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Input-to-State Stabilization of Nonlinear Systems via Event-Triggered Impulsive Control

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ABSTRACT In this work, an event-triggered impulsive control (ETIC) method is proposed to address the input-to-state stabilization (ISS) issue for a class of nonlinear systems under external disturbance. Different from many existing impulsive controllers usually with fixed impulse instants, we design a novel one which is event-triggered and multimodule constrained. Based on that, we establish some ISS criteria for the considered system with and without data dropouts. The presented event-triggered control method can save the communication resources and avoid the Zeno behaviors. Finally, an example with simulations results is provided to illustrate the validity of the method.

INDEX TERMS Impulsive control, event-triggered control, input-to-state stabilization, multimodule impulse, data dropouts.

I. INTRODUCTION

Hybrid systems refer to the mathematical representation of models with continuous-time behavior and discrete-event behavior. Such systems have attracted considerable interest during the last few decades [1]–[11]. Impulse is a typical hybrid behavior which depicts state jump at a time sequence. In the view of control, impulsive control has drawn much attention for several decades. Impulsive control arises from engineering, economics, biology and medicine. It is prior in improving the transient response [12] and saving the bandwidth resource [13]. For more related research, one can refer to [14]–[18].

Moreover, in order to save the network bandwidth, event-triggered control was proposed from relevant research on networked systems. The main idea of event-triggered scheme is to design a well-defined event beforehand and trigger an action according to the event. Therefore, a system adaptively adjusts sample rates by the event, thereby reducing the communication frequency. There have been many relevant results concerning event-triggered control, such as event-triggered control for linear and nonlinear systems [19], [20], distributed event-triggered control for interconnected systems [21], distributed event-triggered synchronization [22], event-triggered switching control [23], and event-triggered H_∞ load frequency control [24]. For more related work, one can see [25], [26] and references therein. Notice that many current results considered event-triggered continuous control and ETIC was rarely studied. Different from conventional event-triggered continuous control, ETIC provides an effective control method that can reduce control frequency and save resources.

As mentioned above, impulsive control can reduce the control cost, and event-triggered control can save the communication and computation resources. However, there has been rare work considering ETIC especially when impulse is constrained until now. The work [27] addresses exponential stability for continuous-time systems by designing ETIC. However, the impulse instants therein are generated continuously according to the event, which brings much computational burden. In our previous work [28], some exponential stability criteria were established by ETIC for nonlinear systems without external disturbance. When external disturbance affects the system, its ISS analysis is a difficult and meaningful topic that attracts many interests, which motivates our research.

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Due to the priorities of impulsive control and event-triggered control, we will present a novel ETIC scheme for a class of nonlinear systems under external disturbance. The novelty lies in that impulse instants and impulse gains are event-triggered and multimodule constrained. The multimodule framework can model control systems when only a finite number of modules are available, such as the multimodule propulsion systems for orbit transfer [29].

The main contributions of this paper are listed as follow. First, we propose an ETIC method for continuous-time nonlinear systems. The designed impulsive controller is event-triggered and multimodule constrained, and thereby flexible in reducing control/communication frequency and improving system performance. Second, we derive some new ISS criteria for the considered system when data dropouts exist or not, which are more general than many exiting results. Third, according to our control design, the impulse instant sequence admits a positive dwell time, and thereby the Zeno behaviors are easily avoided.

Notations: In this paper, $\mathbf{R}$ stands for the set of all real numbers; $\mathbf{N}$ symbols the set of all natural numbers; $\mathbf{R}^n$ is the set of all n-dimensional real vectors; $\mathbf{R}^{n\times n}$ is the set of all $n \times n$ real matrices; $|\cdot|$ denotes the standard Euclidean norm; $M = \{1, \cdots, m\}$ is a finite set of indices, where $m \in \mathbf{N}$; and $|w|_\infty = \sup_{t\geq t_0} |w(t)| < \infty$.

