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Research Article

Global Stabilization of Nonlinear Networked Control System with System Delays and Packet Dropouts via Dynamic Output Feedback Controller

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The stabilization problem is investigated for a class of nonlinear discrete-time networked control systems (NCSs). Nonideal network Quality of Services (QoS) are considered, more specifically data packet dropouts and network-induced delays. A state feedback controller for a class of NCSs is proposed. Subsequently, an observer is designed to estimate the state space. Based on the Lyapunov-Krasovskii functional, sufficient conditions (expressed in terms of LMIs) for the existence of a dynamic output feedback controller are derived. The stabilization is achieved without mathematical transformations or fuzzy logic approximations and without state space augmentation. Finally, illustrative examples are provided to show the effectiveness of the proposed method.

1. Introduction

Control systems in which control loops are closed via some form of communication network are called networked control systems (NCSs) [1].

In the past few decades, increasing attention has been focused on NCSs because of their great advantages over traditional point to point networks, such as simplicity of installation and maintenance, system flexibility, reduction of the necessary budgets for wiring, several benefits of resources sharing, easier expansion, and reliability improvement.

These advantages have given NCSs great practical interest and allowed their wide use in several industrial environments [2], such as unmanned aerial vehicles and automated highway systems [3, 4], networks with mobile sensors [5], haptic collaboration in Internet [6–8], and remote surgical interventions [9], to name a few.

However, the incorporation of communication networks in feedback control loops results in many new emerged problems. Some factors, such as bandwidth constraints, network-induced delays, quantization, and packet dropping effects, may often degrade the performance of a NCS or even cause instability of the feedback control loops. In order to overcome the negative effects of such problems, modeling, stability analysis, safety, security, and control design of NCSs have drawn considerable attention in recent years (e.g., [10–19] and the references therein).

Li et al. derived sufficient conditions for stability based on linear matrix inequality (LMI) in [20], by choosing the proper Lyapunov-Krasovskii functionals and using a descriptor model transformation of the system. By considering all the possibilities of delays, an augmented state space model of the closed-loop system, which characterizes all the delay cases, was obtained in [21].

A control scheme which is constituted by a control prediction generator and a network delay compensator was proposed in [22]. In [23], Xiong and Lam modeled the closed-loop system as new Markovian jump linear system with an extended state space, by considering the time varying state delay and the constant time delay in the mode signal.

A sufficient condition for exponential mean-square stability of the NCSs was obtained in [24], by designing an observer and an augmented model for NCSs, based on Lyapunov stability theory with LMIs techniques.

The problem of the robust memoryless H_∞ controllers for uncertain NCSs with the effects of both networked-induced delay and data dropout was considered in [25]. A class of discrete-time networked nonlinear systems with mixed random delays and packet dropouts was introduced in [26], and the filtering problem was investigated. Sufficient conditions for the existence of an admissible filter were established, which ensured the asymptotical stability as well as a prescribed H_∞ performance.

In [27, 28], the logarithmic quantization scheme was employed in the network-based information communication, and a reset state observer was introduced to suppress sensor quantization effects. The extension of this method to nonlinear NCS with both transmission delays and packet dropouts could be very interesting.

In [29], the output tracking problem for sampled-data nonlinear system was investigated using adaptive neural network (NN) control. Then, considering the dynamics of the overall closed-loop system, a nonlinear model predictive control method was proposed to guarantee the stability of the local nonlinear industrial system and compensate the network-induced delays and packet dropouts. However, the presented results are obtained through mathematical transformations that transform the nonlinear system to a linear one; thus the results are local and not global.

Since it has been proved that any smooth nonlinear system can be approximated by a set of local linear systems using the fuzzy model, increasing attention has been focused on fuzzy controller techniques [30–33]. In [34], a stabilizing controller design based on approximate discrete-time models for nonlinear NCSs was developed.

Most papers in the literature deal only with one of the two major problems in NCSs, packet dropouts or transmission delays, while ignoring the other. The few papers that address this issue concern mainly linear NCSs (in addition to [25, 26]; we may refer the reader to [22, 35, 36]). The fact that relatively few papers discussed the stability analysis and control synthesis of nonlinear discrete-time NCSs in the simultaneous presence of network-induced delays and data packet dropouts is one of the motivations of the present study.

As it can be noticed in the references above, most of the papers that addressed the problem of control design for NCS have mainly focused on two approaches: first, using fuzzy approximations or mathematical transformations to transform the original nonlinear system into a linear system and second, augmenting the state space of NCS with network-induced delays to obtain a system without delay.

Considering the observations above, the key contributions of this paper can be summarized as follows:

(1) The developed method can be considered as an extension of the Jurdjevic-Quinn controller and the passivity theory in nonlinear systems [37, 38] to this class of nonlinear NCS.

(2) We focus on the stabilization of a discrete-time nonlinear NCS dealing simultaneously with both NCS negative effects, namely, packet dropouts and transmission delays.

(3) In order to keep a low computation complexity, the proposed method does not use any mathematical transformations or fuzzy logic approximations, nor does it augment the system state space.

(4) From an appropriate Lyapunov-Krasovskii functional, sufficient conditions that guarantee the convergence of the state variables and state estimation errors to the origin are deduced and expressed in terms of LMIs.

The outline of the paper is as follows: the problem formulation and modeling are presented in Section 2. Section 3 deals with state feedback stabilization. In Section 4, we introduce the observer to estimate the state space. Section 5 is devoted to the dynamic output feedback stabilization. Simulation results are presented in Section 6 and concluding remarks are given in Section 7.

2. Problem Formulation

A NCS structure as considered in the literature is presented in Figure 1.

Consider a discrete nonlinear time-invariant delay system in the following state space form:

$$\begin{aligned} x_{k+1} &= Ax_k + A_d x_{k-h} + g(x_k)\,u_k, \\ y_k &= Cx_k, \end{aligned} \tag{1}$$

where $x_k \in \mathbb{R}^n$, $u_k \in \mathbb{R}^m$, and $y_k \in \mathbb{R}^q$ denote the state, input, and output vectors, respectively, at time instant k. A, A_d, and C_d are constant matrices of appropriate dimensions. $g(x_k)$ is a nonlinear map of appropriate dimension and h is a constant positive number representing the delay. For simplicity of notations, we replace $g(x_k)$ by g_k in the rest of the paper.

The control of a networked control system means that communication will occur through the network from the sensor to the controller and from the controller to the actuator. So delay may occur in both communications: the controller signal (h_1) and the measurement outputs (h_2). Suppose that $h_1 < h$ and $h_2 < h$.

A buffer is added into the acceptance port of the actuator and another one in the acceptance port of the observer so that the output delay and the control delay are changed into a constant delay. Without loss of generality we consider that the value of this constant delay is equal to the state delay h.

