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Research Article

State-Feedback Sampled-Data Control Design for Nonlinear Systems via Passive Theory

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This paper investigates the problem of passive controller design for a class of nonlinear systems under variable sampling. The Takagi-Sugeno (T-S) fuzzy modeling method is utilized to represent the nonlinear systems. Attention is focused on the design of passive controller for the T-S fuzzy systems via sampled-data control approach. Under the concept of very-strict passivity, a novel time-dependent Lyapunov functional is constructed to develop passive analysis criteria and passive controller synthesis conditions. A new sampled-data controller is designed to guarantee that the resulting closed-loop system is very-strictly passive. These conditions are formulated in the form of linear matrix inequalities (LMIs), which can be solved by convex optimization approach. Finally, an application example is given to demonstrate the feasibility and effectiveness of the proposed results.

1. Introduction

Recently, it is well known that the fuzzy logic control [1–6] is one of effective approaches to handle complex nonlinear systems and has some applications in various real systems. It is well known that the Takagi-Sugeno (T-S) [7] fuzzy model has become a popular and effective method to control complex nonlinear systems. T-S fuzzy model is described as a weighted sum of some simple linear subsystems and thus are easily analyzable. During the past few decades, the problem of stability analysis and controller synthesis of nonlinear systems in Takagi-Sugeno (T-S) [7–10] fuzzy model has been extensively studied and some stability analysis and controller synthesis results have been reported, see, for instance, [11–18] and the references therein. To mention a few, the book [11] proposed fuzzy control systems design and analysis results via linear matrix inequality (LMI) approach [19–26] and the paper [12] presented a survey on the state-of-the-art and recent developments of the art of analysis and design of model-based fuzzy control systems. In addition, due to the effect of time delay in systems, the study of T-S fuzzy systems with time delays has received considerable attention in recent years and the results have been developed in [27–35]. The authors in [35] dealt with the problem of reliable fuzzy H_∞ controller design for uncertain active suspension systems with actuator delay and fault.

In practical control systems, it is important to investigate the controller design problem for sampled-data systems [36, 37]. Recently, the researchers in [38–43] discussed two main methods to develop stability analysis and control synthesis for sampled-data systems. The first one is to model a sampled data system as a discrete-time system [44], in which a sampled data system with a delay is modeled as a discrete-time system and a stability condition is derived. However, it should be mentioned that this method is very difficult to analyze or synthesize for complex systems. The second one is a delayed control input method by modeling the sampled-data system as a continuous-time system with a delayed control input, which was proposed in [41] and later used in [42, 45]. More recently, many sampled-data analysis and synthesis results have been reported for T-S fuzzy systems [46–50]. Among these results, the state-feedback control design method has been used in [47–51] and observed-based control approach has been used in [46]. Using input delay approach, the stabilization of nonuniform sampling fuzzy control systems have been investigated in [48–52], where the systems are regarded as ordinary continuous-time systems with a fast-varying delay. The authors in [51] used the time-dependent delay Lyapunov-Krasovskii functional idea [42] and introduced some slack matrices to improve the sampled-data control results about stabilization for fuzzy systems [48, 52]. However, these slack matrices may lead to a significant increase in the computational demand.

The passive properties of a system can keep the system internally stable and is frequently used in control systems to prove the stability of systems. There are extensive applications for passivity problem in various engineering areas such as electrical circuits, complex networks, mechanical systems, and nonlinear systems. The problems of passivity analysis and passive control have been extensively applied in many areas such as signal processing, fuzzy control, sliding mode control [53], and networked control systems [54]. More recently, the passive control problem has been studied for fuzzy systems [55–57]. In [57], the authors considered the passive control problems for a class of continuous-time T-S fuzzy systems with both state and input delays. The state-feedback fuzzy controller was designed such that the resulting closed-loop system is very-strictly passive. To the best of the authors' knowledge, so far no attempt has been made towards solving the problem of passive control design results for nonlinear systems with variable sampling. This problem still remains challenging, which motivates this study.

In this paper, the passive controller design problem is investigated for a class of nonlinear systems under variable sampling. Firstly, the T-S fuzzy model is employed to represent the nonlinear systems. By using the input delay approach, the T-S fuzzy system with variable uncertain sampling is transformed into a continuous-time T-S fuzzy system with a delay in the state. Secondly, by constructing a novel time-dependent Lyapunov functional, under the concept of very-strict passivity, new passive analysis criteria are proposed and then novel sampled-data controller is designed to guarantee that the resulting closed-loop system is very-strictly passive. The existence conditions of the obtained controller can be expressed as linear matrix inequalities (LMIs), which can be solved using standard numerical software. Finally, an application example is given to illustrate the feasibility and effectiveness of the proposed passive control approach. The remainder of this paper is organized as follows. The problem to be solved is formulated in Section 2. Main results, including passive analysis and passive controller design are presented in Section 3. Section 4 provides an illustrative example to show the effectiveness and potential of the proposed design techniques. We conclude this paper in Section 4.

Notation. The notation used throughout the paper is fairly standard. The notation $X > 0$ (resp., $X \geq 0$), for $X \in \mathbb{R}^{n\times n}$ means that the matrix X is real symmetric positive definite (resp., positive semidefinite). Identity matrices, of appropriate dimensions, will be denoted by I. If not explicitly stated, all matrices are assumed to have compatible dimensions for algebraic operations. The symbol "$*$" in a matrix $A \in \mathbb{R}^{n\times n}$ stands for the transposed elements in the symmetric positions. The superscripts "T" and "-1" denote the matrix transpose and inverse, respectively.

2. Problem Formulation

In this paper, we consider the following nonlinear system:

$$\dot{x}(t) = f(x(t), u(t)), \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state, $u(t) \in \mathbb{R}^n$ denotes the control input, and $f(x(t), u(t))$ is a known nonlinear continuous function and satisfies $f(0,0) = 0$. In order to consider the passive controller design problem, under the concept of sector nonlinearity, the nonlinear system in (1) can be represented by the following T-S fuzzy systems.