II. PRELIMINARIES

Consider a continuous-time nonlinear dynamical system

$$\begin{cases} \dot{x}(t) = f(x(t), w(t), t), & t \geq t_0, \\ x(t_0) = x_0, \end{cases} \tag{1}$$

where $x(t) \in \mathbf{R}^n$ is the system state, $w(t) \in \mathbf{R}^n$ is the external disturbance, t_0 is the initial time, $f(0, 0, \cdot) = 0$. In this work, we mainly study ISS problem for system (1) based on impulsive control, i.e., to design an impulsive controller such that the following system

$$\begin{cases} \dot{x}(t) = f(x(t), w(t), t), & t \neq t_k, \\ x(t^+) = U(x(t^-)), & t = t_k, \quad k = 1, 2, \ldots \\ x(t_0) = x_0, \end{cases} \tag{2}$$

is ISS, where $\{t_k\}_{k=1}^{\infty}$ is the impulse instant sequence to be designed, $U(x) \in \{B_1x, \cdots, B_mx\}$ is the multimodule constrained impulsive control input, $B_j \in \mathbf{R}^{n\times n}$, $\forall j \in M$. We suppose that the system state is continuous from the left.

Assumption 1: The control time satisfies

$$t_{k+1} - t_k \in \{\tau_1, \cdots, \tau_r\}, \quad \forall k \in \mathbf{N},$$

where r is a positive integer, and τ_i is a positive real number for all $i \in \{1, 2, \cdots, r\}$.

Assumption 1 indicates that the impulse time interval between any two consecutive impulses is among a known set.

Assumption 2: There exists a positive real number $\mu < 1$, such that $\min_{j\in \mathbf{M}} |B_jx| \leq \mu|x|$.

For convenience, we define $j^*(x) = \arg\min_{j\in\mathbf{M}} |B_jx|, \forall x \in \mathbf{R}^n$.

Remark 1: Notice that the set of impulse gain matrices are given variables in this paper. We focus on designing proper impulsive controller that combines impulse instants and gain matrices to steer the system ISS. Assumption 2 means that any point in the state space can be contracted by some B_j and the whole state space can be contracted by the set of matrices. In this sense, it is less conservative than many existing results which usually choose a simple or diagonal impulse gain matrix.

Assumption 3: The state of system (1) is measurable and

$$D^+|x|_{(1)} \leq \rho|x|, \quad \textit{whenever } |x| \geq K|w|_\infty,$$

where ρ and K are positive constants and $D^+|x|_{(1)}$ is the Dini derivative of $|x|$ along system (1).

In this assumption, $\rho > 0$ means that system (1) may not be input-to-state stable.

Notice that event-triggered control can reduce control and communication frequency [30], [31]. We will design an ETIC that steers the system (1) input-to-state stable. Let $\beta < 1$ be a positive real number, and design the events and impulsive controller as

$$E_1: \begin{cases} \Lambda_{1k} = \{t | \exists t \in \{t_k + \tau_1, \cdots, t_k + \tau_r\}, s.t., \\ \qquad\qquad |x(t)| \geq \beta|x(t_k^+)| + K|w|_\infty\}, \\ t_{k+1} = \min\{t : t \in \Lambda_{1k}\}, \\ x(t_{k+1}^+) = B_{j*(x(t_{k+1}))}x(t_{k+1}), \end{cases} \tag{3}$$

$$E_2: \begin{cases} \Lambda_{2k} = \{t | \forall t \in \{t_k + \tau_1, \cdots, t_k + \tau_r\}, \\ \qquad\qquad |x(t)| < \beta|x(t_k^+)| + K|w|_\infty\}, \\ t_{k+1} = t_k + \max\{\tau_1, \cdots, \tau_r\}, \\ x(t_{k+1}^+) = x(t_{k+1}). \end{cases} \tag{4}$$

Based on the ETIC (3)-(4), system (2) can be converted into

$$\begin{cases} \dot{x}(t) = f(x(t), w(t), t), \ t \in [t_k, t_{k+1}), \quad k \in \mathbf{N}, \\ x(t_{k+1}^+) = \\ \begin{cases} B_{j*(x(t_{k+1}))}x(t_{k+1}), & t_{k+1} \in \Lambda_{1k}, \\ x(t_{k+1}), & t_{k+1} \in \Lambda_{2k}, \end{cases} \\ x(t_0) = x_0. \end{cases} \tag{5}$$

Remark 2: Notice that system (5) is different from those studied in [2]–[4], [17], [18]. In this work, impulse instants and impulse gains are event-triggered and multimodule constrained, which makes the considered system one special type of impulsive systems.