The measurement data packet dropouts from the sensors to the controller are modelled as Bernoulli process λ_k with the probability distribution as follows:

$$\begin{aligned} \operatorname{Prob}\{\lambda_k = 1\} &= E\{\lambda_k\} = \lambda, \\ \operatorname{Prob}\{\lambda_k = 0\} &= 1 - E\{\lambda_k\} = 1 - \lambda, \\ \operatorname{Var}\{\lambda_k) &= E\{(\lambda_k - \lambda)^2\} = \lambda(1-\lambda) = \overline{\lambda}, \end{aligned} \tag{2}$$

where $\lambda_k = 1$ means that the packet transmission will be successful, $\lambda_k = 0$ means that the packet will be lost,

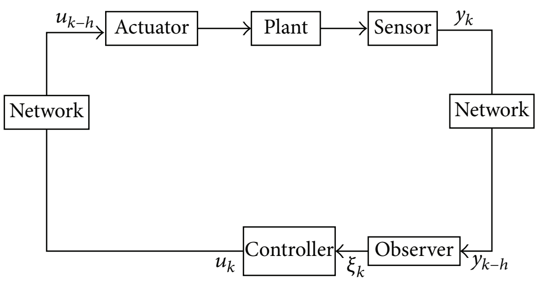

Figure 1: Structure of NCS.

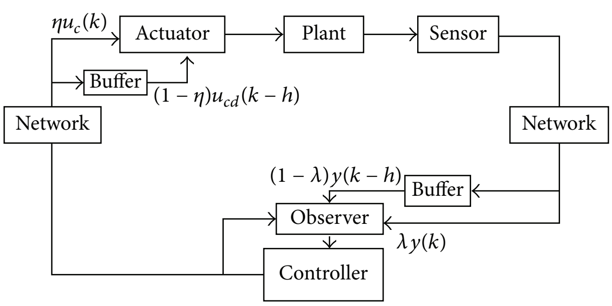

Figure 2: Structure of dynamic output feedback for NCS.

the positive constant $0 < \lambda < 1$ is the probability of successful packet transmission, and $\bar{\lambda}$ is the variance of λ_k.

Since the system states are not measurable, we will use an observer to estimate these states variables through the measured system outputs. If the transmission of system outputs to the observer through the network is successful, then the data $y(k)$ will be used by the observer. Or, if the output data is lost then the most recent delayed data $y(k-h)$ will be used. Thus, the system output can be rewritten

$$y_c(k) = \lambda y(k) + (1-\lambda) y(k-h). \quad (3)$$

Similarly as for the output data, the controller signal can also be delayed or lost through network, and then we have

$$u(k) = u_k(x_k, x_{k-h}) = \eta u_c(x_k) + (1-\eta) u_{cd}(x_{k-h}); \quad (4)$$

$u_c(x_k)$ and $u_{cd}(x_{k-h})$ will be detailed later (in Theorem 1). So, the control data transfer from the controller to the actuator is also modelled as Bernoulli process η_k with the probability distribution as follows:

$$\begin{aligned} \operatorname{Prob}\{\eta_k = 1\} &= E\{\eta_k\} = \eta, \\ \operatorname{Prob}\{\eta_k = 0\} &= 1 - E\{\eta_k\} = 1-\eta, \\ \operatorname{Var}\{\eta_k\} &= E\{(\eta_k - \eta)^2\} = \eta(1-\eta) = \bar{\eta}, \end{aligned} \quad (5)$$

where $\eta_k = 1$ when the packet is transferred successfully (in real time), $\eta_k = 0$ when the packet is lost, the known positive constant $0 < \eta < 1$ is the probability of packet successful transmission, and $\bar{\eta}$ is the variance of η_k.

As a result, we obtain the following networked control system (shown in Figure 2):

$$\begin{aligned} x_{k+1} = {} & A x_k + A_d x_{k-h} + g(x_k)\eta u_c(x_k) \\ & + g(x_k)(1-\eta) u_{cd}(x_{k-h}), \end{aligned} \quad (6)$$

$$y_c(k) = \lambda C x_k + (1-\lambda) C x_{k-h}. \quad (7)$$

This approach takes account of both of the main problems in NCSs, namely, data packet dropouts and network-induced delays. Our approach considers that the data signal may arrive in real time, or, if it is lost or delayed, the last signal that arrived will be used after it is placed in the acceptance buffer in order to have a signal with constant delay for all measurement and control signals.

3. State Feedback Stabilization

Before proceeding, let us define the sets

$$\begin{aligned} \Omega &= \left\{x_k \in \mathbb{R}^n : x_k^T\left(A^TPA - P + Q + A^TPA_dM^{-1}A_d^TPA\right)x_k = 0, \quad k = 0, 1, \ldots\right\}, \\ S1 &= \left\{x_k \in \mathbb{R}^n : g_k^TPAx_k = 0,\ k = 0, 1, \ldots\right\}, \\ S2 &= \left\{x_k \in \mathbb{R}^n : g_k^TPA_dx_{k-h} = 0,\ k = h, h+1, \ldots\right\}, \\ H &= \left\{x_k \in \mathbb{R}^n : A_d^TPAx_k - \left(Q - A_d^TPA_d\right)x_{k-h} = 0, \quad k = h, h+1, \ldots\right\}. \end{aligned} \quad (8)$$

Theorem 1. *Suppose that there exist an $n \times n$ positive-definite matrix P and an $n \times n$ nonnegative-definite matrix Q, such that*

$$\begin{bmatrix} P - A^TPA - Q & A^TPA_d \\ A_d^TPA & M \end{bmatrix} \geq 0, \quad (9)$$

where

$$M = Q - A_d^TPA_d > 0. \quad (10)$$

If $\Omega \cap S1 \cap S2 \cap H = \{0\}$, *then the nonlinear discrete-time NCS (6) is globally asymptotically stabilized by the bounded-state feedback (4), where*

$$u_c(x_k) = -\alpha_1 \left[I + g_k^T P g_k\right]^{-1} \frac{g_k^T P A x_k}{1 + \|g_k^T P A x_k\|},$$
$$u_{cd}(x_{k-h}) = -\alpha_2 \left[I + g_k^T P g_k\right]^{-1} \frac{g_k^T P A_d x_{k-h}}{1 + \|g_k^T P A_d x_{k-h}\|}, \quad (11)$$

(for any $0 < \alpha_1 < 1$ *and* $0 < \alpha_2 < 1$*).*

Proof. Set

$$\gamma_1 = \frac{\alpha_1 * \eta}{1 + \|g_k^T P A x_k\|},$$
$$\gamma_2 = \frac{\alpha_2 * (1-\eta)}{1 + \|g_k^T P A_d x_{k-h}\|}; \quad (12)$$

then, the control bounded-state feedback can also be written

$$u_k = u(k) = -\gamma_1 K_1 x_k - \gamma_2 K_2 x_{k-h}. \quad (13)$$

To show the stability of the closed-loop system (6)–(13), we consider the following Lyapunov-Krasovskii functional:

$$V_k = x_k^T P x_k + \sum_{i=k-h}^{k-1} x_i^T Q x_i. \quad (14)$$

Notice that, since P is positive definite and Q nonnegative definite, V_k is then positive definite.

The difference of this Lyapunov-Krasovskii functional along the trajectory of the closed-loop (6)–(13) is given by

$$\Delta V_k = x_{k+1}^T P x_{k+1} + x_k^T Q x_k - x_k^T P x_k - x_{k-h}^T Q x_{k-h}. \quad (15)$$

Using (6) and (13) and after some matrix manipulations, we get

$$\begin{aligned} \Delta V_k = {} & x_k^T \left[A^T P A - P + Q\right] x_k \\ & + 2x_k^T A^T P \left[A_d - \gamma_2 g_k K_2\right] x_{k-h} - x_{k-h} M x_{k-h} \\ & - 2\gamma_1 x_k^T A^T P g_k K_1 x_k + \gamma_1^2 x_k^T A P g_k K_1 x_k \\ & - 2\gamma_1 x_{k-h}^T A_d^T P g_k K_1 x_k + \gamma_1 \gamma_2 x_{k-h}^T A_d^T P g_k K_1 x_k \\ & - 2\gamma_2 x_{k-h}^T A_d^T P g_k K_2 x_{k-h} \\ & + \gamma_2^2 x_{k-h}^T A_d P g_k K_2 x_{k-h} - u_k^T u_k, \end{aligned} \quad (16)$$

with $M = Q - A_d^T P A_d$.

