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Input-to-State Stabilization of Nonlinear Time-Delay Systems via a Modified Event-Triggered Impulsive Control

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Abstract. This paper, based on Lyapunov stability analysis, designs a more flexible triggering mechanism for a class of nonlinear systems with time-delay effects. The proposed event-triggered pulse control scheme can ensure global input-to-state stability (ISS) and strictly prevent Zeno behavior. The advantages and optimized performance of the findings are verified through typical numerical examples. Simulation results show that, under the same external disturbance conditions, traditional schemes generate a large number of pulse events, whereas the adaptive mechanism proposed here only requires a few pulses to maintain system stability, significantly reducing communication resource usage. At the same time, under strong disturbance conditions, the system's peak state deviation is noticeably suppressed, showing better robustness and lower triggering frequency. Considering that in practical engineering, pulse actions can introduce additional delays, future research will further analyze scenarios where pulse execution has delays and explore delay-related pulse issues within the proposed triggering framework.

Keywords: Event-triggered impulsive control (ETIC), input-to-state stability (ISS), time delay, Zeno behavior, nonlinear impulsive systems.

1. Introduction

Research on the relationship between system input and state stability (ISS) under event-triggered impulsive control (ETIC) has become quite mature. Because it can greatly reduce the number of redundant control updates, event-triggered impulsive control has received widespread attention in recent years [1]. Existing literature [2] focuses on the super-exponential stability analysis of time-delay neural networks and proposes an event-triggered impulsive control scheme with a delay in execution; literature [3] designs a self-triggered impulsive control strategy closely related to event-triggered impulsive control for stochastic nonlinear systems, reflecting the latest research progress of event-triggered ideas in the field of impulsive control. However, most current studies simplify system delays: for example, literature [4] only analyzes state delays, and literature [5] only studies impulse delays; although some literature further explores the dual-delay problem, their proof process lacks rigor, so this paper does not cite them. Chen et al. [6] studied a large-scale nonlinear system that involves complex structures, delays, and uncertainties in measurement channels. It's worth noting that the vast majority of existing methods either use fixed triggering parameters or fail to fully consider system state delays, which limits their performance in handling more complex delay

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scenarios. To address these issues, this paper proposes a brand-new event-triggered impulsive control strategy that enhances the flexibility of the triggering mechanism and improves system stability. Unlike the approach in literature [4] that uses fixed triggering parameters, this paper introduces variable exponential coefficients w_k and s_k in the triggering function. These coefficients can be adjusted as needed and change dynamically with k. Traditional fixed-threshold event-triggered impulsive control schemes often result in overly frequent pulse triggers when handling nonlinear components.

2. Preliminaries

Notation: Define $\mathbb{PC}\left(\mathscr{X} \to Y\right) := \{\phi : \mathscr{X} \to Y | \phi \text{ is piecewise right-continuous}\}$ for $\mathscr{X} \subset \mathbb{R}$ and $Y \subset \mathbb{R}^n$. A continuous function $\eta : \mathbb{R}_+ \to \mathbb{R}_+$ is said to belong to class $\mathscr{K}$ if it is strictly increasing and $\eta\left(0\right) = 0$. If, in addition, $\eta\left(a\right) \to \infty$ as $a \to \infty$, then η is said to belong to class $\mathscr{K}_\infty$. A function $o : \mathbb{R}_+ \times \mathbb{R}_+ \to \mathbb{R}_+$ is said to belong to class $\mathscr{K}\mathscr{L}$ if, for each fixed $t \geq 0$, $o\left(g, t\right)$ is of class $\mathscr{K}$, and for each fixed $r \geq 0$, $o\left(r, t\right) \to 0$ as $t \to \infty$. For $\sigma > 0/$, let $\mathbb{PC}_\sigma := \mathbb{PC}\left([-\sigma, 0], \mathbb{R}^n\right)$ nbe the space endowed with the norm $\|\phi\|_\sigma := \underset{a\in[-\sigma,0]}{sup} |\phi\left(a\right)|, \phi \in \mathbb{PC}_\sigma$.