Definition 1: System (1) is called globally uniformly exponentially input-to-state stabilized, if the closed-loop system (2) is globally uniformly exponentially input-to-state stable (GUEISS) under (3)-(4) with convergence rate α, i.e., the following inequality

$$|x(t)| \leq ce^{-\alpha(t-t_0)}|x_0| + K|w|_\infty, \quad \forall t \geq t_0$$

holds for positive real numbers c, α and K.

III. MAIN RESULTS

A. STABILITY ANALYSIS WITHOUT DATA DROPOUTS

Denote $N_j^{(i,k]}$ as the number of event E_j occuring during the time interval $(t_i, t_k]$, $\forall i, k \in \mathbf{N}, k > i, j = 1, 2$.

Based on designed events and impulsive controller as in Section II, we obtain the following stability criteria.

Theorem 1: If Assumptions 1-3 and the following condition hold

$$N_1^{(i,k]}(\ln\mu+\rho\tau_{\max})+N_2^{(i,k]}\ln\beta \le \gamma-\alpha(k-i), \quad \forall k>i \tag{6}$$

for two constants $\alpha > 0$ and $\gamma > 0$, then system (2) is GUEISS with convergence rate $\frac{\alpha}{\tau_{\max}}$, where $\tau_{\max} = \max\{\tau_1, \cdots, \tau_r\}$.

Proof: According to Assumption 1, the impulse instant sequence satisfies $t_{k+1} - t_k \ge \min\{\tau_1, \cdots, \tau_r\} > 0$, $\forall k \in \mathbf{N}$, then the designed ETIC can avoid Zeno behaviors. Next, we prove that system (2) is GUEISS under condition (6). For any $k \in \mathbf{N}$, if $t_{k+1} \in \Lambda_{1k}$, we have

$$\begin{aligned}|x(t_{k+1}^+)| &= |B_{j^*(x(t_{k+1}))}x(t_{k+1})|\\ &\le \mu|x(t_{k+1})|\\ &\le \mu e^{\rho(t_{k+1}-t_k)}[|x(t_k^+)|+K|w|_\infty]\\ &\le \mu e^{\rho\tau_{\max}}[|x(t_k^+)|+K|w|_\infty].\end{aligned}$$

If $t_{k+1} \in \Lambda_{2k}$, we obtain

$$|x(t_{k+1}^+)| = |x(t_{k+1})| \le \beta|x(t_k^+)| + K|w|_\infty.$$

Let $a_{k+1} = |x(t_{k+1}^+)|$, then it holds that

$$a_{k+1} \le c_k a_k + b_k,$$

where

$$c_k = \begin{cases}\mu e^{\rho\tau_{\max}}, & t_{k+1} \in \Lambda_{1k},\\ \beta, & t_{k+1} \in \Lambda_{2k},\end{cases} \tag{7}$$

and

$$b_k = \begin{cases}K|w|_\infty, & t_{k+1} \in \Lambda_{1k},\\ \mu e^{\rho\tau_{\max}}K|w|_\infty, & t_{k+1} \in \Lambda_{2k}.\end{cases} \tag{8}$$

By Lemma 1 in [32], we conclude that

$$\begin{aligned}a_{k+1} &\le \prod_{i=0}^{k} c_i a_0 + \Big(b_k + \sum_{i=1}^{k}\Big(\prod_{j=i}^{k} c_j\Big)b_{i-1}\Big)\\ &\le (\mu e^{\rho\tau_{\max}})^{N_1^{(0,k]}}\beta^{N_2^{(0,k]}}a_0\\ &\quad + \Big(b_k + \sum_{i=1}^{k}(\mu e^{\rho\tau_{\max}})^{N_1^{(i,k]}}\beta^{N_2^{(i,k]}}b_{i-1}\Big).\end{aligned} \tag{9}$$

If condition (6) holds, inequality (9) is translated into

$$a_{k+1} \le Ce^{-\alpha k}a_0 + \bar{K}|w|_\infty, \tag{10}$$

where $C = e^\gamma$, and $\bar{K} = \frac{\max\{1,\mu e^{\rho\tau_{\max}}\}CK}{(1-e^{-\alpha})}$.