Adding and subtracting $x_k^T A^T P \widehat{A} M^{-1} \widehat{A}^T P A x_k$ to and from inequality (16), we have

$$\begin{aligned} \Delta V_k = {} & x_k^T \left[A^T P A - P + Q + A^T P \widehat{A} M^{-1} \widehat{A}^T P A\right] x_k \\ & - 2\gamma_1 x_k^T A^T P g_k K_1 x_k + \gamma_1^2 x_k^T A P g_k K_1 x_k \\ & - 2\gamma_1 x_{k-h}^T A_d^T P g_k K_1 x_k + \gamma_1 \gamma_2 x_{k-h}^T A_d^T P g_k K_1 x_k \\ & - 2\gamma_2 x_{k-h}^T A_d^T P g_k K_2 x_{k-h} \\ & + \gamma_2^2 x_{k-h}^T A_d P g_k K_2 x_{k-h} - u_k^T u_k \\ & + 2x_k^T A^T P \widehat{A} x_{k-h} - x_{k-h} M x_{k-h} \\ & - x_k^T A^T P \widehat{A} M^{-1} \widehat{A}^T P A x_k, \end{aligned} \quad (17)$$

where $\widehat{A} = A_d - \gamma_2 g_k K_2$. Furthermore

$$\begin{aligned} \Delta V_k = {} & x_k^T \left[A^T P A - P + Q + A^T P \widehat{A} M^{-1} \widehat{A}^T P A\right] x_k \\ & - 2\gamma_1 x_k^T A^T P g_k K_1 x_k + \gamma_1^2 x_k^T A P g_k K_1 x_k \\ & - 2\gamma_1 x_{k-h}^T A_d^T P g_k K_1 x_k + \gamma_1 \gamma_2 x_{k-h}^T A_d^T P g_k K_1 x_k \\ & - 2\gamma_2 x_{k-h}^T A_d^T P g_k K_2 x_{k-h} \\ & + \gamma_2^2 x_{k-h}^T A_d P g_k K_2 x_{k-h} - u_k^T u_k \\ & - \left[M^{-1/2} \widehat{A}^T P A x_k - M^{1/2} x_{k-h}\right]^T \\ & \cdot \left[M^{-1/2} \widehat{A}^T P A x_k - M^{1/2} x_{k-h}\right]. \end{aligned} \quad (18)$$

Since $0 < \eta < 1$, $0 < \alpha_1 < 1$, and $0 < \alpha_2 < 1$, we have

$$\begin{aligned} 2\gamma_1 &> \gamma_1^2, \\ 2\gamma_1 &> \gamma_1 \gamma_2, \\ 2\gamma_2 &> \gamma_2^2. \end{aligned} \quad (19)$$

Then, from (18), we obtain the following inequality:

$$\Delta V_k \le x_k^T \left[A^T P A - P + Q + A^T P \widehat{A} M^{-1} \widehat{A}^T P A\right] x_k. \quad (20)$$

A sufficient condition to have $\Delta V_k \le 0$ is

$$A^T P A - P + Q + A^T P \widehat{A} M^{-1} \widehat{A}^T P A \le 0. \quad (21)$$

Let us compute $\widehat{A}$

$$\begin{aligned} \widehat{A} &= A_d - \gamma_2 g_k K_2, \\ \widehat{A} &= A_d - \gamma_2 g_k \left(I + g_k^T P g_k\right)^{-1} g_k^T P A_d, \\ \widehat{A} &= \left(I - \gamma_2 g_k \left(I + g_k^T P g_k\right)^{-1} g_k^T P\right) A_d, \\ \widehat{A} &= P^{-1} \left(P - P \gamma_2 g_k \left(I + g_k^T P g_k\right)^{-1} g_k^T P\right) A_d. \end{aligned} \quad (22)$$

Since $P - P\gamma_2 g_k(I + g_k^T P g_k)^{-1} g_k^T P \leq P$ we conclude that

$$\begin{aligned} &A^T PA - P + Q + A^T P\widehat{A} M^{-1} \widehat{A}^T PA \\ &\quad \leq A^T PA - P + Q + A^T PA_d M^{-1} A_d^T PA. \end{aligned} \tag{23}$$

So, if the LMI (9) is verified, then

$$\Delta V_k = V_{k+1} - V_k \leq 0. \tag{24}$$

This proves that the closed loop (6)–(13) is Lyapunov stable. To show the asymptotic stability of the origin, it suffices to show that the largest subset of $\Delta V_k = 0$ invariant under closed-loop dynamics is $\{0\}$.

Setting $\Delta V_k = 0$, it follows from (18) that

$$x_k^T \left[A^T PA - P + Q + \widehat{A}^T PA_d M^{-1} A_d^T P\widehat{A} \right] x_k = 0, \tag{25}$$

$$g_k^T PAx_k = 0, \tag{26}$$

$$g_k^T PA_d x_{k-h} = 0, \tag{27}$$

$$M^{-1/2} A_d^T P\widehat{A} x_k - M^{1/2} x_{k-h} = 0, \tag{28}$$

$$u(k) = 0. \tag{29}$$

Using (29), (25), (26), (27), and (28) become

$$\begin{aligned} x_k^T \left[A^T PA - P + Q + A^T PA_d M^{-1} A_d^T PA \right] x_k &= 0, \\ g_k^T PAx_k &= 0, \\ g_k^T PA_d x_{k-h} &= 0, \\ A_d^T PAx_k - \left(Q - A_d^T PA_d \right) x_{k-h} &= 0. \end{aligned} \tag{30}$$

Thus, we can conclude from the assumption

$$\Omega \cap S1 \cap S2 \cap H = \{0\} \tag{31}$$

that

$$\Delta V(x_k) = 0, \tag{32}$$

for

$$k = 0, 1, \ldots, \tag{33}$$

implies

$$x_k \equiv 0. \tag{34}$$

The asymptotic stability is, then, proved because all the conditions of LaSalle's invariance principle are verified.

Therefore, the origin is an asymptotically stable equilibrium of the closed-loop system (6)–(13) since $V(x_k) \rightarrow \infty$ as $\|x_k\| \rightarrow \infty$. □

4. Observer Design

In this section a simple and a useful observer design, without state augmentation, for a nonlinear discrete-time NCS will be given.