Plant Rule i. If $\theta_1(t)$ is N_{i1} and $\cdots \theta_p(t)$ is N_{ip}, then

$$\begin{aligned} \dot{x}(t) &= A_i x(t) + B_i u(t) + B_{wi} w(t), \\ z(t) &= C_i x(t) + D_i u(t) + D_{wi} w(t), \end{aligned} \tag{2}$$

where $z(t) \in \mathbb{R}^p$ is the control output and $w(t) \in \mathbb{R}^p$ is the disturbance input. A_i, B_i, B_{wi}, C_i, D_i, and D_{wi} are system matrices with appropriate dimensions. $i \in 1, 2, \ldots, r$, the scalar r is the number of IF-Then rules. $\theta_j(t)$ and N_{ij} are the premise variable and the fuzzy set, respectively, $j = 1, 2, \ldots, p$. The defuzzified output of system (2) is inferred as follows:

$$\begin{aligned} \dot{x}(t) &= \sum_{i=1}^{r} h_i(\theta(t)) \left[A_i x(t) + B_i u(t) + B_{wi} w(t)\right], \\ z(t) &= \sum_{i=1}^{r} h_i(\theta(t)) \left[C_i x(t) + D_i u(t) + D_{wi} w(t)\right], \end{aligned} \tag{3}$$

where $h_i(\theta(t)) = \mu_i(\theta(t)) / \sum_{i=1}^{r} \mu_i(\theta(t))$, $\mu_i(\theta(t)) = \prod_{j=1}^{p} N_{ij}(\theta_j(t))$, and $N_{ij}(\theta_j(t))$ is the degree of the membership of $\theta_j(t)$ in fuzzy set N_{ij}. In this paper, we assume that $\mu_i(\theta(t)) \geq 0$ for $i = 1, 2, \ldots, k$ and $\sum_{i=1}^{r} \mu_i(\theta(t)) > 0$ for all t. Therefore, $h_i(\theta(t)) \geq 0$ (for $i = 1, 2, \ldots, k$) and $\sum_{i=1}^{r} h_i(\theta(t)) = 1$. Suppose that the updating signal successfully transmitted signal from the sampler to the controller and to the Zero-Order Hold (ZOH) at the instant t_k. We assume that the sampling intervals are bounded

$$t_{k+1} - t_k \leq h, \quad k = 0, 1, 2 \ldots. \tag{4}$$

Here h denotes the maximum time span between the time t_k at which the state is sampled and the time t_{k+1} at which the next update arrives at the destination. The initial conditions of $x(t)$ and $u(t)$ are given as $x(t) = \varphi(t)$ and $u(t) = 0$ for $t \in [t_0 - h, t_0]$, where $\varphi(t)$ is a differentiable function. Similar to the fuzzy model, the same fuzz rule is used to construct the following overall fuzzy control law:

$$u(t) = \sum_{s=1}^{r} h_s(\theta(t_k)) K_s x(t_k), \quad t_k \le t < t_{k+1}, \quad k = 0, 1, 2, \ldots, \tag{5}$$

where t_k ($k = 0, 1, 2, \ldots$) denotes the kth sampling instant, $t_0 \ge 0$, and $\lim_{k\to\infty} t_k = \infty$. K_s ($s = 1, 2, \ldots, r$) are the local control gains and t_{k+1} is the next updating instant time of the ZOH after t_k. Denote $d(t) = t - t_k$ for $t_k \le t < t_{k+1}$. It is clear that $0 \le d(t) < t_{k+1} - t_k \le h$. It can be seen that $d(t)$ is sawtooth structure, that is, piecewise-linear with derivative $\dot{d}(t) = 1$, $t \ne t_k$. Then, from (5), we have

$$u(t) = \sum_{s=1}^{r} h_s(\theta(t_k)) K_s x(t - d(t)), \quad t_k \le t < t_{k+1}, \quad k = 0, 1, 2, \ldots. \tag{6}$$

Then, substituting (6) into (3) yields

$$\begin{aligned} \dot{x}(t) &= \sum_{i=1}^{r}\sum_{s=1}^{r} h_i h_s^k \left[A_i x(t) + B_i K_s x(t - d(t)) + B_{wi} w(t)\right], \\ z(t) &= \sum_{i=1}^{r}\sum_{s=1}^{r} h_i h_s^k \left[C_i x(t) + D_i K_s x(t - d(t)) + D_{wi} w(t)\right], \end{aligned} \tag{7}$$

where h_i and h_s^k stand for $h_i(\theta(t))$ and $h_s(\theta(t_k))$, respectively.

In order to develop the main results in the next section, the following definition is introduced.

Definition 1 (see [58]). Consider the following.

(D1) System (7) is said to be passive if there exists constant ρ such that

$$2\int_0^t z^T(s) w(s)\, ds \ge \rho \tag{8}$$

holds for all $t \ge 0$.

(D2) System (7) is said to be strictly passive if there exist constants $\delta > 0$ and ρ such that

$$2\int_0^t z^T(s) w(s)\, ds \ge \rho + \delta \int_0^t w^T(s) w(s)\, ds \tag{9}$$

holds for all $t \ge 0$.

(D3) System (7) is said to be output strictly passive if there exist constants $\varepsilon > 0$ and ρ such that

$$2\int_0^t z^T(s) w(s)\, ds \ge \rho + \varepsilon \int_0^t z^T(s) z(s)\, ds \tag{10}$$

holds for all $t \ge 0$.

(D4) System (7) is said to be very-strictly passive if there exist constants $\varepsilon > 0$, $\delta > 0$ and ρ such that

$$2\int_0^t z^T(s) w(s)\, ds \ge \rho + \varepsilon \int_0^t z^T(s) z(s)\, ds + \delta \int_0^t w^T(s) w(s)\, ds \tag{11}$$

holds for all $t \ge 0$.

The main objective of this paper is to give the novel sampled-data control conditions for T-S fuzzy system in (7) via passive control method. The controller is designed to guarantee that the resulting closed-loop system is very-strictly passive.

2.1. Main Results. This section focuses on designing the passive controller for fuzzy system (7). Firstly, the passivity analysis criterion is established for system (7) in the following theorem.

Theorem 2. *Consider system in* (7)*, for given constant h and matrix K_s, system* (7) *is very-strictly passive if there exist scalars $\varepsilon > 0$, $\delta > 0$, matrices $P > 0$, $Q_{is} > 0$, $R_{is} > 0$, $Z_1 > 0$, and $Z_2 > 0$ with appropriate dimensions, such that the following LMIs hold for $i, s = 1, 2, \ldots, r$,*

$$\begin{bmatrix} \Xi_{11is} + \Theta_{1is} & \Xi_{12is}^T & \Xi_{13is}^T \\ * & \Xi_{22is} & 0 \\ * & * & \Xi_{33} \end{bmatrix} < 0, \tag{12}$$

$$\begin{bmatrix} \Xi_{11is} + \Theta_{2is} & \Xi_{12is}^T \\ * & \Xi_{22is} \end{bmatrix} < 0, \tag{13}$$

$$Q_{si} < R_{is}, \tag{14}$$

where

$$\Xi_{11is} = \begin{bmatrix} PA_i + A_i^T P - Q_{is} - \frac{1}{h}Z_1 - Z_2 & PB_i K_s + Q_{is} + \frac{1}{h}Z_1 + Z_2 & 0 & PB_{wi} - C_i^T \\ * & -2Q_{is} - \frac{1}{h}Z_1 - Z_2 & Q_{is} & -K_s^T D_i^T \\ * & * & -Q_{is} & 0 \\ * & * & * & \delta I - D_{wi} - D_{wi}^T \end{bmatrix},$$

$$\Xi_{12is}=\begin{bmatrix} C_i & D_iK_s & 0 & D_{wi} \\ hR_{is}A_i & hR_{is}B_iK_s & 0 & hR_{is}B_{wi}\end{bmatrix},\qquad \Xi_{22is}=\operatorname{diag}\{-\varepsilon I,-R_{is}\},$$
$$\Theta_{1is}=\begin{bmatrix} -Q_{is} & Q_{is} & 0 & 0 \\ * & -Q_{is} & 0 & 0 \\ * & * & 0 & 0 \\ * & * & * & 0\end{bmatrix},\qquad \Theta_{2is}=\begin{bmatrix} 0 & 0 & 0 & 0 \\ * & -Q_{is} & Q_{is} & 0 \\ * & * & -Q_{is} & 0 \\ * & * & * & 0\end{bmatrix},$$
$$\Xi_{13is}=\begin{bmatrix} hZ_2 & -hZ_2 & 0 & 0 \\ hA_i & hB_iK_s & 0 & hB_{wi} \\ hZ_1A_i & hZ_1B_iK_s & 0 & hZ_1B_{wi}\end{bmatrix},\qquad \Xi_{33}=\operatorname{diag}\{-hI,-hI,-hZ_1\}. \tag{15}$$

