed linear multi-variable system theories, some researchers used Takagi–Sugeno (*T–S*) fuzzy technique. T–S fuzzy models have been proven to be universal function approximators in the sense that they are able to approximate any smooth nonlinear functions to any degree of accuracy in any convex compact set [14]. The appeal of T–S fuzzy models is therefore creating the ability to combine the flexible fuzzy logic theory and good linear multi-variable theories into a unified framework. A number of important issues have been studied for fuzzy control of nonlinear NCSs based on T–S models [15,16]. The common drawback of most of the prescribed studies is that they cannot guarantee the closed-loop stability, unless the network delay and/or packet loss rate is small.

Motivated by the aforementioned issues, in the present paper, a *Nonlinear variable selective control* (*NVSC*) strategy is proposed by combining the variable selective control and fuzzy T–S methods. In order to deal with the network delay and packet loss, NVSC includes two parts: off-line control design and on-line control implementation. In the former, T–S fuzzy model is used to model the nonlinear system as a set of linear subsystems. Secondly, associated with a range of pre-specified time delays, appropriate discrete-time models is calculated for each subsystem. Using linear matrix inequalities (*LMIs*) and for all of the calculated subsystems, some stabilizing state feedback gains are then designed. In the on-line procedure, event-driven sensors are implemented to sample the plant output only when the new control input signal is received by the actuator. Based on the parallel distributed compensation (*PDC*) method and by fuzzy blending of the designed gains, appropriate, instantaneous, control signals are constructed for the pre-specified time delays. Similar to the traditional packet-base control methodology, this control signals are then packed in the control-side packet and are transmitted back to the plant side. To cope with the packet loss issue, a simple algorithm is adopted in the controller. In the light of this formulation, the nonlinear NCS can be considered as a mixture of fuzzy and switched linear systems and therefore, the important theoretic results, previously extended to such systems, can be used for stability analysis and controller design of the NVSC. Simulation studies on well-known benchmark problems demonstrate the effectiveness of the proposed method.

The proposed NVSC method has the following advantages: (1) the actual plant input is known to the controller at each time step, therefore, it can cope with relatively large network delays and packet losses; (2) a new controller design methodology is proposed by taking the delay variation into account; (3) sampling period is adapted based on the network condition; (4) the tracking issue is addressed well.

The paper is organized as follows. The current section will end with introducing some notational conventions and concepts. In Section 3.1, problem definition and assumptions are provided. In Section 2.1, the idea of VSC is elaborated. The main idea of the T–S fuzzy modeling and PDC methodologies are described in Section 2.2. The proposed NVSC method is then described in Section 3.2. Sufficient conditions for asymptotic stability of the VSC are derived in Section 3.3 and based on them, a controller design methodology is then proposed. The off-line control design and on-line control implementation procedures are summarized in Section 3.4. The effectiveness of the proposed method is demonstrated through well-known benchmark example in Section 4.

Notations: Throughout the paper, $\mathbb{R}^n$ denotes the n-dimensional Euclidean space. $\mathbb{R}^{m\times n}$ is the set of all $m\times n$ real matrices. $0_{m\times n}$ and $I_{m\times n}$ stand for a $m\times n$ zero matrix and $m\times n$ identity matrix, respectively. The notation $P>0$ means that P is a symmetric and positive definite (PD) matrix. For a matrix P, P^T represents the transpose of P.

2. Preliminaries

2.1. Review of linear VSC method

Consider a typical NCS shown in Fig. 1. Suppose that the physical plant is a *multi-input multi-output* (*MIMO*), linear time-invariant system described by

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t), \\ y(t) = x(t), \end{cases} \tag{1}$$

where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$ are state, input vectors, respectively.

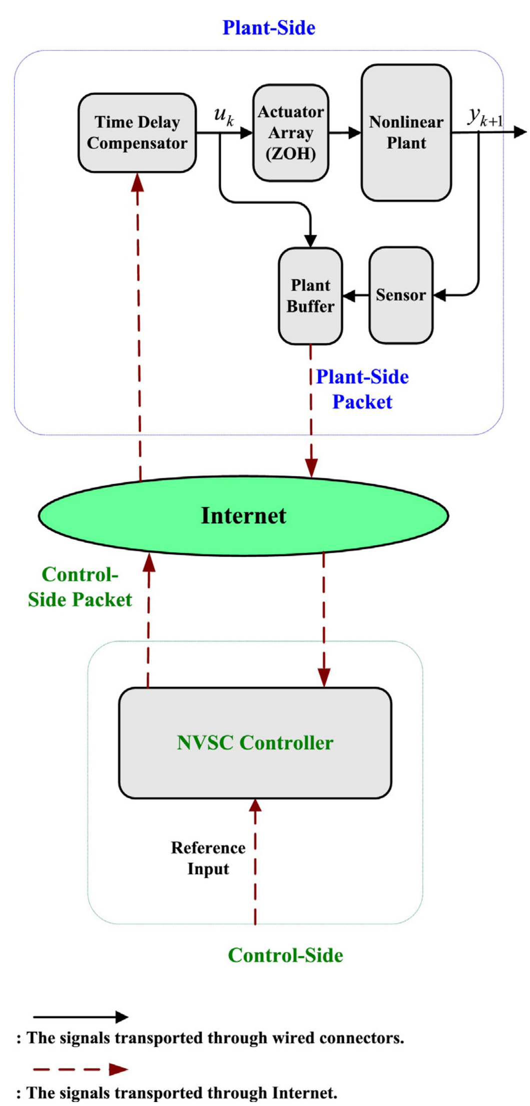

Fig. 1. Nonlinear variable selective control structure.