Theorem 2. *Suppose that the function g_k is globally Lipschitz on $\mathbb{R}^{n\times n}$ with a Lipschitz constant β; that is*

$$\left\| g\left(x_k^1\right) - g\left(x_k^2\right) \right\| \leq \beta \left\| x_k^1 - x_k^2 \right\|. \tag{35}$$

If there exists an $n \times n$ positive-definite matrix S, and an $n \times n$ nonnegative-definite matrix F, the following LMI holds:

$$\begin{bmatrix} \Pi_1 & \Pi_2 & -\lambda C^T L^T S & 0 \\ * & \Pi_3 & (1-\lambda) C^T L^T S & (1-\lambda) C^T L^T S \\ * & * & S & 0 \\ * & * & * & S \end{bmatrix} \geq 0, \tag{36}$$

where

$$\begin{aligned} \Pi_1 &= S - A^T SA - F + I + \lambda A^T SLC + \lambda C^T L^T SA, \\ \Pi_2 &= A^T SA_d - (1-\lambda) A^T SLC - \lambda C^T L^T SA_d, \\ \Pi_3 &= F - 2A_d^T SA_d + 2(1-\lambda) A_d^T SLC \\ &\quad + 2(1-\lambda) C^T L^T SA_d. \end{aligned} \tag{37}$$

Then, the following observer,

$$\begin{aligned} \xi_{k+1} &= A\xi_k + A_d \xi_{k-h} + g(\xi_k) u(k) \\ &\quad + L\left[y_c(k) - \lambda C\xi_k - (1-\lambda) C\xi_{k-h} \right], \end{aligned} \tag{38}$$

is an asymptotic observer for system (6) and (7).

Proof. Let

$$e_k = x_k - \xi_k; \tag{39}$$

then,

$$\begin{aligned} e_{k+1} &= (A - \lambda LC) e_k + \left(A_d - (1-\lambda) LC \right) e_{k-h} \\ &\quad + \left[g(x_k) - g(\xi_k) \right] u(k). \end{aligned} \tag{40}$$

Let $\widehat{A} = A - \lambda LC$, $\widetilde{A} = A_d - (1-\lambda)LC$, and $\phi = g(x_k) - g(\xi_k)$.

The Lyapunov-Krasovskii functional is given by

$$W_k = e_k^T S e_k + \sum_{i=k-h}^{k-1} e_i^T F e_i; \tag{41}$$

then,

$$\begin{aligned} \Delta W_k &= W_{k+1} - W_k, \\ &= e_{k+1}^T S e_{k+1} + e_k^T F e_k - e_k^T S e_k - e_{k-h}^T F e_{k-h}; \end{aligned} \tag{42}$$

or, equivalently,

$$\begin{aligned}\Delta W_k = {} & e_k^T\left[\widehat{A}^T S\widehat{A} - S + F\right] e_k + e_{k-h}^T\left[\widetilde{A}^T S\widetilde{A} - F\right] e_{k-h} \\ & + u(k)^T \phi^T S\phi u(k) + e_k^T \widehat{A}^T S\phi u(k) \\ & + u(k)^T \phi^T S\widehat{A} e_k + e_k^T \widehat{A}^T S\widetilde{A} e_{k-h} \\ & + e_{k-h}^T \widetilde{A}^T S\widehat{A} e_k + e_{k-h}^T \widetilde{A}^T S\phi u(k) \\ & + u(k)^T \phi S^T \widetilde{A} e_{k-h};\end{aligned} \tag{43}$$

then,

$$\begin{aligned}\Delta W_k = {} & e_k^T\left[\widehat{A}^T S\widehat{A} - S + F\right] e_k + u(k)^T \phi^T S\phi u(k) \\ & + 2e_k^T \widehat{A}^T S\phi u(k) - e_{k-h}^T M1 e_{k-h} \\ & + 2e_k^T \widehat{A}^T S\widetilde{A} e_{k-h} + 2u(k)^T \phi^T S\widetilde{A} e_{k-h},\end{aligned} \tag{44}$$

with $M1 = F - \widetilde{A}^T S\widetilde{A}$.

Since $2z^T Dy \le z^T Dz + y^T Dy$, we have

$$\begin{aligned}\Delta W_k \le {} & e_k^T\left[\widehat{A}^T S\widehat{A} - S + F\right] e_k + u(k)^T \phi^T S\phi u(k) \\ & + 2e_k^T \widehat{A}^T S\phi u(k) - e_{k-h}^T M1 e_{k-h} \\ & + 2e_k^T \widehat{A}^T S\widetilde{A} e_{k-h} + u(k)^T \phi^T S\phi u(k) \\ & + e_{k-h}^T \widetilde{A}^T S\widetilde{A} e_{k-h};\end{aligned} \tag{45}$$

then,

$$\begin{aligned}\Delta W_k \le {} & e_k^T\left[\widehat{A}^T S\widehat{A} - S + F\right] e_k \\ & + u(k)^T\left(\phi^T S\phi + \phi^T S\phi\right) u(k) \\ & + 2e_k^T \widehat{A}^T S\phi u(k) - e_{k-h}^T\left(M1 - \widetilde{A}^T S\widetilde{A}\right) e_{k-h} \\ & + 2e_k^T \widehat{A}^T S\widetilde{A} e_{k-h},\end{aligned} \tag{46}$$

or

$$\begin{aligned}\Delta W_k \le {} & e_k^T\left[\widehat{A}^T S\widehat{A} - S + F\right] e_k + 2u(k)^T \phi^T S\phi u(k) \\ & + 2e_k^T \widehat{A}^T S\phi u(k) - e_{k-h}^T N e_{k-h} \\ & + 2e_k^T \widehat{A}^T S\widetilde{A} e_{k-h},\end{aligned} \tag{47}$$

with $N = M1 - \widetilde{A}^T S\widetilde{A} = F - 2\widetilde{A}^T S\widetilde{A}$.

Adding and subtracting $e_k^T \widehat{A}^T S\widetilde{A} N^{-1} \widetilde{A}^T S\widehat{A} e_k$, we have

$$\begin{aligned}\Delta W_k \le {} & e_k^T\left[\widehat{A}^T S\widehat{A} - S + F + \widehat{A}^T S\widetilde{A} N^{-1} \widetilde{A}^T S\widehat{A}\right] e_k \\ & + 2u(k)^T \phi^T S\phi u(k) + 2e_k^T \widehat{A}^T S\phi u(k) \\ & - \left[N^{-1/2} \widetilde{A}^T S\widehat{A} e_k - N^{1/2} e_{k-h}\right]^T \\ & \cdot \left[N^{-1/2} \widetilde{A}^T S\widehat{A} e_k - N^{1/2} e_{k-h}\right].\end{aligned} \tag{48}$$

This, in turn, implies that

$$\begin{aligned}\Delta W_k \le {} & e_k^T\left[\widehat{A}^T S\widehat{A} - S + F + \widehat{A}^T S\widetilde{A} N^{-1} \widetilde{A}^T S\widehat{A}\right] e_k \\ & + 2u(k)^T \phi^T S\phi u(k) + 2e_k^T \widehat{A}^T S\phi u(k).\end{aligned} \tag{49}$$

Using the LMI (36), we have

$$\Delta W_k \le -e_k^T e_k + 2u(k)^T \phi^T S\phi u(k) + 2e_k^T \widehat{A}^T S\phi u(k), \tag{50}$$

or

$$\begin{aligned}\Delta W_k < {} & -e_k^T e_k + 2u(k)^T\left[g(x_k) - g(\xi_k)\right]^T \\ & \cdot S\left[g(x_k) - g(\xi_k)\right] u(k) \\ & + 2e_k^T \widehat{A}^T S\left[g(x_k) - g(\xi_k)\right] u(k).\end{aligned} \tag{51}$$

From the Lipschitz condition of $g(\cdot)$ and the boundness of the state feedback $u(k)$ $(u(k) < \alpha = \alpha_1 + \alpha_2)$, we deduce that

$$\begin{aligned}& \Delta W_k \\ & \quad < -\left\|e_k\right\|^2\left(1 - 2\alpha^2\beta^2\|S\| - 2\alpha\beta\|(A - \lambda LC) S\|\right),\end{aligned} \tag{52}$$

where β is the Lipschitz constant associated with $g(\cdot)$.