Proof. Now, define a Lyapunov-Krasovskii function for system (7) as follows:

$$\begin{aligned} V(x(t)) &= V_1(x(t))+V_2(x(t))+V_3(x(t)),\\ V_1(x(t)) &= x^T(t)Px(t),\\ V_2(x(t)) &= h\int_{-h}^{0}\int_{t+\theta}^{t}\dot{x}^T(s)R(s)\dot{x}(s)\,\mathrm{d}s\,\mathrm{d}\theta,\\ V_3(x(t)) &= (h-d(t))\int_{t-d(t)}^{t}\dot{x}^T(s)Z_1\dot{x}(s)\,\mathrm{d}s\\ &\quad+(h-d(t))\vartheta^T(t)Z_2\vartheta(t), \end{aligned} \tag{16}$$

where $P>0$, $R(t)=\sum_{i=1}^{r}\sum_{s=1}^{r}h_ih_s^kR_{is}>0$, $Z_1>0$ and $Z_2>0$, $\vartheta(t)=(x(t)-x(t-d(t)))$, $t_k\le t<t_{k+1}$. It can be found that the term $V_3(x(t))$ vanishes after the jumps because $x(t)_{|t=t_k}=x(t-d(t))_{|t=t_k}$. Hence $V(x(t))>0$ and is continuous in time. The time-derivative of $V_1(x(t))$, $V_2(x(t))$, and $V_3(x(t))$ can be obtained as

$$\begin{aligned} \dot{V}_1(x(t)) &= 2x^T(t)P\dot{x}(t),\\ \dot{V}_2(x(t)) &= h^2\dot{x}^T(t)R(t)\dot{x}(t)\\ &\quad-h\int_{t-h}^{t}\dot{x}^T(s)R(s)\dot{x}(s)\,\mathrm{d}s,\\ \dot{V}_3(x(t)) &= -\int_{t-d(t)}^{t}\dot{x}^T(s)Z_1\dot{x}(s)\,\mathrm{d}s\\ &\quad+(h-d(t))\dot{x}^T(t)Z_1\dot{x}(t)\\ &\quad-\vartheta^T(t)Z_2\vartheta(t)+2(h-d(t))\vartheta^T(t)Z_2\dot{x}(t). \end{aligned} \tag{17}$$

From the condition in (14), we have $Q(t)=\sum_{i=1}^{r}\sum_{s=1}^{r}h_ih_s^kQ_{is}<R(t)$. According to Jensen's inequality and the second term in $\dot{V}_2(x(t))$, we can have the following inequalities:

$$\begin{aligned} &-h\int_{t-h}^{t}\dot{x}^T(s)R(s)\dot{x}(s)\,\mathrm{d}s\\ &<-h\int_{t-h}^{t}\dot{x}^T(s)Q(t)\dot{x}(s)\,\mathrm{d}s\\ &=-h\int_{t-d(t)}^{t}\dot{x}^T(s)Q(t)\dot{x}(s)\,\mathrm{d}s\\ &\quad-h\int_{t-h}^{t-d(t)}\dot{x}^T(s)Q(t)\dot{x}(s)\,\mathrm{d}s\\ &=-(h-d(t))\int_{t-d(t)}^{t}\dot{x}^T(s)Q(t)\dot{x}(s)\,\mathrm{d}s\\ &\quad-d(t)\int_{t-d(t)}^{t}\dot{x}^T(s)Q(t)\dot{x}(s)\,\mathrm{d}s\\ &\quad-(h-d(t))\int_{t-h}^{t-d(t)}\dot{x}^T(s)Q(t)\dot{x}(s)\,\mathrm{d}s\\ &\quad-d(t)\int_{t-h}^{t-d(t)}\dot{x}^T(s)Q(t)\dot{x}(s)\,\mathrm{d}s\\ &\le-\frac{(h-d(t))}{h}\zeta_1^T(t)Q(t)\zeta_1(t)-\zeta_1^T(t)Q(t)\zeta_1(t)\\ &\quad-\zeta_2^T(t)Q(t)\zeta_2(t)-\frac{d(t)}{h}\zeta_2^T(t)Q(t)\zeta_2(t)\\ &=\zeta_3^T(t)\begin{bmatrix} -Q(t) & Q(t) & 0 \\ Q(t) & -2Q(t) & Q(t) \\ 0 & Q(t) & -Q(t)\end{bmatrix}\zeta_3(t) \end{aligned}$$

$$+\frac{(h-d(t))}{h}\zeta_3^T(t)\begin{bmatrix}-Q(t) & Q(t) & 0\\ Q(t) & -Q(t) & 0\\ 0 & 0 & 0\end{bmatrix}\zeta_3(t)$$
$$+\frac{d(t)}{h}\zeta_3^T(t)\begin{bmatrix}0 & 0 & 0\\ 0 & -Q(t) & Q(t)\\ 0 & Q(t) & -Q(t)\end{bmatrix}\zeta_3(t), \quad (18)$$

where

$$\zeta_1(t)=\int_{t-d(t)}^{t}\dot{x}(s)\,\mathrm{d}s, \qquad \zeta_2(t)=\int_{t-h}^{t-d(t)}\dot{x}(s)\,\mathrm{d}s,$$
$$\zeta_3^T(t)=\left[x^T(t)\;\; x^T(t-d(t))\;\; x^T(t-h)\right]. \quad (19)$$

Similarly, for the first term in $\dot{V}_3(x(t))$, we can have the following inequalities,

$$-\int_{t-d(t)}^{t}\dot{x}^T(s)Z_1\dot{x}(s)\,\mathrm{d}s\le\zeta_4^T(t)\begin{bmatrix}-\frac{1}{h}Z_1 & \frac{1}{h}Z_1\\ \frac{1}{h}Z_1 & -\frac{1}{h}Z_1\end{bmatrix}\zeta_4(t), \quad (20)$$

where

$$\zeta_4^T(t)=\left[x^T(t)\;\; x^T(t-d(t))\right]. \quad (21)$$

For the last term in $\dot{V}_3(x(t))$, it can be found that

$$2(h-d(t))\vartheta^T(t)Z_2\dot{x}(t)$$
$$\le\frac{(h-d(t))}{h}\left[h\vartheta^T(t)Z_2Z_2\vartheta(t)+h\dot{x}^T(t)\dot{x}(t)\right]. \quad (22)$$