Consider the following impulsive delay system:

$$\begin{cases} \dot{y}(t) = f(t, y_t, \zeta(t)), t \neq t_k, t \geq t_0, \\ y(t) = g(t, y(t^-), \zeta(t^-)), t = t_k, k \in \mathbb{Z}_+, \\ y(t) = \xi(t), t_0 - \sigma \leq t \leq t_0 \end{cases} \tag{1}$$

where $y \in \mathbb{R}^n$ is the system state, and $\dot{y}$ is right-hand derivative of y ; $\zeta(t) \in \mathbb{PC}([t_0, \infty), \mathbb{R}^m)$ is a disturbance input. $\xi \in \mathbb{PC}_\sigma$ is the initial function; $y_t\left(a\right) = y\left(t + a\right)$, $a \in [-\sigma, 0]$, $\sigma > 0$. Assuming that f and g meet the necessary regularity requirements, the existence of solutions over the specified time intervals is guaranteed. The solution of system*(1)* is assumed to be right-continuous, i.e., $y\left(t^+\right) = y\left(t\right)$ for all $t \geq t_0$.

Definition1 For a given sequence $\{t_k\}$, system*(1)* is said to be ISS if there exist functions $\beta \in \mathscr{K}\mathscr{L}$ and $\gamma \in \mathscr{K}_\infty$ such that for any input $\zeta \in \mathbb{PC}([t_0, \infty), \mathbb{R}^m)$ and any initial condition $\xi \in \mathbb{PC}_\sigma$, the solution $x\left(t, t_0, \xi\right)$ exists globally and satisfies

$$|y(t)| \leq \beta\left(\|\xi\|_\sigma, t - t_0\right) + \underset{t_0 \leq a \leq t}{sup}\, \gamma\left(|\zeta(a)|\right), \forall t \geq t_0.$$

Definition2 Given a locally Lipschitz function $V : \mathbb{R}^n \to \mathbb{R}_+$, the upper right-hand Dini derivative of V along the solution of system*(1)* is defined by

$$D^+V\left(y\right) = \underset{d\to 0^+}{limsup} \frac{1}{d}\left[V\left(y + df\left(y, \zeta\right)\right) - V\left(y\right)\right]$$

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3. Results

In this section, we derive criteria for excluding Zeno behavior for system *(1)*, and establish the ISS performance of the system under the event-triggered impulsive control framework. We begin with the following ETM:

$$t_k = min\{t_k^\circ, t_{k-1} + \Delta_k\},$$

$$t_k^\circ = inf\left\{\begin{array}{c} t \geq t_{k-1} : V(y(t)) \geq exp(w_k)V(y(t_{k-1})) \\ +exp\left(s_k\right)\varpi\left(\|\zeta\|_{[t_0,t]}\right) + \iota exp\left(-\chi\left(t_{k-1} - t_0\right)\right)V\left(y\left(t_0\right)\right) \end{array}\right\} \tag{2}$$

Where $k \in \mathbb{Z}_+, \varpi \in \mathscr{K}_\infty, \chi, \iota > 0$, and $V_0 = \sup_{a\in[-\sigma,0]} V\left(t_0 + a\right)$. The Lyapunov function is defined as $V(y(t))$. Regarding the parameters $\Delta_k, w_k, s_k \in \mathbb{R}_+$, and $\inf_{k\in\mathbb{Z}_+}\{\Delta_k\} > 0$.

Lemma1 Assume that there exists locally Lipschitz function $V : [t_0 - \sigma, \infty) \times \mathbb{R}^n \to \mathbb{R}_+$ and a constant $0 < \vartheta < 1$ such that

$$(i)\ V\left(t_k, y(t_k^-)\right) \leq \vartheta V\left(t_k^-, y(t_k^-)\right) + \varpi\left(\left\|\zeta\left(t_k^-\right)\right\|\right),\ k \in \mathbb{Z}_+$$

Where $\varpi \in \mathscr{K}_\infty$ and $\zeta \in \mathbb{PC}([t_0, \infty), \mathbb{R}^m)$. Let $\boldsymbol{\nu(t) := V(t, y(t))}$. Under the event-triggered mechanism*(2)*, for any $t \in [t_{k-1}, t_k)$, the Lyapunov function satisfies

$$\nu(t) \leq \vartheta^{k-1}exp(\textstyle\sum_{i=0}^{k-1} w_{k-i})v_0 + \sum_{l=0}^{k-1}\vartheta^l exp(\sum_{i=0}^{l-1} w_{k-i} + s_{k-l})\varpi(\|\zeta\|_{[t_0,t]}) \tag{3}$$

$$+\textstyle\sum_{l=0}^{k-2}\vartheta^l exp(\sum_{i=0}^{l} w_{k-i})\varpi(\|\zeta(t_{k-l-1}^-)\|) + \sum_{l=0}^{k-1}\vartheta^l \iota exp(\sum_{i=0}^{l-1} w_{k-i} - \chi(t_{k-l-1} - t_0))\nu_0 = G_k(t)$$