Obviously it is possible to choose $\alpha > 0$ sufficient small so that for some θ, $0 < \theta < 1$

$$\Delta W_k = W_{k+1} - W_k < -\theta e_k^T S e_k; \tag{53}$$

then, we ensure the global asymptotic stability of system (40). We can conclude also that

$$\left\|e_k\right\| \le \sigma, \quad \text{for } k = 1, 2, 3, \ldots, \ \sigma > 0. \tag{54}$$

□

5. Dynamic Output Feedback

Theorem 3. *Under assumption that* $\Omega \cap S1 \cap S2 \cap H = \{0\}$ *and if the LMI (9) is verified, then a nonlinear discrete-time NCS (6) and (7) can be globally asymptotically stabilized by the dynamic compensator (38) with the control input*

$$u(k) = u_k\left(\xi_k, \xi_{k-h}\right), \tag{55}$$

defined as in (4) and (11) for a sufficient small $\alpha > 0$ $(\alpha = \alpha_1 + \alpha_2)$*.* $g(\xi)$ *is globally Lipschitz and L is such that the LMI (36) is verified.*

Proof. By Theorem 1, for a given positive matrix B, the following inequality,

$$\begin{aligned}& \left\|A\xi_k + A_d\xi_{k-h} + g(\xi_k) u(k)\right\|_B^2 \le \left\|\xi_k\right\|_B^2, \\ & \qquad k = 1, 2, 3, \ldots,\end{aligned} \tag{56}$$

is satisfied.

Without loss of generality, let $B = I$ in (56). We deduce from (38), (40), and (56) that

$$\begin{aligned}\left\|\xi_{k+1}\right\| & \le \left\|A\xi_k + A_d\xi_{k-h} + g(\xi_k) u(k)\right\| + \left\|LC_d e_{k-h}\right\| \\ & \le \left\|\xi_k\right\| + \sigma \le \cdots \le \left\|\xi_0\right\| + \sigma.\end{aligned} \tag{57}$$

Inequalities (54) and (57) allow us to conclude that all trajectories of the closed-loop system (38)–(40) are bounded.

Now, we consider that (e_k, ξ_k) is a trajectory of system (38)–(40) with the initial value (e_0, ξ_0).

Let mo denote its ω-limit set. It is clear that mo is nonempty, compact, and invariant because (e_k, ξ_k) is bounded for $k = 1, 2, 3, \ldots$. In addition, we conclude from Theorem 2 that $\lim_{k\to\infty} e(k) = 0$.

Then, any point in mo must be of the form $(0, \xi_k)$. Let $(0, \overline{\xi}) \in mo$ and $(0, \overline{\xi}_k)$ be the corresponding trajectory. This trajectory is described by the following equation:

$$\overline{\xi}_{k+1} = A\overline{\xi}_k + A_d\overline{\xi}_{k-h} + g\left(\overline{\xi}_k\right) u_k. \tag{58}$$

We already proved that this trajectory is globally asymptotically stable at $\xi = 0$. This means that the global asymptotic behavior of the closed-loop system (38)–(40) at $(e, \xi) = (0, 0)$ is determined by the flow on the invariant manifold governed by system (58) [39]. Since this last system is globally asymptotically stable, so is the closed-loop system (38)–(40). □

Remark 4. The obtained results can be applied to a system of the form:

$$x_{k+1} = Ax_k + Bu_k^1 + g\left(x_k\right) u_k^2, \tag{59}$$

where

$$u_k^1 = Kx_{k-h}. \tag{60}$$

Remark 5. Compared with other approaches in the literature, note the following:

(1) The approach proposed in this paper has the advantage of taking into account the two major problems in the NCS, namely, data packet dropouts and network-induced delays, from both the sensor-to-controller and the controller-to-actuator.

(2) In the NCS literature, as mentioned in the introduction, a significant method for the stability analysis is the state augmentation. This approach reduce the closed-loop stability problem to the analysis of a finite dimensional time varying system by augmenting the system model to include delayed variables (past values of plant state, input, or output) as additional states which allow obtaining an augmented delay-free system. In the method we developed, the state space was not augmented. This allows to not increase the computational complexity, especially for large systems.

6. Illustrative Examples

In this section, two examples are provided to illustrate the results developed in this paper. The first example is a numerical illustration of the applicability and the effectiveness of the proposed method. The second example is a well known practical example in nonlinear filed, that is, the inverted pendulum system.

6.1. Example 1.

Consider system (6) and (7) with the following matrices:

$$A = \begin{bmatrix} 0.73624 & 0.0452 \\ 0.0915 & 0.4462 \end{bmatrix}, \quad A_d = \begin{bmatrix} 0.2456 & 0.0151 \\ 0.0305 & 0.1487 \end{bmatrix}, \quad g\left(x_k\right) = \begin{pmatrix} g_1\left(x_k\right) \\ g_2\left(x_k\right) \end{pmatrix}, \tag{61}$$

where

$$g_1\left(x_k\right) = \frac{x_1(k)}{1 + x_1^2(k) + x_2^2(k)}, \quad g_2\left(x_k\right) = \frac{x_2(k)}{1 + x_1^2(k) + x_2^2(k)}, \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix}, \tag{62}$$

with

$$x_0 = \begin{pmatrix} -3.5 \\ 2.8 \end{pmatrix}, \quad \xi_0 = \begin{pmatrix} 2.5 \\ -2.3 \end{pmatrix}, \tag{63}$$

and delay $h = 4$.

Resolution of the LMI (9) gives

$$P = \begin{bmatrix} 614.0062 & -48.2905 \\ -48.2905 & 456.6416 \end{bmatrix}, \quad Q = \begin{bmatrix} 162.4833 & -41.6186 \\ -41.6186 & 212.3097 \end{bmatrix}. \tag{64}$$

And resolution of the LMI (36) gives the following results:

$$S = \begin{bmatrix} 2.2751 & -0.0006 \\ -0.0006 & 2.2766 \end{bmatrix}, \quad F = \begin{bmatrix} 1.8578 & -0.0200 \\ -0.0200 & 1.6645 \end{bmatrix}. \tag{65}$$

We obtain then an observer gain

$$L = \begin{pmatrix} 0.0248 \\ 0.0186 \end{pmatrix}. \tag{66}$$

Verification of the assumption $\Omega \cap S1 \cap S2 \cap H = \{0\}$ shows that the only point of intersection is 0.

Applying the control law (55) with the observer (38), with $\lambda = 0.5$ and $\eta = 0.5$, we ensure, as shown in Figures 3–6, the decrease of the Lyapunov-Krasovskii functionals (14) and (41) and that $(x, e) = (0, 0)$ is a globally asymptotically stable equilibrium of (38)–(40).

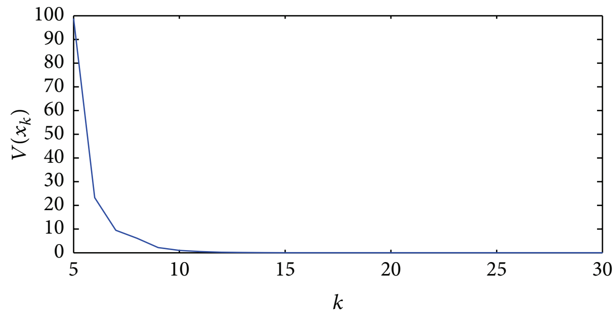

FIGURE 3: $V(x_k)$ with respect to sampling time k.