In addition,

$$z^T(t)z(t)$$
$$=\left\{\sum_{i=1}^{r}\sum_{s=1}^{r}h_ih_s^k\left[C_ix(t)+D_iK_sx(t-d(t))+D_{wi}w(t)\right]\right\}^T$$
$$\times\left\{\sum_{i=1}^{r}\sum_{s=1}^{r}h_ih_s^k\left[C_ix(t)+D_iK_sx(t-d(t))+D_{wi}w(t)\right]\right\}$$
$$\le\sum_{i=1}^{r}\sum_{s=1}^{r}h_ih_s^k\left[C_ix(t)+D_iK_sx(t-d(t))+D_{wi}w(t)\right]^T$$
$$\times\left[C_ix(t)+D_iK_sx(t-d(t))+D_{wi}w(t)\right]. \quad (23)$$

Then, we establish the passivity analysis performance of system in (7),

$$\dot{V}(x(t))+\varepsilon^{-1}z^T(t)z(t)+\delta w^T(t)w(t)-2z^T(t)w(t)$$
$$\le\sum_{i=1}^{r}\sum_{s=1}^{r}h_ih_s^k\eta^T(t)$$
$$\times\left[\Xi_{11is}-\Xi_{12is}^T\Xi_{22is}^{-1}\Xi_{12is}+\frac{(h-d(t))}{h}\right.$$
$$\left.\times\left(\Theta_{1is}-\Xi_{13is}^T\Xi_{33}^{-1}\Xi_{13is}\right)+\frac{d(t)}{h}\Theta_{2is}\right]\eta(t)$$
$$=\sum_{i=1}^{r}\sum_{s=1}^{r}h_ih_s^k\eta^T(t)$$
$$\times\left[\frac{(h-d(t))}{h}\left(\Xi_{11is}-\Xi_{12is}^T\Xi_{22is}^{-1}\Xi_{12is}\right.\right.$$
$$\left.+\Theta_{1is}-\Xi_{13is}^T\Xi_{33}^{-1}\Xi_{13is}\right)+\frac{d(t)}{h}$$
$$\left.\times\left(\Xi_{11is}-\Xi_{12is}^T\Xi_{22is}^{-1}\Xi_{12is}+\Theta_{2is}\right)\right]\eta(t), \quad (24)$$

where

$$\eta^T(t)=\left[x^T(t)\;\; x^T(t-d(t))\;\; x^T(t-h)\;\; w^T(t)\right]. \quad (25)$$

It follows from Theorem 2 and $(h-d(t))/h+d(t)/h=1$; it is derived that

$$\dot{V}(x(t))+\varepsilon^{-1}z^T(t)z(t)+\delta w^T(t)w(t)-2z^T(t)w(t)\le 0. \quad (26)$$

Integrating both sides of (26) yields

$$2\int_0^t z^T(s)w(s)\,\mathrm{d}s\ge V(x(t))-V(x(0))$$
$$+\varepsilon\int_0^t z^T(s)z(s)\,\mathrm{d}s+\delta\int_0^t w^T(s)w(s)\,\mathrm{d}s \quad (27)$$
$$\ge\rho+\varepsilon\int_0^t z^T(s)z(s)\,\mathrm{d}s+\delta\int_0^t w^T(s)w(s)\,\mathrm{d}s,$$

where $\rho=-V(x(0))$. Then, it can be seen from Definition 1 that system (7) is very-strictly passive. The proof is finished. □

Remark 3. In the proof of Theorem 2, we construct a new time-dependent and membership-dependent Lyapunov functional and use the advance methods to present the passivity analysis conditions, resulting in less number of slack variable being introduced in Theorem 2.

Based on the passivity analysis condition in Theorem 2, the controller is derived in the form of (6) for the system in (7).

Theorem 4. *Consider system in* (7)*, for given positive scalars* h*,* $\nu_{R_{is}}$*,* ν_{Z_1}*, and* ν_{Z_2}*, system* (7) *is very-strictly passive if there exist scalars* $\varepsilon > 0$*,* $\delta > 0$*, matrices* $\overline{P} > 0$*,* $\overline{Q}_{is} > 0$*,* $\overline{R}_{is} > 0$*,* $\overline{Z}_1 > 0$ *and* $\overline{K}_s$ *with appropriate dimensions, such that the following LMIs hold for* $i, s = 1, 2, \ldots, r$*,*

$$\begin{bmatrix} \overline{\Xi}_{11is} + \overline{\Theta}_{1is} & \overline{\Xi}_{12is}^T & \overline{\Xi}_{13is}^T \\ * & \overline{\Xi}_{22is} & 0 \\ * & * & \overline{\Xi}_{33} \end{bmatrix} < 0, \quad (28)$$

$$\begin{bmatrix} \overline{\Xi}_{11is} + \overline{\Theta}_{2is} & \overline{\Xi}_{12is}^T \\ * & \overline{\Xi}_{22is} \end{bmatrix} < 0, \quad (29)$$

$$\overline{Q}_{si} < \overline{R}_{is}, \quad (30)$$

where

$$\overline{\Xi}_{11is} = \begin{bmatrix} A_i\overline{P} + \overline{P}A_i^T - \overline{Q}_{is} - \frac{1}{h}\overline{Z}_1 - \nu_{Z_2}\overline{P} & B_i\overline{K}_s + \overline{Q}_{is} + \frac{1}{h}\overline{Z}_1 + \nu_{Z_2}\overline{P} & 0 & B_{wi} - \overline{P}C_i^T \\ * & -2\overline{Q}_{is} - \frac{1}{h}\overline{Z}_1 - \nu_{Z_2}\overline{P} & \overline{Q}_{is} & -\overline{K}_s^T D_i^T \\ * & * & -\overline{Q}_{is} & 0 \\ * & * & * & \delta I - D_{wi} - D_{wi}^T \end{bmatrix},$$

$$\overline{\Xi}_{12is} = \begin{bmatrix} C_i\overline{P} & D_i\overline{K}_s & 0 & D_{wi} \\ hA_i\overline{P} & hB_i\overline{K}_s & 0 & hB_{wi} \end{bmatrix}, \qquad \overline{\Xi}_{22is} = \operatorname{diag}\left\{-\varepsilon I, \nu_{R_{is}}^2\overline{R}_{is} - 2\nu_{R_{is}}\overline{P}\right\},$$

$$\overline{\Theta}_{1is} = \begin{bmatrix} -\overline{Q}_{is} & \overline{Q}_{is} & 0 & 0 \\ * & -\overline{Q}_{is} & 0 & 0 \\ * & * & 0 & 0 \\ * & * & * & 0 \end{bmatrix}, \qquad \overline{\Theta}_{2is} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ * & -\overline{Q}_{is} & \overline{Q}_{is} & 0 \\ * & * & -\overline{Q}_{is} & 0 \\ * & * & * & 0 \end{bmatrix}, \quad (31)$$

$$\overline{\Xi}_{13is} = \begin{bmatrix} h\nu_{Z_2}I & -h\nu_{Z_2}I & 0 & 0 \\ hA_i\overline{P} & hB_i\overline{K}_s & 0 & hB_{wi} \\ hA_i\overline{P} & hB_i\overline{K}_s & 0 & hB_{wi} \end{bmatrix}, \qquad \overline{\Xi}_{33} = \operatorname{diag}\left\{-hI, -hI, h\left(\nu_{Z_1}^2\overline{Z}_1 - 2\nu_{Z_1}\overline{P}\right)\right\}.$$

