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Event-based prescribed-time control for uncertain nonlinear systems with unknown time-varying powers: a non-adaptive control scheme

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In modern control theory, system stability and convergence speed remain fundamental concerns. In recent years, many scholars have made significant strides in improving the steady-state performance of nonlinear systems. A variety of control strategies have been developed, including finite-time control and fixed-time control. While these methods ensure that the system state converges to the origin within a finite time, the exact duration remains somewhat uncertain, as it depends on initial conditions or specific design parameters. To address these uncertainties, the recently introduced PT control method by [1] has gained considerable attention. As the name suggests, this method enables the designer to specify the exact time at which the system achieves stability, regardless of initial conditions or system parameters. This control scheme has proven highly effective in practical applications like missile guidance systems. Therefore, the exploration of prescribed time control is essential. The PT state feedback stabilization problems for stochastic high-order nonlinear systems were studied in [2]. A non-singular PT control scheme was developed in [3] based on a periodic delay sliding surface, ensuring PT convergence under non-singularity conditions.

In another aspect, the majority of existing conclusion support the use of adaptive control methods in the presence of system uncertainty. However, adaptive control is often associated with complex designs and high computational demands. Hence, it becomes crucial to develop a control method with a simple control structure. With the increasing complexity of practical engineering applications, traditional linear or fixed-structure control methods often fail to satisfy the performance requirements of systems operating under multiple modes, multitasking conditions, or varying environments. Switching control has therefore gained prominence as an effective approach, allowing systems to achieve stable or optimal performance across different operational modes through suitable switching strategies. In recent years, switching control has garnered considerable research attention [4]. However, this method also fails to specify the time required for the system to achieve stabilization and may introduce discontinuities in the controller. Therefore, addressing these issues will be another focus of this study.

Moreover, scholars have conducted extensive research on event-triggered control. However, these conclusions are limited to cases where the powers of the control systems are known and remain constant. Once the powers are unknown and time-varying [5], these schemes become inapplicable.

Building on the previous discussion, the present study addresses the event-based PT control problem for nonlinear systems subject to unknown time-varying powers. The major innovations of this study are concisely summarized as follows. (1) This study proposes a novel non-adaptive PT control method that guarantees convergence of the system state to zero within a predetermined time. Compared with existing adaptive schemes, the proposed approach features a simpler control architecture and lower computational complexity. (2) This study develops a time-varying high-gain control algorithm and constructs a continuous PT controller. The proposed approach overcomes the limitations of existing switching control schemes, specifically the discontinuity of the controller and the inability to determine the stabilization time. (3) This study proposes a dynamic event-triggering mechanism for nonlinear systems with unknown and time-varying powers. Moreover, through a rigorous proof by contradiction, it is shown that the proposed method is free from the Zeno phenomenon.

Notations: The arguments of some functions in this article are either omitted or presented in a simplified form, with the notation explained as follows. For instance, f_i or f will be used to represent the functions $f_i(\bar{x}_i(t), t, \theta_i)$. $\mathbb{R}$ denotes all real numbers, $\mathbb{R}^+$ stands for all nonnegative real numbers, and $\mathbb{R}^i$ refers to the i-dimensional Euclidean space. $sign(\xi)$ stands for symbolic function. For any constant $c > 0$, $\lceil z \rfloor^c := |z|^c sign(z)$. $N_{\overline{1,n}}$ represents $1, \ldots, n$.

System formulation. The following nonlinear systems characterized by unknown time-varying powers are addressed in this work:

$$\begin{cases} \dot{x}_i = b_i(\bar{x}_i, t)\lceil x_{i+1} \rfloor^{p_i(t)} + f_i(\bar{x}_i, t, \theta_i), \\ \dot{x}_n = b_n(\bar{x}_n, t)\lceil u \rfloor^{p_n(t)} + f_n(\bar{x}_n, t, \theta_n), \end{cases} \tag{1}$$

where $i \in N_{\overline{1,n-1}}$, $x_i(t) \in \mathbb{R}$ and $u \in \mathbb{R}$ are state variables and control input; $\theta_i \in \mathbb{R}$ are the unknown parameters; $p_i(t) \in \mathbb{R}^+ \to \mathbb{R}$

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are unknown time-varying functions called the powers of the systems; $b_i(\bar{x}_i,t) \neq 0$ and $f_i(\bar{x}_i,t,\theta_i) \in \mathbb{R}^i \times \mathbb{R}^+ \times \mathbb{R} \to \mathbb{R}$ are unknown nonlinear functions.

The following are some common and necessary reasonable assumptions.

Assumption 1. There exist known constants $\bar{p}$ and $\underline{p}$ for which,

$$1 \geqslant \bar{p} \geqslant p_1(t) \geqslant p_2(t) \geqslant \cdots \geqslant p_n(t) \geqslant \underline{p} > 0. \tag{2}$$

Assumption 2. For $i \in N_{\overline{1,n}}$, there exist nonnegative smooth functions h_i such that

$$|f_i(\bar{x}_i,t,\theta_i)| \leqslant \theta h_i(\bar{x}_i,t) \sum_{j=1}^{i} |x_j|^{\bar{p}}, \tag{3}$$

where θ is an unknown constant.