Proof: First, we show that the conclusion holds on the initial interval. obviously, $\nu\left(t\right) \leq \nu_0$, for $t \in [t_0 - \sigma, t_0]$. From the continuous dynamics of system*(1)* on the interval $t \in [t_0, t_1)$, it follows that

$$v\left(t\right) \leq \left(exp\left(w_1\right) + \iota\right)v_0 + exp\left(s_1\right)\varpi\left(\|\zeta\|_{[t_0,t]}\right)$$

Therefore, the inequality holds on the interval $t \in [t_0, t_1)$. Next, by condition (iii), for $t \in [t_1, t_2)$, we obtain

$$\nu(t) \leq exp(w_2)\nu(t_1) + exp(s_2)\varpi(\|\zeta\|_{[t_0,t]}) + \iota exp(-\chi(t_1 - t_0))\nu_0$$

$$+s_1)\varpi(\|\zeta\|_{[t_0,t]}) + \iota exp(-\chi(t_1 - t_0))\nu_0 + \vartheta\iota exp(w_2)\nu_0 + exp(s_2)\varpi(\|\zeta\|_{[t_0,t]})$$

Assume that for some $k \geq 2$, the conclusion holds for $t \in [t_{k-2}, t_{k-1})$, that is,

$$\nu(t) \leq \vartheta^{k-2}exp(\textstyle\sum_{i=0}^{k-2} w_{k-i-1})\nu_0 + \sum_{l=0}^{k-2}\vartheta^l exp(\sum_{i=0}^{l-1} w_{k-i-1} + s_{k-l-1})\varpi(\|\zeta\|_{[t_0,t]})$$

$+\sum_{l=0}^{k-3}\vartheta^l exp(\sum_{i=0}^{l} w_{k-i-1})\varpi(\|\zeta(t_{k-l-2}^{-})\|)+\sum_{l=0}^{k-1}\vartheta^l \iota exp(\sum_{i=0}^{l-1} w_{k-i-1}-\chi(t_{k-l-2}-t_0))\nu_0$

By the induction hypothesis and the continuous dynamics of system*(1)* on $t\in[t_{k-1},t_k)$, we obtain

$$\nu(t)\le exp(w_k)\nu(t_{k-1})+exp(s_k)\varpi(\|\zeta\|_{[t_0,t]})+\iota exp(-\chi(t_{k-1}-t_0))\nu_0$$

$$\le \vartheta exp(w_k)\nu(t_{k-1}^{-})+exp(w_k)\varpi\|\zeta(t_{k-1}^{-})\|$$

Thus, by mathematical induction, the conclusion holds for all $t\ge t_0-\sigma$. This completes the proof.

Lemma2 Assume that there exists locally Lipschitz continuous function $V:[t_0-\sigma,\infty)\times\mathbb{R}^n\to\mathbb{R}_+$, $\varpi\in\mathscr{K}_\infty$, and positive constant $\kappa_1,\kappa_2,\kappa_3,\varsigma$,such that for all $t\in[t_0-\sigma,\infty),k\in\mathbb{Z}_+,y\in\mathbb{R}^n$ and $\zeta\in\mathbb{R}^m$, the following conditions are satisfied:

$$(ii)\ D^+V\big(t,y(t)\big)\le\kappa_1V\big(t,y(t)\big)+\kappa_2V\big(t+a,y(t+a)\big)+\varpi\big(\|\zeta(t)\|\big),a\in\big[-\sigma,0\big];$$

(iii) The following cumulative inequality holds for any $k\ge 2$ and $0\le l\le k-2$:

$$lln\vartheta+\sum_{i=0}^{l+1}w_{k-i}+s_{k-l}\le-\kappa_3 l+\varsigma$$

Then, under the ETM*(2)*, system*(1)* exhibits no Zeno behavior.