Then, the control gain matrix is $K_s = \overline{K}_s\overline{P}^{-1}$*.*

Proof. Firstly, it can be seen that the two inequalities $-\overline{P}\,\overline{R}_{is}^{-1}\overline{P} \le \nu_{R_{is}}^2\overline{R}_{is} - 2\nu_{R_{is}}\overline{P}$ and $-\overline{P}\,\overline{Z}_1^{-1}\overline{P} \le \nu_{Z_1}^2\overline{Z}_1 - 2\nu_{Z_1}\overline{P}$ hold for positive scalars $\nu_{R_{is}}$ and ν_{Z_1} due to the following two inequalities:

$$\left(\nu_{R_{is}}\overline{R}_{is} - \overline{P}\right)\overline{R}_{is}^{-1}\left(\nu_{R_{is}}\overline{R}_{is} - \overline{P}\right) \ge 0,$$
$$\left(\nu_{Z_1}\overline{Z}_1 - \overline{P}\right)\overline{Z}_1^{-1}\left(\nu_{Z_1}\overline{Z}_1 - \overline{P}\right) \ge 0. \quad (32)$$

Then, define the variables as $P = \overline{P}^{-1}$, $Q_{is} = \overline{P}^{-1}\overline{Q}_{is}\overline{P}^{-1}$, $R_{is} = \overline{P}^{-1}\overline{R}_{is}\overline{P}^{-1}$, $Z_1 = \overline{P}^{-1}\overline{Z}_1\overline{P}^{-1}$, and $Z_2 = \nu_{Z_2}\overline{P}^{-1}$, and replace the terms $\nu_{R_{is}}^2\overline{R}_{is} - 2\nu_{R_{is}}\overline{P}$ and $\nu_{Z_1}^2\overline{Z}_1 - 2\nu_{Z_1}\overline{P}$ with $-\overline{P}\,\overline{R}_{is}^{-1}\overline{P}$ and $-\overline{P}\,\overline{Z}_1^{-1}\overline{P}$ in (28) and (29). We perform congruence transformation to (28) and (29) by

$$\operatorname{diag}\{P \ \ P \ \ P \ \ I \ \ I \ \ R_{is} \ \ I \ \ I \ \ Z_1\},$$
$$\operatorname{diag}\{P \ \ P \ \ P \ \ I \ \ I \ \ R_{is}\}, \quad (33)$$

respectively. We can see that the LMIs conditions in (12) and (13) hold. Therefore, all the conditions in Theorem 2 are satisfied. The proof is completed. □

If the assumption $\dot{d}(t) = 1$ is removed, which means that Lyapunov functional candidate (16) does not include the term $V_3(x(t))$. Similar to the proof of Theorems 2 and 4, we have the following corollaries.

Corollary 5. *Consider system in* (7)*, for given constant* h *and matrix* K_s*, system* (7) *is very-strictly passive if there exist scalars*

$\varepsilon > 0$, $\delta > 0$, matrices $P > 0$, $Q_{is} > 0$, and $R_{is} > 0$ with appropriate dimensions, such that the following LMIs hold for $i, s = 1, 2, \ldots, r$,

$$\begin{bmatrix} \Xi_{11is} + \Theta_{1is} & \Xi_{12is}^T \\ * & \Xi_{22is} \end{bmatrix} < 0,$$

$$\begin{bmatrix} \Xi_{11is} + \Theta_{2is} & \Xi_{12is}^T \\ * & \Xi_{22is} \end{bmatrix} < 0, \qquad Q_{si} < R_{is}, \tag{34}$$

where

$$\Xi_{11is} = \begin{bmatrix} PA_i + A_i^T P - Q_{is} & PB_i K_s + Q_{is} & 0 & PB_{wi} - C_i^T \\ * & -2Q_{is} & Q_{is} & -K_s^T D_i^T \\ * & * & -Q_{is} & 0 \\ * & * & * & \delta I - D_{wi} - D_{wi}^T \end{bmatrix},$$

$$\Xi_{12is} = \begin{bmatrix} C_i & D_i K_s & 0 & D_{wi} \\ hR_{is}A_i & hR_{is}B_i K_s & 0 & hR_{is}B_{wi} \end{bmatrix}, \qquad \Xi_{22is} = \operatorname{diag}\{-\varepsilon I, -R_{is}\}, \tag{35}$$

$$\Theta_{1is} = \begin{bmatrix} -Q_{is} & Q_{is} & 0 & 0 \\ * & -Q_{is} & 0 & 0 \\ * & * & 0 & 0 \\ * & * & * & 0 \end{bmatrix}, \qquad \Theta_{2is} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ * & -Q_{is} & Q_{is} & 0 \\ * & * & -Q_{is} & 0 \\ * & * & * & 0 \end{bmatrix}.$$

Corollary 6. *Consider system in (7), for given positive scalars h, $\nu_{R_{is}}$, ν_{Z_1}, and ν_{Z_2}, system (7) is very-strictly passive if there exist scalars $\varepsilon > 0$, $\delta > 0$, matrices $\overline{P} > 0$, $\overline{Q}_{is} > 0$, $\overline{R}_{is} > 0$, $\overline{Z}_1 > 0$, and $\overline{K}_s$ with appropriate dimensions, such that the following LMIs hold for $i, s = 1, 2, \ldots, r$,*

$$\begin{bmatrix} \overline{\Xi}_{11is} + \overline{\Theta}_{1is} & \overline{\Xi}_{12is}^T \\ * & \overline{\Xi}_{22is} \end{bmatrix} < 0,$$

$$\begin{bmatrix} \overline{\Xi}_{11is} + \overline{\Theta}_{2is} & \overline{\Xi}_{12is}^T \\ * & \overline{\Xi}_{22is} \end{bmatrix} < 0,$$

$$\overline{Q}_{si} < \overline{R}_{is}, \tag{36}$$

where

$$\overline{\Xi}_{11is} = \begin{bmatrix} A_i\overline{P} + \overline{P}A_i^T - \overline{Q}_{is} & B_i\overline{K}_s + \overline{Q}_{is} & 0 & B_{wi} - \overline{P}C_i^T \\ * & -2\overline{Q}_{is} & \overline{Q}_{is} & -\overline{K}_s^T D_i \\ * & * & -\overline{Q}_{is} & 0 \\ * & * & * & \delta I - D_{wi} - D_{wi}^T \end{bmatrix},$$