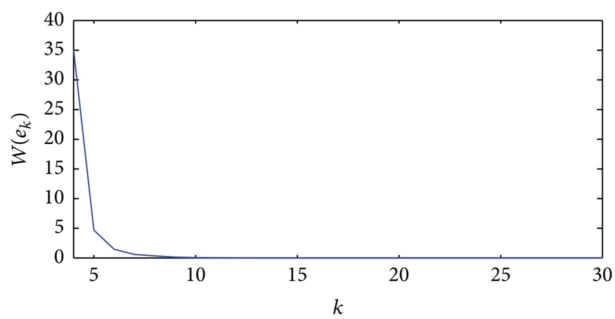

FIGURE 4: $W(e_k)$ with respect to sampling time k.

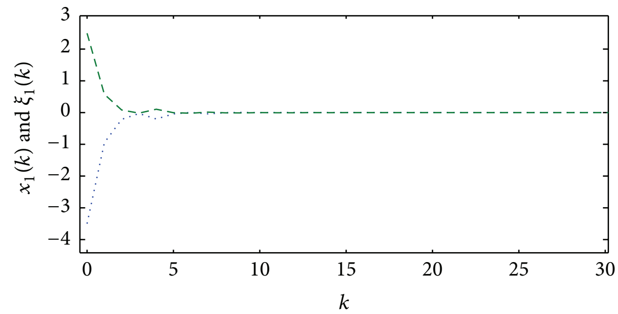

FIGURE 5: $x_1(k)$ and $\xi_1(k)$ with respect to sampling time k.

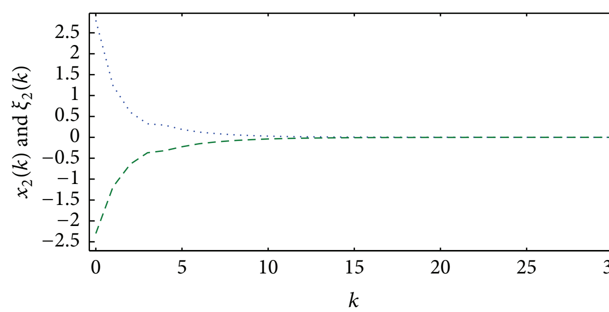

FIGURE 6: $x_2(k)$ and $\xi_2(k)$ with respect to sampling time k.

This numerical example illustrate how the developed method is simple to be implemented and the practical applicability of LMI conditions (9) and (36) in the stabilization of this class of NCS. We can see on the figures that the system has been effectively stabilized by the designed dynamic output feedback controller.

6.2. Example 2. In this example, the inverted pendulum is used to emphasize the applicability of the proposed results. Consider the model of the inverted pendulum presented in [40]

$$\begin{pmatrix} \dot{\theta} \\ \dot{\omega} \\ \dot{x} \\ \dot{v} \end{pmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \dfrac{((M+m)\cdot g)}{(M\cdot l)} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -\dfrac{(m\cdot g)}{M} & 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} \theta \\ \omega \\ x \\ v \end{pmatrix} + \begin{bmatrix} 0 \\ -\dfrac{1}{(M*l)} \\ 0 \\ \dfrac{1}{M} \end{bmatrix} u(t), \tag{67}$$

where $M = 2\,\text{kg}$, $m = 0.1\,\text{kg}$, $l = 0.5\,\text{m}$, and $g = 9.81\,\text{m/s}$. The system is sampled with the sampling period $T = 20\,\text{ms}$ and a digital state feedback control that is affected by delays:

$$u(t) = Kx(k-\tau), \quad \forall t \in [kT, (k+1)T], \tag{68}$$

where

$$K = [56 \;\; 12 \;\; 0.45 \;\; 1.4]. \tag{69}$$

For simulation we add a second input channel of the form $u_k^2 = g(x_k)u_k$. The resulting system is of the form (6).

Let

$$g(x_k) = \begin{pmatrix} g_1(x_k) \\ g_2(x_k) \\ g_3(x_k) \\ g_4(x_k) \end{pmatrix}, \tag{70}$$

where

$$\begin{aligned} g_1(x_k) &= \frac{x_1(k)}{1+x_1^2(k)+x_2^2(k)}, \\ g_2(x_k) &= \frac{x_2(k)}{1+x_1^2(k)+x_2^2(k)}, \\ g_3(x_k) &= \frac{x_3(k)}{1+x_3^2(k)+x_4^2(k)}, \\ g_4(x_k) &= \frac{x_4(k)}{1+x_3^2(k)+x_4^2(k)}, \\ C &= [1 \;\; 0 \;\; 1 \;\; 0] \end{aligned} \tag{71}$$

with

$$x_0 = \begin{pmatrix} -2.4 \\ -1.8 \\ 2 \\ 2.8 \end{pmatrix}, \qquad \xi_0 = \begin{pmatrix} 1.5 \\ 1.8 \\ -2.2 \\ -1.7 \end{pmatrix} \tag{72}$$

and the delay $h = 5$.

Solving the LMIs (9) and (36), we obtain

$$P = \begin{bmatrix} 31.2711 & 0.8623 & 1.9844 & 1.4253 \\ 0.8623 & 45.9557 & -0.1260 & 4.3524 \\ 1.9844 & -0.1260 & 17.4690 & 0.2475 \\ 1.4253 & 4.3524 & 0.2475 & 37.3286 \end{bmatrix},$$
$$Q = \begin{bmatrix} 11.2285 & 0.5903 & 1.1660 & 1.6855 \\ 0.5903 & 9.6467 & 0.0033 & 1.1667 \\ 1.1660 & 0.0033 & 10.9369 & 0.2660 \\ 1.6855 & 1.1667 & 0.2660 & 12.2965 \end{bmatrix},$$
$$S = \begin{bmatrix} 11.1095 & -0.4943 & -0.0174 & 0.4746 \\ -0.4943 & 16.8389 & -0.6588 & 1.1418 \\ -0.0174 & -0.6588 & 5.8880 & 0.0581 \\ 0.4746 & 1.1418 & 0.0581 & 12.4568 \end{bmatrix}, \tag{73}$$
$$F = \begin{bmatrix} 4.5491 & 0.6204 & 0.6320 & 1.1922 \\ 0.6204 & 2.9264 & 0.0878 & 0.7341 \\ 0.6320 & 0.0878 & 2.9112 & 0.2304 \\ 1.1922 & 0.7341 & 0.2304 & 3.6032 \end{bmatrix},$$
$$L = \begin{pmatrix} 0.0712 \\ 0.1144 \\ 0.0466 \\ 0.0348 \end{pmatrix}.$$

For this example also, it can be seen that the verification of the assumption $\Omega \cap S1 \cap S2 \cap H = \{0\}$ indicates that the only possible point of intersection is 0.

The nonlinear discrete-time system was simulated using the developed dynamic output feedback controller (55). Simulation results illustrated in Figures 7–12 show that the closed-loop system is stable.

The above illustrative examples show that the dynamic output feedback we proposed is effective in controlling this class of nonlinear NCS.

Remark 6. Since the robustness of data-based control is extremely important, recent interesting results on control and monitoring in the data-based techniques [41–44] could be further studied and integrated into the proposed dynamic output feedback control scheme to achieve more promising results from a practical point of view.