Proof: To proceed with the analysis, the following three cases are considered according to the properties of the ETM*(2),* Let $\boldsymbol{\nu(t)}:=\boldsymbol{V(t,y(t))}$.

Case I: The impulsive sequence $\{t_k\}$ is comprised exclusively of the forced-triggering instants $\{t_k+\varDelta_k\}$, implying that $t_k=t_k+\varDelta_k$ for each $k\in\mathbb{Z}_+$. Consequently, Zeno behavior is inherently precluded by the construction of these forced instants.

Case II: The impulse sequence $\{t_k\}$ contains only the event-triggered times $\{t_k^\circ\}$, meaning that $\{t_k^\circ\}$ for all $k\in\mathbb{Z}_+$. According to t_k° , Zeno behavior is excluded by construction.

According to (3) and condition (iii), when $t\in[t_{k-1},t_k)$, one has

$$\nu(t)\le exp(-\kappa_3(k-1)+\varsigma)\nu_0+\iota\sum_{l=0}^{k-1}exp(-\kappa_3 l+\varsigma-\chi(t_{k-l-1}-t_0))\nu_0+2\sum_{l=0}^{k-2} \tag{4}$$

$$exp(-\kappa_3 l+\varsigma)\varpi(\|\zeta\|_{[t_0,t]})\le exp(\varsigma)(exp(-\kappa_3(k-1))+\tfrac{\iota}{1-exp(-\kappa_3)})\nu_0+\tfrac{2exp(\varsigma)}{1-exp(-\kappa_3)}\varpi(\|\zeta\|_{[t_0,t]})$$

Accordingly, for $t\in[t_{k-1},t_k)$, it follows that

$$\nu\Big(t+a\Big)\le exp(\varsigma\Big)\Big(exp(-\kappa_3\Big(k-1\Big)\Big)+\frac{\iota}{1-exp(-\kappa_3)}\Big)\nu_0+\frac{2exp(\varsigma)}{1-exp(-\kappa_3)}\varpi\Big(\|\zeta\|_{[t_0,t]}\Big)$$

For $t\in[t_{k-1},t_k)$, according to condition(i), the following inequality holds:

$$D^{+}\nu\Big(t\Big) \leq \kappa_1\nu\Big(t\Big) + \kappa_2\Big[exp(\varsigma\Big)\Big(exp(-\kappa_3\Big(k-1\Big)\Big) + \frac{\iota}{1-exp(-\kappa_3)}\Big)\nu_0 + \frac{2exp(\varsigma)}{1-exp(-\kappa_3)}$$
$$\varpi\Big(\|\zeta\|_{[t_0,t]}\Big)\Big] + \varpi\left(\|\zeta\|_{[t_0,t]}\right)$$

Then, integrating the above inequality in $[t_{k-1}, t_k)$, $\varpi := \underset{t\in[t_0,t_k]}{sup}\ \varpi\left(\|\zeta\|_{[t_0,t]}\right)$, also note:

$$G(t) = \kappa_2[exp(\varsigma)(exp(-\kappa_3(k-1)) + \tfrac{\iota}{1-exp(-\kappa_3)})\nu_0$$

$$+\tfrac{2exp(\varsigma)}{1-exp(-\kappa_3)}\varpi(\|\zeta\|_{[t_0,t]})] + \varpi(\|\zeta\|_{[t_0,t]})$$

one obtains

$$\nu(t) \leq exp(\kappa_1(t-t_{k-1}))\nu(t_{k-1}) + \textstyle\int_{t_k}^{t} exp(\kappa_1(t-s))G(t)ds$$

$$\leq exp(\kappa_1(t-t_{k-1}))\nu(t_{k-1}) + \tfrac{G(t)}{\kappa_1}(exp(\kappa_1(t-t_{k-1}))-1)$$

Let $t = t_k^-$, then $\nu\left(t_k^-\right) \leq exp(\kappa_1\big(t_k - t_{k-1})\big)\left(\nu(t_{k-1}) + J\right) - J$.