$$\overline{\Xi}_{12is} = \begin{bmatrix} C_i\overline{P} & D_i\overline{K}_s & 0 & D_{wi} \\ hA_i\overline{P} & hB_i\overline{K}_s & 0 & hB_{wi} \end{bmatrix}, \qquad \overline{\Xi}_{22is} = \operatorname{diag}\left\{-\varepsilon I, \nu_{R_{is}}^2 \overline{R}_{is} - 2\nu_{R_{is}}\overline{P}\right\},$$

$$\overline{\Theta}_{1is} = \begin{bmatrix} -\overline{Q}_{is} & \overline{Q}_{is} & 0 & 0 \\ * & -\overline{Q}_{is} & 0 & 0 \\ * & * & 0 & 0 \\ * & * & * & 0 \end{bmatrix}, \qquad \overline{\Theta}_{2is} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ * & -\overline{Q}_{is} & \overline{Q}_{is} & 0 \\ * & * & -\overline{Q}_{is} & 0 \\ * & * & * & 0 \end{bmatrix}. \tag{37}$$

The control gain matrix is computed as $K_s = \overline{K}_s \overline{P}^{-1}$.

3. Simulation Results

In this section, an application example is used to demonstrate the applicability of the controller design method proposed in this paper.

Example 7. Consider the problem of balancing and swing-up of an inverted pendulum on a cart. The equations of the pendulum motion are given by [4]:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t), \\ \dot{x}_2(t) &= \left(g \sin(x_1(t)) - \frac{\text{aml}\, x_2^2(t) \sin(2x_1(t))}{2} \right. \\ &\quad \left. - a \cos(x_1(t))\, u(t) \right) \\ &\quad \times \left(\frac{4l}{3} - \text{aml} \cos^2(x_1(t)) \right)^{-1}, \end{aligned} \tag{38}$$

where $x_1(t)$ stands for the angle (in radians) of the pendulum from the vertical, $x_2(t)$ denotes the angular velocity, and $u(t)$ is the force applied to the cart (in newtons). $g = 9.8\,\text{m/s}^2$ is the gravity constant, m denotes the mass of the pendulum, M stands for the mass of the cart, $2l$ is the length of the pendulum, and $a = 1/(m+M)$. Here, we choose $m = 2.0\,\text{kg}$, $M = 8.0\,\text{kg}$, and $2l = 1.0\,\text{m}$ in simulations [3].

The control objective here is to balance the inverted pendulum for the approximate range $x_1(t) \in (-(\pi/2), (\pi/2))$ through a sampled-data control approach. First, we represent the system in (38) by a two-rule Takagi-Sugenofuzzy model [39].

Plant Rule 1. If $x_1(t)$ is 0, then

$$\dot{x}(t) = A_1 x(t) + B_1 u(t), \tag{39}$$

Plant Rule 2. If $x_1(t)$ is $\pm(\pi/2)(|x_1(t)| < \pi/2)$, then

$$\dot{x}(t) = A_2 x(t) + B_2 u(t), \tag{40}$$

where

$$\begin{gathered} A_1 = \begin{bmatrix} 0 & 1 \\ \dfrac{g}{4l/3 - \text{aml}} & 0 \end{bmatrix}, \qquad B_1 = \begin{bmatrix} 0 \\ -\dfrac{a}{4l/3 - \text{aml}} \end{bmatrix}, \\ A_2 = \begin{bmatrix} 0 & 1 \\ \dfrac{2g}{\pi (4l/3 - \text{aml}\beta^2)} & 0 \end{bmatrix}, \\ B_2 = \begin{bmatrix} 0 \\ -\dfrac{a\beta}{\pi 4l/3 - \text{aml}\beta^2} \end{bmatrix}, \end{gathered} \tag{41}$$

and $\beta = \cos(88^\circ)$ (notice that when $x_1(t) = \pm(\pi/2)$, the system is uncontrollable). Membership functions for Rules 1 and 2 are listed below:

$$h_1(\theta(t)) = \begin{cases} 1 - \dfrac{2}{\pi}\theta(t), & \text{if } 0 \le \theta(t) < \dfrac{\pi}{2}, \\ 1 + \dfrac{2}{\pi}\theta(t), & \text{if } -\dfrac{\pi}{2} \le \theta(t) < 0, \end{cases} \tag{42}$$

and $h_2(\theta(t)) = 1 - h_1(\theta(t))$, where $\theta(t) = x_1(t)$. Figure 1 shows the membership functions.

In order to demonstrate the effectiveness of the proposed passive control design method, we consider the system in (38) and other parameters in system (2):

$$\begin{gathered} B_{w1} = [-0.01 \;\; 0.01]^T, \qquad B_{w2} = [0.01 \;\; -0.01]^T, \\ C_1 = [0.1 \;\; 0.01], \qquad C_2 = [-0.01 \;\; 0.1], \\ D_1 = -0.01, \qquad D_2 = 0.02, \\ D_{w1} = 0.01, \qquad D_{w2} = 0.02. \end{gathered} \tag{43}$$

We choose the disturbance input $w(t) = -1/(2+t)$. It can be calculated that $\int_0^\infty w^T(t) w(t) dt = 0.5 < \infty$, which means $w(t) \in L_2[0,\infty)$. Let

$$\begin{aligned} \varrho(t) &= 2\int_0^t z^T(s) w(s)\, ds \\ &\quad - \varepsilon \int_0^t z^T(s) z(s)\, ds - \delta \int_0^t w^T(s) w(s)\, ds. \end{aligned} \tag{44}$$

In Figure 2, it can be observed that $2\int_0^\infty z^T(t) w(t) dt$ decreases as the time t increases, which means that there may

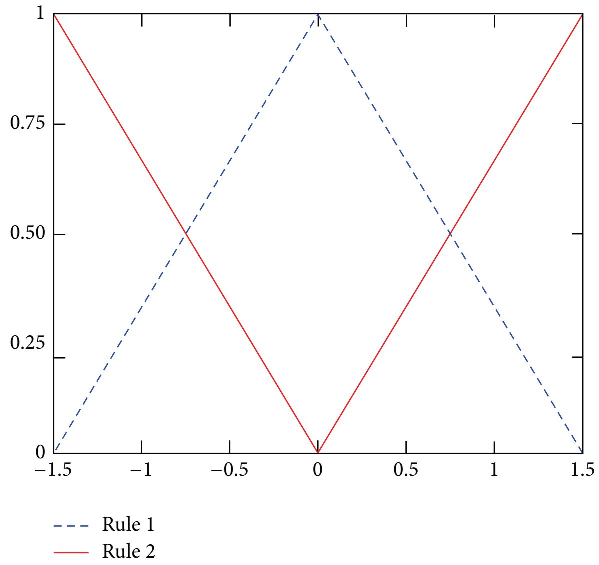

FIGURE 1: Membership functions of two rules.