Notice that for any $t \in (t_k, t_{k+1}]$, the fact $k \ge \frac{t-t_0}{\tau_{\max}}$ holds, which together with (10) gives

$$|x(t)| \le Ce^{-\frac{\alpha}{\tau_{\max}}(t-t_0)}a_0 + \bar{K}|w|_\infty.$$

Therefore, system (2) is GUEISS with convergence rate $\frac{\alpha}{\tau_{\max}}$.

B. DATA DROPOUTS EXIST IN THE ETIC

If data dropouts exist in the ETIC, the ISS analysis should take the effects of data dropouts into consideration. When data dropouts of the ETIC occur, the state jump caused by impulse will not occur.

We define $d_j^{(i,k]}$ as the number of dropouts of event E_j occurring during the time interval $(t_i, t_k]$, and $s_j^{(i,k]}$ as the number of event E_j received successfully by the system during $(t_i, t_k]$, $j = 1, 2$. Define η_j as the maximal allowable dropout rate of event E_j. Now we establish the following GUEISS criteria for system (5) with data dropouts existing in the ETIC.

Theorem 2: Under ETIC (3)-(4) with data dropouts, if Assumptions 1-3 and the following condition hold

$$\begin{aligned}(1-\eta_1)N_1^{(i,k]}\ln\mu + N_1^{(i,k]}\rho\tau_{\max} + N_2^{(i,k]}\ln\beta&\\ \le \gamma-\alpha(k-i), \quad \forall k>i&\end{aligned} \tag{11}$$

for two constants $\alpha > 0$ and $\gamma > 0$, then system (2) is GUEISS with convergence rate $\frac{\alpha}{\tau_{\max}}$, where $\tau_{\max} = \max\{\tau_1, \cdots, \tau_r\}$, and η_1 is the maximal allowable dropout rate of event E_1.

Proof: When data dropouts exist in the ETIC, it holds that

$$N_j^{(i,k]} = s_j^{(i,k]} + d_j^{(i,k]}, \quad j = 1, 2.$$

According to the definition of the maximal allowable dropout rate of the event E_j, we obtain

$$d_j^{(i,k]} \le \eta_j N_j^{(i,k]},$$

which leads to

$$s_j^{(i,k]} \ge (1-\eta_j)N_j^{(i,k]}.$$

If data dropouts exist in the ETIC, similar to the proof of Theorem 1, then expression (9) is changed to

$$\begin{aligned}a_{k+1} &\le \mu^{(1-\eta_1)N_1^{(0,k]}}e^{N_1^{(0,k]}\rho\tau_{\max}}\beta^{N_2^{(0,k]}}a_0\\ &\quad + \Big(b_k + \sum_{i=1}^{k}\mu^{(1-\eta_1)N_1^{(i,k]}}e^{N_1^{(i,k]}\rho\tau_{\max}}\beta^{N_2^{(i,k]}}b_{i-1}\Big).\end{aligned} \tag{12}$$

If condition (11) holds, inequality (12) leads to

$$a_{k+1} \le Ce^{-\alpha k}a_0 + \bar{K}|w|_\infty, \tag{13}$$

where $C = e^\gamma$, and $\bar{K} = \frac{\max\{1,\mu e^{\rho\tau_{\max}}\}CK}{(1-e^{-\alpha})}$.

Notice that for any $t \in (t_k, t_{k+1}]$, it holds that $k \ge \frac{t-t_0}{\tau_{\max}}$, which together with (13) gives

$$|x(t)| \le Ce^{-\frac{\alpha}{\tau_{\max}}(t-t_0)}a_0 + \bar{K}|w|_\infty.$$

Therefore, system (2) is GUEISS with convergence rate $\frac{\alpha}{\tau_{\max}}$. This completes the proof.