Where $J = \frac{\kappa_2}{\kappa_1}\left(exp\left(\varsigma\right)\left(-\kappa_3\left(k-1\right) + \frac{\iota}{1-exp(-\kappa_3)}\right)\nu_0 + \frac{2exp(\varsigma)}{1-exp(-\kappa_3)}\varpi\right) + \frac{\varpi}{\kappa_1}$ .together with $\nu\left(t_k^-\right) = exp\left(w_k\right)\nu\left(t_{k-1}\right) + exp\left(s_k\right)\varpi\left(\|\zeta\|_{[t_0,t]}\right) + \iota exp\left(-\chi\left(t_{k-1}-t_0\right)\right)\nu_0$, implies that

$$exp(w_k)\nu\left(t_{k-1}\right) + exp\left(s_k\right)\varpi + \iota exp\left(-\chi\left(t_{k-1}-t_0\right)\right)\nu_0 \leq exp(\kappa_1(t_k - t_{k-1}))\left(\nu(t_{k-1}) + J\right) - J$$

If the Zeno behavior appears, then there exists a constant $t_e > 0$ such that $\underset{k\to\infty}{lim} t_k = t_e$. It follows from the above estimate that

$$0 \leq \frac{1}{\kappa_1} ln\left(\frac{exp(w_k)\nu(t_{k-1}) + exp(s_k)\varpi + \iota exp(-\chi(t_{k-1}-t_0))\nu_0 + J}{\nu(t_{k-1}) + J}\right) \leq t_k - t_{k-1}, \text{ and } t_k - t_{k-1} \to 0 \text{ as } k \to \infty$$

This results in a contradiction. Accordingly, the conditions given in Theorem1 prevent Zeno behavior, and the proof is complete.

Case III: The impulsive time sequence $\{t_k\}$ is determined by both forced and event-triggered mechanisms, i.e., $t_k = min\{t_k + \Delta_k, t_k^\circ\}$. Since both Case I and Case II exclude the existence of an accumulation point for $\{t_k\}$, Zeno behavior is also excluded in this mixed scenario.

Theorem1 Under the conditions in Lemma1 and Lemma2, assume that there exist function $\delta_1, \delta_2 \in \mathscr{K}_\infty$ such that

$$(iv)\ \delta_1\left(|y|\right) \leq V(t,y) \leq \delta_2(|y|),\ t \geq t_0 - \sigma, y \in \mathbb{R}^n.$$

Then, system(1) coupled with ETM(2) is ISS

According to(4), for each $t \in [t_{k-1}, t_k)$, the following result holds:

$$\nu\Big(t\Big) \leq exp(\Big(k-1\Big)ln\vartheta + \sum_{i=0}^{k-1} w_{k-i}\Big)\nu_0 + 2\sum_{l=0}^{k-2} exp(lln\vartheta + \sum_{i=0}^{l+1} w_{k-i} + s_{k-l}\Big)\varpi\Big(\|\zeta\|_{[t_0,t]}\Big)$$

$$+\iota\sum_{l=0}^{k-1} exp(lln\vartheta + \sum_{i=0}^{l-1} w_{k-i} - \chi(t_{k-l-1} - t_0)\Big)\nu_0$$

$$\leq exp(\varsigma\Big)\left(exp\left(-\kappa_3\left(k-1\right)\right) + \frac{\iota}{1-exp(-\kappa_3)}\right)\nu_0 + \frac{2exp\left(\varsigma\right)}{1-exp\left(-\kappa_3\right)}\varpi\left(\|\zeta\|_{[t_0,t]}\right)$$

From condition(iii), $\forall t \in [t_{k-1}, t_k)$,one has

$$\|y(t)\| \leq \delta_1^{-1}\nu(t) \leq \tfrac{1}{2}\delta_1^{-1}\{2exp(\varsigma)(exp(-\kappa_3(k-1)) + \tfrac{\iota}{1-exp(-\kappa_3)})\delta_2(\|\xi\|_\sigma)\}$$

$$+\tfrac{1}{2}\delta_1^{-1}\{\tfrac{4exp(\varsigma)}{1-exp(-\kappa_3)}\varphi(\|\zeta\|_{[t_0,t]})\}$$

Hence, system(1) is ISS under the event-triggering mechanism(2), thereby completing the proof.