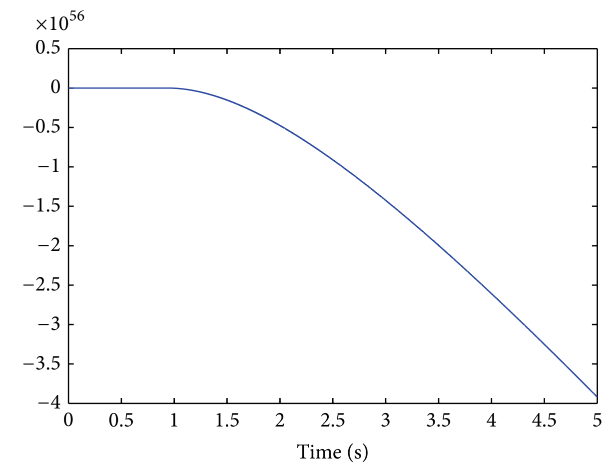

FIGURE 2: Response of $2\int_0^\infty z^T(t)w(t)dt$ of the open-loop system.

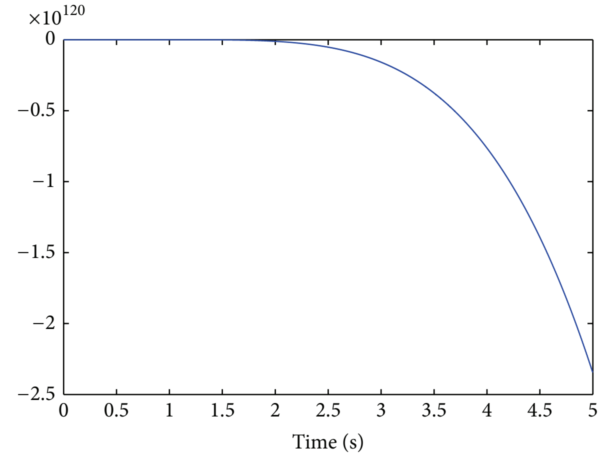

FIGURE 3: Response of $\varrho(t)$ of the open-loop system.

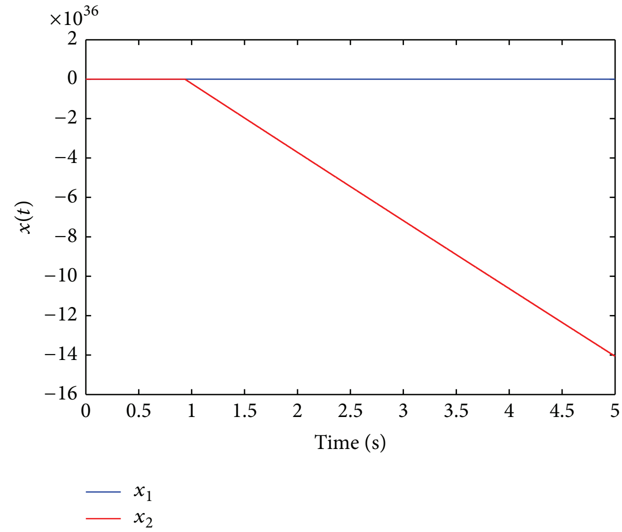

FIGURE 4: State response of the open-loop system.

not exist a scalar ρ such $2\int_0^\infty z^T(t)w(t)dt \geq \rho$ holds for all $t \geq 0$. In addition, Figure 3 still holds that there may not exist a scalar ρ such that $\varrho(t) \geq \rho$, which means that the open-loop system is not passive in the sense of Definition 1, and it is not very-strictly passive. Figure 4 demonstrates that the open-loop system is not stable.

In Theorem 4, letting $\nu_{R_{11}} = 0.01$, $\nu_{R_{12}} = 0.02$, $\nu_{R_{21}} = 0.02$, $\nu_{R_{22}} = 0.01$, $\nu_{Z_1} = 10$, and $\nu_{Z_2} = 1$, it can be found that the closed-loop system is very-strictly passive for the allowable upper bound of $h = 9$ ms. The control gain matrices are listed below:

$$\begin{aligned} K_1 &= [279.1851 \quad 74.3281], \\ K_2 &= [3363.479 \quad 1083.6839]. \end{aligned} \tag{45}$$

Under the control gain matrices in (45), Figure 5 plots the responses of $2\int_0^\infty z^T(t)w(t)dt$ for the closed-loop system, which means that there may exist a scalar ρ such $2\int_0^\infty z^T(t)w(t)dt \geq \rho$ holds for all $t \geq 0$. In Figure 6, it can be seen that there may exist a scalar ρ such that $\varrho(t) \geq \rho$. Then, one can know that the closed-loop system is very-strictly passive under the control gain matrices in (45). In addition, Figure 7 shows that the closed-loop system is stable. The computed control inputs arriving at the ZOH are shown in Figure 8, in which we can see that the piecewise continuous holding behavior of the control inputs.

According to the above observation, these simulation results can demonstrate that the designed sampled-data controller meets the specified design requirements.

4. Conclusions

In this paper, the problems of passivity analysis and passive control have been investigated for nonlinear systems under variable sampling. By using the nonlinear sector method, the T-S fuzzy model was established to describe the nonlinear

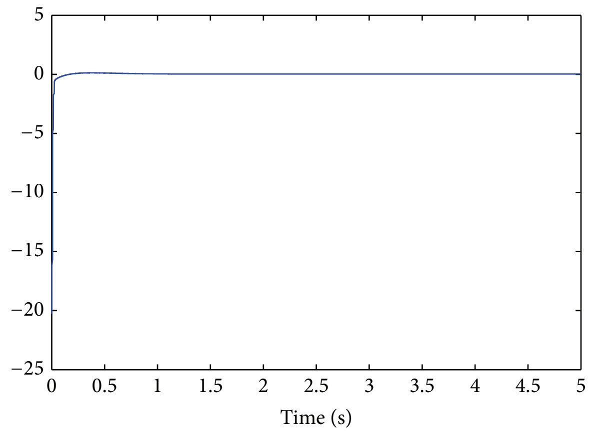

Figure 5: Response of $2\int_0^\infty z^T(t)w(t)\mathrm{d}t$ of the closed-loop system.

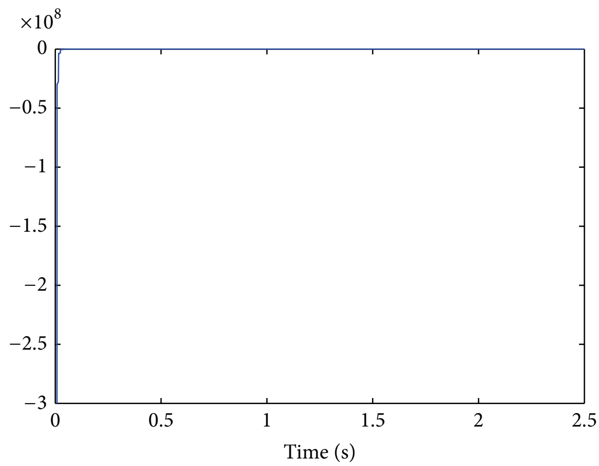

Figure 6: Response of $\varrho(t)$ of the closed-loop system.