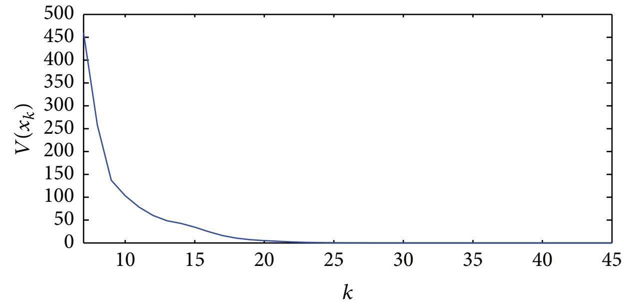

Figure 7: $V(x_k)$ with respect to sampling time k.

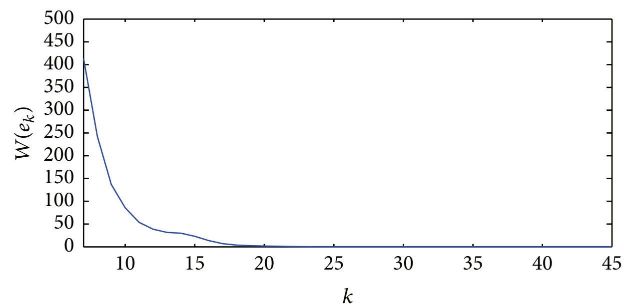

Figure 8: $W(e_k)$ with respect to sampling time k.

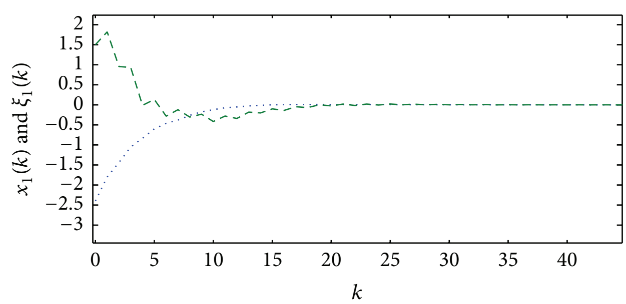

Figure 9: $x_1(k)$ and $\xi_1(k)$ with respect to sampling time k.

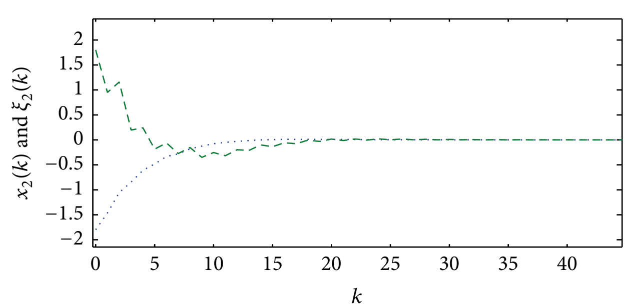

Figure 10: $x_2(k)$ and $\xi_2(k)$ with respect to sampling time k.

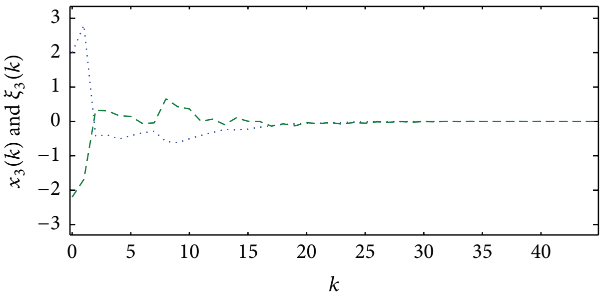

Figure 11: $x_3(k)$ and $\xi_3(k)$ with respect to sampling time k.

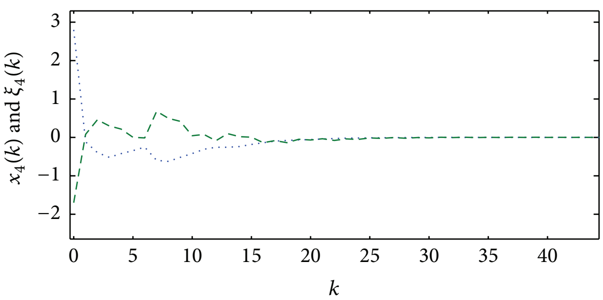

Figure 12: $x_4(k)$ and $\xi_4(k)$ with respect to sampling time k.

7. Conclusion

This paper investigated the stabilization problem of a class of discrete-time nonlinear NCS with simultaneous consideration of network-induced delays and data packet dropouts. A state feedback that guarantees the convergence of the state space to the origin was presented. Then, we presented an observer that estimates the state variables of this class of systems. A dynamic output feedback that stabilizes this class of nonlinear NCS was also achieved. LMI sufficient conditions to characterize the state feedback controller, the observer, and dynamic output feedback have been developed. The developed method can be considered as an extension of Jurdjevic Quinn theory and the passivity theory for nonlinear systems to this class of nonlinear NCS. Finally, two examples have been presented to demonstrate the effectiveness of the proposed method. Future work would attempt to extend the developed method to a class of nonlinear NCS with nonlinear free dynamics.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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References

[1] G. C. Walsh and H. Ye, "Scheduling of networked control systems," *IEEE Control Systems Magazine*, vol. 21, no. 1, pp. 57–65, 2001.

[2] J. P. Hespanha, P. Naghshtabrizi, and Y. Xu, "A survey of recent results in networked control systems," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 138–172, 2007.

[3] P. Seiler and R. Sengupta, "Analysis of communication losses in vehicle control problems," in *Proceedings of the American Control Conference*, vol. 2, pp. 1491–1496, IEEE, Arlington, Va, USA, June 2001.

[4] P. Seiler and R. Sengupta, "An H_∞ approach to networked control," *IEEE Transactions on Automatic Control*, vol. 50, no. 3, pp. 356–364, 2005.

[5] P. Ogren, E. Fiorelli, and N. E. Leonard, "Cooperative control of mobile sensor networks: adaptive gradient climbing in a distributed environment," *IEEE Transactions on Automatic Control*, vol. 49, no. 8, pp. 1292–1302, 2004.

[6] J. P. Hespanh, M. L. McLaughlin, and G. Sukhatme, "Haptic collaboration over the internet," in *Proceedings of the 5th Phantom Users Group Workshop (PUG '00)*, Aspen, Colo, USA, 2000.

[7] K. Hikichi, H. Morino, I. Arimoto, K. Sezaki, and Y. Yasuda, "The evaluation of delay jitter for haptics collaboration over the Internet," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '02)*, vol. 2, pp. 1492–1496, IEEE, Taipei, Taiwan, November 2002.

[8] S. Shirmohammadi and N. H. Woo, "Evaluating decorators for haptic collaboration over internet," in *Proceedings of the 3rd IEEE International Workshop on Haptic, Audio and Visual Environments and Their Applications (HAVE '04)*, pp. 105–109, IEEE, Ottawa, Canada, October 2004.

[9] C. Meng, T. Wang, W. Chou, S. Luan, Y. Zhang, and Z. Tian, "Remote surgery case: robot-assisted teleneurosurgery," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '04)*, vol. 1, pp. 819–823, IEEE, New Orleans, La, USA, May 2004.

[10] K. Ji and W.-J. Kim, "Real-time control of networked control systems via ethernet," *International Journal of Control, Automation and Systems*, vol. 3, no. 4, pp. 591–600, 2005.

