ICIC Express Letters ICIC International ©2024 ISSN 1881-803X
Volume **18**, Number **2**, February **2024** pp. **159–165**

EVENT-TRIGGERED MODEL REFERENCE ADAPTIVE SLIDING MODE CONTROL WITH UNKNOWN DIRECTION CONTROL GAIN

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Received May 2023; accepted July 2023

Abstract. *For a class of first-order linear time-invariant systems with unknown direction control gain, the topic of event-triggered model reference adaptive sliding mode control is investigated. The integral sliding mode control strategy, including the sign function, is designed to alleviate the chattering problem. An additional adaptive law is introduced to eliminate uncertainty caused by unknown direction control gain and triggering event. The Nussbaum-type function handles the unknown control directions. Then, the tracking error can converge to a small domain of zero by designing a suitable event-triggered controller. Finally, the simulation result proves the effectiveness of the proposed control method.*

Keywords: Event-triggered control, Model reference adaptive control, Sliding mode control, Unknown direction control gain, Nussbaum-type function

1. **Introduction.** Model reference adaptive control is a popular adaptive control design technique. Here, we study the event-triggered model reference adaptive sliding mode control (MRASMC) with unknown direction control gain. The Nussbaum-type function is known to be a powerful way to handle unknown direction control gain [1, 2, 3]. A specific model reference adaptive control scheme was proposed for a class of first-order linear time-invariant systems (FLTS) with static output constraints in [4]. Based on a new error transformation function and the Nussbaum gain technique, the proposed control method [5] can eliminate the uncertainty in the system without using any approximate structure. Stimulated by [5], an additional adaptive law will be introduced to eliminate the uncertainty and is applied to FLTS.

Compared with the traditional control method, the event-triggered control strategy can reduce the number of data transmissions and the waste of communication resources [6, 7]. Three different event-triggered strategies were elaborated in [8]. The event-triggered control of the switching threshold strategy was proposed on fixed and relative threshold triggering in [9]. In [10], the fault tolerant control challenge of a class of uncertain systems was solved by combining the event-triggered technique. The unified event-triggered adaptive dynamic surface control of output-constrained stochastic nonlinear systems based on command filters was investigated in [11]. With regard to the event-triggered control, the researchers mainly focus on how to avoid the Zeno-behavior, which means that the controller is triggered infinitely in a finite time and cannot be regulated efficiently. In this paper, we consider a fixed-threshold event-triggered strategy and avoid the occurrence of the Zeno-behavior.

DOI: 10.24507/icicel.18.02.159

The strong robustness and insensitivity to the uncertainty of a sliding mode control are well recognized [12, 13]. The conventional linear sliding surface can converge quickly by designing appropriate parameters to achieve asymptotic stability and ensure that the system states converge to equilibrium when time tends to infinity [14, 15]. Based on a two-step design method, a low-sensitivity sliding mode control method was studied in [16] to effectively suppress the spillover effect. Combined with the adaptive control technique, an integral sliding mode control strategy was proposed to overcome the chattering challenge in [17]. Furthermore, in most existing control techniques which include backstepping-based adaptive control [18, 19, 20] and dynamic surface-based adaptive control [21, 22, 23], the adaptive control law only deals with parameter uncertainties or calculates the boundaries of uncertainty.

Motivated by recent research works [4, 5, 17], a fixed threshold event-triggered MRA-SMC with unknown direction control gain is studied. The major contributions of this work are listed as follows.

1) Compared to [4], the integral sliding mode control strategy is designed to prove that the tracking error can asymptotically converge to zero, which including the sign function, is constructed to alleviate the chattering problem.
2) The fixed-threshold event-triggered control with unknown direction control gain considered in this paper is inspired by [5]. An adaptive law is introduced to eliminate the uncertainty caused by the unknown control gain and event triggering.
3) Different from the sliding mode control under the unknown direction actuator fault considered in [17], we consider the model reference adaptive sliding mode control under the unknown direction control gain.