Remark Condition(i) specifies the continuous dynamics of system (1), including the delay-independent and delay-dependent terms, thereby restricting the rate at which the solution can grow. Condition(ii) specifies how the state of system(1) changes at the discrete impulse time t_k , that is, the impulse effect, ensuring that the system can maintain stability at these discrete moments through a certain contraction mechanism .Condition(iv) ensures that the Lyapunov function remains positive and increases without bound with respect to the system state. Compared with the event-triggering mechanism using fixed constant parameters in reference [4], it can be flexibly changed according to needs in the design and expands its scope of application.

4. Numerical Example

Consider the following nonlinear delayed impulsive system motivated by [7]:

$$(t) = \tfrac{1.2|cost|y^3(t)}{1+y^2(t)} - 0.9|sint|y(t) + 0.5costy(t-8) + \omega(t), t \neq t_k y(t_k^-) \tag{5}$$

$$= exp(-0.7)y(t_k^-) + \omega(t_k^-), t = t_k,$$

where $y\left(t\right) \in \mathbb{R}$, the exogenous input $\omega\left(t\right) = sint$, and the fixed delay is $\tau = 8$ .Select the ISS-Lyapunov function $V\left(y\right) = |y|$. For $t \neq t_k$, one has

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$\overset{g}{V}(y(t)) \leq 1.2V(y(t)) + 0.5V(y(t-8)) + |\omega(t)|$,

with $\mu = exp(-0.7) < 1$, the impulsive instants $t = t_k$ satisfy the ISS-related criteria defined in Theorem1. With $\iota = 0.3$, $\chi = 0.05$, and coefficients $w_k = (50 + 0.1k) \times 10^{-6}$, $s_k = (20 + 0.1k) \times 10^{-6}$ satisfying the cumulative decay condition(iii), In this article, these parameters w_k, s_k can be adjusted flexibly and can also change with k . Traditionally, it is a constant greater than 1 and cannot be adjusted flexibly, $\kappa_3 = 0.1$, $\varsigma = 5$. The system starts with an initial state of $y(t) = 1.2$, which is set over the interval $t \in [-8,0]$, and the input is $\omega(t) = sint$.

Figure 1 shows the state trajectory of system (5) without any control action, while Figure 2 shows the state trajectory of the system under the adaptive hybrid event/forced-trigger pulse control proposed in this paper. Black dots and red circles represent the moments when event-triggered pulses and forced pulses occur, respectively. This system can achieve input-to-state stability (ISS) and avoids Zeno behavior, offering more flexibility compared to the fixed-coefficient method in reference [4].

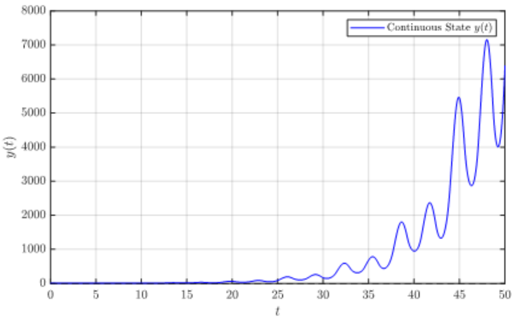

Figure 1. The state trajectories of system (5) without impulsive control

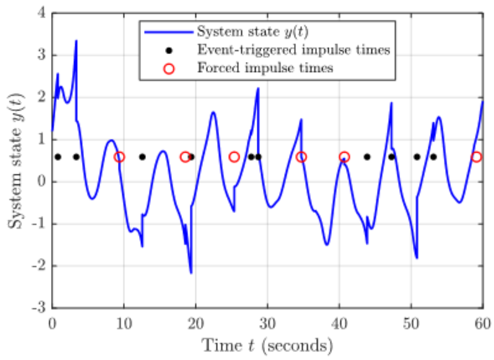

Figure 2. Simulation of system (5) with impulsive control

5. Conclusion

This article is based on Lyapunov stability theory and focuses on a type of nonlinear system with time-delay characteristics, constructing a highly flexible triggering mechanism. The event-triggered pulse control scheme designed based on this mechanism can ensure the input-to-state stability (ISS) of the system and effectively avoid Zeno behavior. Simulation results of typical numerical examples validate the superiority and control performance advantages of the proposed method. Considering that in practical engineering applications, pulse actions usually introduce additional time delays, future research will further explore scenarios where pulse execution has delays, and under the triggering framework established in this article, study time-delay pulse-related issues. The system conditions with delays, novel control stability problems in robotics, and in-depth research on time-delay pulse control under the established triggering framework will be conducted.

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