[11] H. Gao and T. Chen, "New results on stability of discrete-time systems with time-varying state delay," *IEEE Transactions on Automatic Control*, vol. 52, no. 2, pp. 328–334, 2007.

[12] H. Gao, T. Chen, and J. Lam, "A new delay system approach to network-based control," *Automatica*, vol. 44, no. 1, pp. 39–52, 2008.

[13] D.-H. Choi and D.-S. Kim, "Wireless fieldbus for networked control systems using LR-WPAN," *International Journal of Control, Automation and Systems*, vol. 6, no. 1, pp. 119–125, 2008.

[14] W.-A. Zhang and L. Yu, "Output feedback stabilization of networked control systems with packet dropouts," *IEEE Transactions on Automatic Control*, vol. 52, no. 9, pp. 1705–1710, 2007.

[15] P. Mendez-Monroy and H. Benitez-Perez, "Supervisory fuzzy control for networked control systems," *ICIC Express Letters*, vol. 3, no. 2, pp. 233–238, 2009.

[16] R. A. Gupta and F. M.-Y. Chow, "Networked control system: overview and research trends," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 7, pp. 2527–2535, 2010.

[17] L. Zhang, H. Gao, and O. Kaynak, "Network-induced constraints in networked control systems-a survey," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 1, pp. 403–416, 2013.

[18] K. E. Bouazza, "Dynamic output feedback for nonlinear networked control system with system delays and packet dropout," in *Proceedings of the Triennal IFAC World Congress*, Cape Town, South Africa, 2014.

[19] H. Sandberg, S. Amin, and K. H. Johansson, "Cyberphysical security in networked control systems: an introduction to the issue," *IEEE Control Systems*, vol. 35, no. 1, pp. 20–23, 2015.

[20] Q. Li, G. Yi, C. Wang, L. Wu, and C. Ma, "LMI-based stability analysis of networked control systems with large time-varying delays," in *Proceedings of the IEEE International Conference on Mechatronics and Automation (ICMA '06)*, pp. 713–717, Luoyang, China, June 2006.

[21] X.-M. Tang and B.-C. Ding, "Design of networked control systems with bounded arbitrary time delays," *International Journal of Automation and Computing*, vol. 9, no. 2, pp. 182–190, 2012.

[22] Y. Xia, G. P. Liu, and D. H. Rees, "H_∞ control for networked control systems in presence of random network delay and data dropout," in *Proceedings of the Chinese Control Conference (CCC '06)*, pp. 2030–2034, IEEE, Harbin, China, August 2006.

[23] J. L. Xiong and J. Lam, "Stabilization of discrete-time markovian jump linear systems via time-delayed controllers," *Automatica*, vol. 42, no. 5, pp. 747–753, 2006.

[24] X. Li, J. Weng, D. Du, and H. Bai, "Observer-based exponential stability analysis for networked control systems with packet dropout," in *Proceedings of the 7th International Conference on Advanced Intelligent Computing (ICIC '11), Zhengzhou, China, August 2011*, Lecture Notes in Computer Science, pp. 694–700, Springer, Berlin, Germany, 2011.

[25] D. Yue, Q.-L. Han, and J. Lam, "Network-based robust H_∞ control of systems with uncertainty," *Automatica*, vol. 41, no. 6, pp. 999–1007, 2005.

[26] R. Yang, P. Shi, and G.-P. Liu, "Filtering for discrete-time networked nonlinear systems with mixed random delays and packet dropouts," *IEEE Transactions on Automatic Control*, vol. 56, no. 11, pp. 2655–2660, 2011.

[27] R. Lu, Y. Xu, A. Xue, and J. Zheng, "Networked control with state reset and quantized measurements: observer-based case," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 11, pp. 5206–5213, 2013.

[28] R. Lu, F. Wu, and A. Xue, "Networked control with reset quantized state based on bernoulli processing," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 9, pp. 4838–4846, 2014.

[29] T. Wang, H. Gao, and J. Qiu, "A combined adaptive neural network and nonlinear model predictive control for multirate networked industrial process control," *IEEE Transactions on Neural Networks and Learning Systems*, 2015.

[30] Y. Zhao, H. Gao, and T. Chen, "Fuzzy constrained predictive control of non-linear systems with packet dropouts," *IET Control Theory and Applications*, vol. 4, no. 9, pp. 1665–1677, 2010.

[31] S. Hu, Y. Zhang, X. Yin, and Z. Du, "T–S fuzzy-model-based robust stabilization for a class of nonlinear discrete-time networked control systems," *Nonlinear Analysis: Hybrid Systems*, vol. 8, no. 1, pp. 69–82, 2013.

[32] H. Li, C. Wu, P. Shi, and Y. Gao, "Control of nonlinear networked systems with packet dropouts: interval type-2 fuzzy model-based approach," *IEEE Transactions on Cybernetics*, no. 99, 2014.

[33] M. A. Khanesar, O. Kaynak, S. Yin, and H. Gao, "Adaptive indirect fuzzy sliding mode controller for networked control systems subject to time-varying network-induced time delay," *IEEE Transactions on Fuzzy Systems*, vol. 23, no. 1, pp. 205–214, 2015.

[34] N. van de Wouw, D. Nešić, and W. P. M. H. Heemels, "A discrete-time framework for stability analysis of nonlinear networked control systems," *Automatica*, vol. 48, no. 6, pp. 1144–1153, 2012.

[35] M. Yu, L. Wang, and T.-G. Chu, "Stability analysis of networked systems with packet dropout and transmission delays: discrete-time case," *Asian Journal of Control*, vol. 7, no. 4, pp. 433–439, 2005.

[36] J. Sun and J. Jiang, "Delay and data packet dropout separately related stability and state feedback stabilisation of networked control systems," *IET Control Theory & Applications*, vol. 7, no. 3, pp. 333–342, 2013.

[37] W. Lin, "Input saturation and global stabilization of nonlinear systems via state and output feedback," *IEEE Transactions on Automatic Control*, vol. 40, no. 4, pp. 776–782, 1995.

[38] W. Lin and C. I. Byrnes, "KYP lemma, state feedback and dynamic output feedback in discrete-time bilinear systems," *Systems and Control Letters*, vol. 23, no. 2, pp. 127–136, 1994.

[39] J. Carr, *Application of Centre Manifold Theory*, Springer, New York, NY, USA, 1981.

[40] P. Marti, *Analysis and design of real-time control systems with time-varying control timing constraints [Ph.D. thesis]*, Automatic Control Department, Technical University of Catalonia, 2002.

[41] S. Yin, S. X. Ding, X. Xie, and H. Luo, "A review on basic data-driven approaches for industrial process monitoring," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 11, pp. 6414–6428, 2014.

[42] S. Yin, X. Li, H. Gao, and O. Kaynak, "Data-based techniques focused on modern industry: an overview," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 1, pp. 657–667, 2015.

[43] S. Yin, X. Zhu, and O. Kaynak, "Improved PLS focused on key-performance-indicator-related fault diagnosis," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 3, pp. 1651–1658, 2015.

[44] S. Yin and Z. Huang, "Performance monitoring for vehicle suspension system via fuzzy positivistic c-means clustering based on accelerometer measurements," *IEEE/ASME Transactions on Mechatronics*, vol. 20, no. 5, pp. 2613–2620, 2015.