The remainder of the paper is structured as the following. The reference model and FLTS are discussed first in Section 2, and then two assumptions and a lemma are given. Section 3 consists of the design of the sliding surface, event-triggered controller, and parameter adaptive laws. Section 4 discusses the system's stability theorem and proof. Finally, Sections 5 and 6 present the simulation findings and conclusions, respectively.

2. **Preliminaries and Problem Description.** Consider the reference model below.

$$Q(s) = \frac{Y_d(s)}{R(s)} = \frac{\kappa_d}{s + b_d} \tag{1}$$

where $R(s)$ and $Y_d(s)$ represent the Laplace transform of the reference input $r(t)$ and the reference output $y_d(t)$, separately. In addition, κ_d and $b_d > 0$ are known constants. The reference signal $r(t), y_d(t) \in L_\infty$.

Suppose the FLTS is as follows:

$$E(s) = \frac{Y(s)}{U(s)} = \frac{\kappa}{s + b} \tag{2}$$

where $U(s)$ and $Y(s)$ represent the Laplace transform of the input $u(t)$ and the output $y(t)$, separately. In addition, κ and b are unknown constants.

The purpose of the control design is to develop an event-triggered controller $u(t)$ such that $y(t)$ tracks $y_d(t)$ with a small enough tracking error. Let $(\tilde{\cdot}) = (\hat{\cdot}) - (\cdot)$ for convenience.

Assumption 2.1. *Control gain κ, containing its direction and magnitude, of FLTS (2) is completely undetermined.*

Assumption 2.2. *Two properties of the Nussbaum-type function $M(\varpi)$ are summarized as follows:*

$$\lim_{t\to\infty} \inf \frac{1}{t} \int_0^t M(\varpi) d\varpi = -\infty \tag{3}$$

$$\lim_{t\to\infty}\sup\frac{1}{t}\int_0^t M(\varpi)d\varpi = +\infty \tag{4}$$

besides, prevalently used Nussbaum-type functions are $\varpi^2\cos(\varpi)$, $\exp\left(\varpi^2\right)\cos\left(\frac{\pi\varpi}{2}\right)$, *and* $\varpi^2\sin(\varpi)$, *etc. Here, we concentrate about* $M(\varpi) = \exp\left(\varpi^2\right)\cos\left(\frac{\pi\varpi}{2}\right)$.

Lemma 2.1. *For non-zero constant* κ, *Nussbaum-type function* $M(\varpi(\xi))$, *and arbitrary differentiable functions* $\varpi(\cdot), V(\cdot) > 0$ *defined on* $[0, t_M)$, *if there are appropriate constants* d_0 *and* α *such that*

$$V(t) \le d_0 + \int_0^t (\kappa M(\varpi(\xi)) + 1)\dot{\varpi}e^{\alpha(\xi - t)}d\xi \tag{5}$$

thus, $\varpi(t)$ *and* $V(t)$ *as well as* $\int_0^t (\kappa M(\varpi(\xi)) + 1)\dot{\varpi}e^{\alpha(\xi-t)}d\xi$ *must be bounded on* $[0, t_M)$.

3. **Event-Triggered MRASMC Design and Main Results.** Through a specific mathematical transformation, that is, the inverse Laplace transform, the reference model (1) and FLTS (2) can be reconstituted as

$$\dot{y}_d(t) = -b_d y_d(t) + \kappa_d(t)r(t) \tag{6}$$

$$\dot{y}(t) = -by(t) + \kappa u(t) \tag{7}$$

Define the tracking error as

$$e(t) = y(t) - y_d(t) \tag{8}$$

The derivative of the tracking error yields

$$\dot{e}(t) = -b_d e(t) + (b_d - b)y(t) + \kappa u(t) - \kappa_d r(t) \tag{9}$$

Then, define the sliding surface as below.

$$s(t) = e(t) + \int_0^t \lambda sign(e(\xi))\left|e(\xi)\right|^{\alpha}d\xi \tag{10}$$

where $\lambda > 0$, $0 < \alpha < 1$ are design parameters. The derivative of $s(t)$ is

$$\begin{aligned}\dot{s}(t) &= \dot{e}(t) + \lambda sign(e(t))\left|e(t)\right|^{\alpha} \\ &= -b_d e(t) + (b_d - b)y(t) + \kappa u(t) - \kappa_d r(t) + \lambda sign(e(t))\left|e(t)\right|^{\alpha}\end{aligned} \tag{11}$$