Assumption 3. For $i \in N_{\overline{1,n}}$, the functions $b_i(\bar{x}_i,t)$ satisfy $0 < \underline{b} \leqslant b_i(\bar{x}_i,t) \leqslant \bar{b}$, where $\underline{b}$ and $\bar{b}$ are unknown constants.

Assumptions 1 and 2 are common general conditions regarding system powers and unknown nonlinear growth, as found in [5]. However, compared to [5], Assumption 3 is relatively relaxed.

Definition 1. If a continuous monotonically increasing positive function $\mu(t)$ satisfies the following conditions: (1) $\lim_{t\to T^-} \mu(t) = +\infty$ with $\mu(0)$ is a positive constant; (2) $\lim_{t\to T^-} \int_\varepsilon^t \mu(s)ds = +\infty$ with $\varepsilon \in [0,T)$ is a constant. Then, $\mu(t)$ is referred to as a PT function (PTF).

There are many functions that satisfy Definition 1, such as $\mu_c = \frac{c}{(T-t)^c}$ with $l \geqslant 2$, $\mu_e = e^{\frac{a}{T-t}}$ and $\mu_\pi = \tan(\frac{\pi t}{2T}) + a$.

Control objective: This work aims to design the PT controller based on an event-triggered mechanism for the nonlinear system (1), which adheres to Assumptions 1–3, thereby ensuring that the system state is regulated to zero by the prescribed time T.

Control design. When designing the virtual control law recursively, the following coordinate transformations are essential:

$$\begin{cases} z_1(t) = x_1(t), \\ z_i(t) = x_i(t) - \chi_{i-1}(t),\ i \in N_{\overline{2,n}}, \\ \chi_i(t) = -\mu^{\frac{2}{\underline{p}}} \gamma_i^{\frac{1}{\underline{p}}}(t)(z_i(t) + \lceil z_i \rceil^{\frac{\bar{p}}{\underline{p}}}(t)),\ i \in N_{\overline{1,n}}, \end{cases} \tag{4}$$

where $\mu = \frac{T^2}{(T-t)^2}$ is a PTF, χ_i are virtual controllers, and γ_i are smooth positive functions that are defined below:

$$\gamma_1 = c_1 + \frac{d_{11}}{4} h_1^2, \tag{5}$$

$$\gamma_i = c_i + \varphi_{i1} + \varphi_{i2} + \varphi_{i3} + (i-1)\varphi_{i4}, \tag{6}$$

c_i and d_{11} are positive constants, and φ_{ij}, $i \in N_{\overline{2,n}}$, $j \in N_{\overline{1,4}}$ are nonnegative functions. In the controller design, the unknown parameters are grouped into a unified set according to the principle of parameter separation, and a switching function is constructed to compensate for them. The detailed derivation process is provided in Appendix B.

Event-trigger mechanism. This subsection introduces a new event-triggering mechanism. First, we construct the controller and the event-triggering mechanism for

$$v(t) = \chi_n(t), \tag{7}$$

$$u(t) = v(t_s),\ \forall t \in [t_s, t_{s+1}),\ s \in N^+, \tag{8}$$

$$t_{s+1} = inf\left\{ t > t_s \big| |z_n e(t)| > \rho\aleph(t) + \sigma c \sum_{j=1}^{n} z_j^{1+\bar{p}} \right\}, \tag{9}$$

where $e(t) = \epsilon^{\underline{p}}(t) + \epsilon(t)$, $\epsilon(t) = \varsigma|u(t) - v(t)|$ is the measurement error. ς is a positive constant. $c, \rho > 0$ and $0 < \sigma < 1$ are design parameters. $\aleph(t)$ is designed as

$$\dot{\aleph}(t) = -c\mu(t)\aleph(t) + c\sigma\mu(t) \sum_{j=1}^{n} z_j^{1+\bar{p}} - \mu(t)|z_n e(t)| \tag{10}$$

with $\aleph(0) > 0$.

Theorem 1. Under Assumptions 1–3, the nonlinear system (1) is regulated to the origin within the prescribed time T by employing the PT controller (8) in combination with the event-triggering mechanism (9).

The proof of Theorem 1 can be found in Appendix C.

Remark 1. The concept of the non-adaptive control presented originates from switching control [4]. However, the design of its switching function can lead to discontinuities in the controller and ambiguity regarding the time it takes for the system to achieve stability. Therefore, this study advances the methodology by leveraging the inherent properties of the PTF, which is continuously time-varying and monotonically increasing, instead of relying on a discrete switching function. This approach effectively compensates for system uncertainty while also allowing us to determine the time required for the system state to reach zero non-dependent switching parameters.

Conclusion. This work investigates event-triggered PT control for uncertain nonlinear systems characterized by unknown powers. First, a new non-adaptive PT control method is developed. This method leverages PTF to compensate for system uncertainties, thereby achieving zero system state within the given time interval. Moreover, we design event-triggered rules suitable for nonlinear systems subject to unknown powers and demonstrate the absence of Zeno's phenomenon using the paradoxical method. Finally, the proposed control algorithm is verified through a simulation example. In the future, efforts will be directed toward non-adaptive PT output feedback control for uncertain nonlinear systems subject to time delays.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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