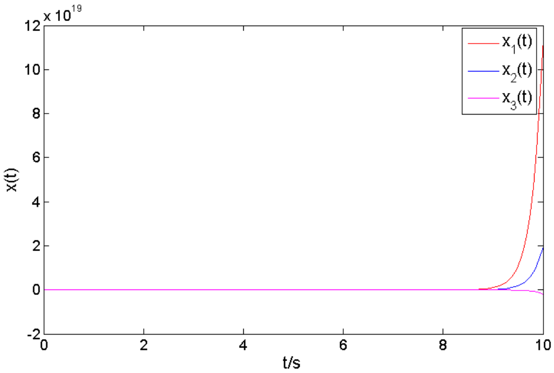

FIGURE 1. The state trajectories of system (14).

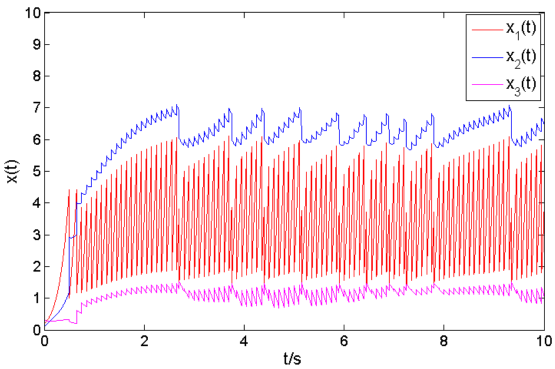

FIGURE 2. The state trajectories of the impulsive control system (15).

IV. EXAMPLE

Consider the Chua's circuit under external disturbance

$$\begin{cases} \dot{x}_1(t) = a[x_2 - x_1 - g(x_1)] + w_1(t), \\ \dot{x}_2(t) = x_1 - x_2 - x_3 + w_2(t), \\ \dot{x}_3(t) = -bx_2 + w_3(t), \end{cases} \tag{14}$$

where $g(x_1) = qx_1 + 0.5(p-q)(|x_1 + d| - |x_1 - d|)$, p, q and d are constant parameters. Let $a = 10$, $b = 15$, $p = -1.27$, $q = -0.65$, $d = 1$, $w_1(t) = \sin 2t$, $w_2(t) = \cos t$, $w_3(t) = 2\sin t$, and set the initial state be $[0.2, 0.1, 0.3]'$. The state trajectories of system (14) are depicted in Fig.1, which show the original system is not ISS.

Next, based on the results in Section III, we design ETIC to stabilize system (14). Let $t_{k+1} - t_k \in \{0.05, 1\}$, $k \in \mathbf{N}$, and $U(x) \in \{B_1 x, B_2 x\}$ with

$$B_1 = \begin{bmatrix} 0.8 & 0.5 & 0.5 \\ 0.2 & 0.1 & 0.1 \\ 0.5 & 0 & 1 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0.2 & 0.1 & 0 \\ 0.5 & 0.6 & 0 \\ 0 & 0.2 & 0.1 \end{bmatrix}.$$

The impulsive control system is represented as

$$\begin{cases} \dot{x}_1(t) = a[x_2 - x_1 - g(x_1)] + w_1(t), \\ \dot{x}_2(t) = x_1 - x_2 - x_3 + w_2(t), \quad t \in [t_k, t_{k+1}), \\ \dot{x}_3(t) = -bx_2 + w_3(t), \\ x(t_{k+1}^+) = \begin{cases} B_{j*(x(t_{k+1}))} x(t_{k+1}), & t_{k+1} \in \Lambda_{1k}, \\ x(t_{k+1}), & t_{k+1} \in \Lambda_{2k}. \end{cases} \end{cases} \tag{15}$$

Choose $\beta = 0.8$ and let the other parameters be same as that of system (14). According to Theorem 1, we can verify that system (15) is EISS. The state trajectories of system (15) are depicted in Fig.2, which show the system is ISS under designed ETIC.

V. CONCLUSION

We studied the ISS problem for a class of continuous-time nonlinear systems via a novel ETIC method. According to our design, impulse instants and gain matrices were event-triggered and multimodule constrained. Notice that the Zeno behaviors were easily avoided and communication resources were saved. How to optimize the ETIC is also an interesting problem that deserves our future study.

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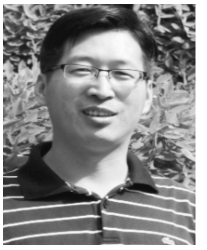

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