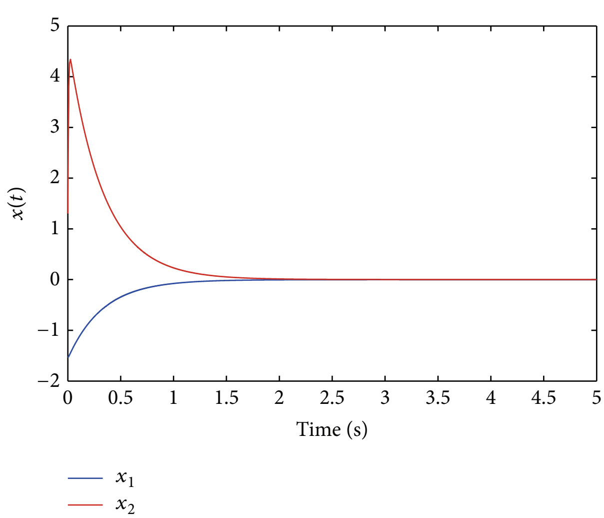

Figure 7: State response of the closed-loop system.

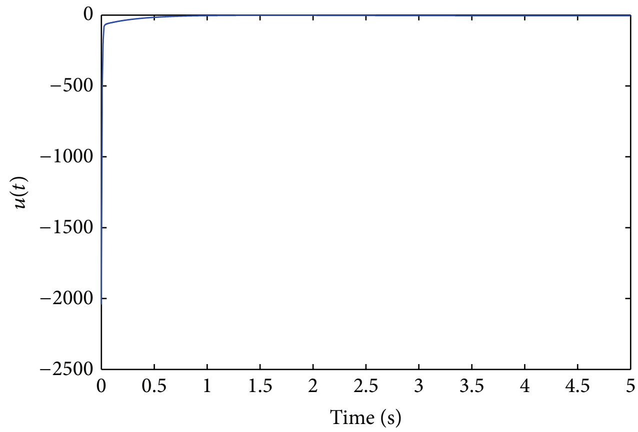

Figure 8: Control signal response of the closed-loop system

systems. Based on the input delay approach, the T-S fuzzy system with variable uncertain sampling was transformed into a continuous-time T-S fuzzy system with a delay in the state. By constructing a novel time-dependent Lyapunov functional, sampled-data controller was designed to guarantee that the resulting closed-loop system is very-strictly passive. The controller existence conditions were expressed as LMIs. This paper has taken into account the main characteristics of sampled-data systems via defining a novel time-dependent Lyapunov functional. An example has been included to demonstrate the advantages of the theoretic results obtained. This paper talks about passivity analysis and passive control for nonlinear systems under variable sampling. In order to achieve more practical oriented results, further work could be considered under data-driven (measurements) framework [59, 60]. The future topics, for example, control [61] and fault tolerant scheme [62] in the identical framework, seem more interesting from both academic and industrial domains.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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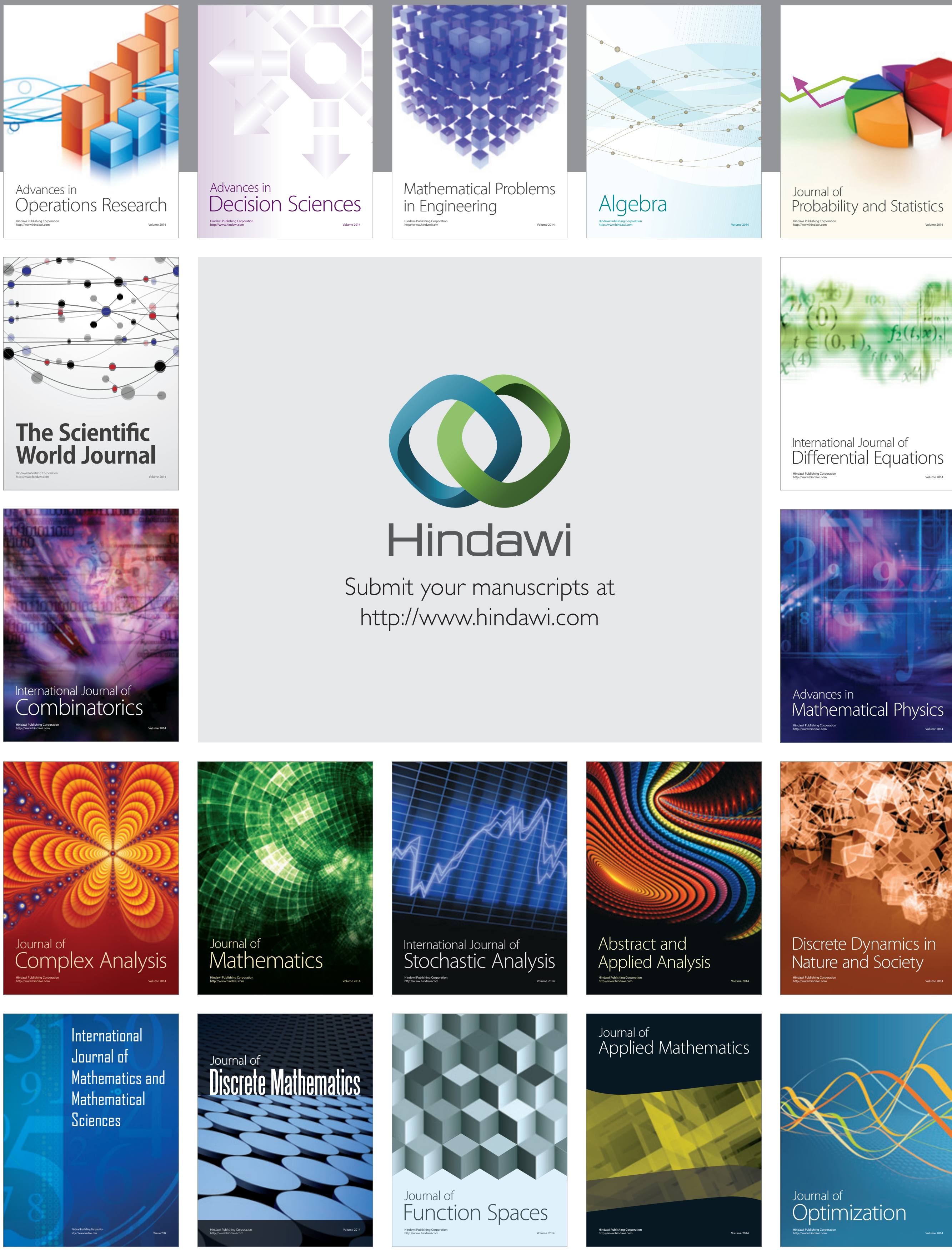
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