Constructing the Lyapunov function as $V_s = \frac{1}{2}s^2(t)$, then the derivative of V_s is

$$\begin{aligned}\dot{V}_s &= s(t)\dot{s}(t) \\ &= s(t)\left(-b_d e(t) + \delta y(t) + \kappa u(t) - \kappa_d r(t) + \lambda sign(e(t))\left|e(t)\right|^{\alpha}\right)\end{aligned} \tag{12}$$

where $\delta = b_d - b$, and $\hat{\delta}$ is the estimated value of δ.

Consider the fixed-threshold event-triggered strategy as

$$u(t) = \hbar(t_q), \quad \forall t \in [t_q, t_{q+1}) \tag{13}$$

$$t_{q+1} = \inf\{t \in R\,|\,|\hbar(t) - u(t)| \ge m, t > t_q\} \tag{14}$$

where $m > 0$, $t_q, t_{q+1} \in R^+$, $q \in Z^+$, when the inequality $|\hbar(t) - u(t)| < m$ holds for $t \in [t_q, t_{q+1})$, if there is a continuous function $\zeta(t)$ that $|\zeta(t)| \le 1$ with $\zeta(t_q) = 0$ and $\zeta(t_{q+1}) = \pm 1$, then $u(t) = \hbar(t) - \zeta(t)m$ exists.

The constant φ is meant to meet the following criterion in order to reduce the uncertainty produced by unknown direction control gain and triggering event.

$$|\kappa\zeta(t)m| \le \varphi \tag{15}$$

where the estimated value of φ is $\hat{\varphi}$, and the parameter adaptive law of $\hat{\varphi}$ is designed as below.

$$\dot{\hat{\varphi}}(t) = \beta\left(|s(t)| - \mu\left(\hat{\varphi}(t) - \varphi_0\right)\right) \tag{16}$$

where $\beta, \mu, \varphi_0 > 0$ are the design parameters.

Construct the following intermediate continuous input control.

$$\hbar(t) = M(\varpi)\left(\hat{\delta}(t)y(t) - \kappa_d r(t) + \lambda sign(e(t))\left|e(t)\right|^{\alpha} + ks(t) - b_d e(t)\right.$$
$$\left. + \frac{s(t)\hat{\varphi}^2}{s(t)\tanh\left(\frac{s(t)}{\varrho(t)}\right)\hat{\varphi}(t) + \varrho(t)}\right) \tag{17}$$

where

$$\dot{\varpi}(t) = s(t)\left(\hat{\delta}(t)y(t) - \kappa_d r(t) + \lambda sign(e(t))\left|e(t)\right|^{\alpha} + ks(t) - b_d e(t)\right.$$
$$\left. + \frac{s(t)\hat{\varphi}^2}{s(t)\tanh\left(\frac{s(t)}{\varrho(t)}\right)\hat{\varphi}(t) + \varrho(t)}\right) \tag{18}$$

that is, $s(t)\hbar(t) = M(\varpi)\dot{\varpi}$, where $\varrho(t) > 0$ and satisfy $0 < \varrho(t) < \bar{\varrho}$, $\forall t \leq 0$. $\bar{\varrho} > 0$ is a constant, and $k > 0$ is a design parameter.

The parameter adaptive law of $\hat{\delta}$ is constructed as follows:

$$\dot{\hat{\delta}}(t) = \gamma\left(sy(t) - \tau\hat{\delta}(t)\right) \tag{19}$$

where $\gamma, \tau > 0$ are design parameters. According to the above MRASMC design, (12) can be expressed as

$$\begin{aligned}\dot{V}_s &\leq s(t)\left(-b_d e(t) + \delta(t)y(t) - \kappa_d r(t) + \lambda sign(e(t))|e(t)|^{\alpha}\right) + \kappa M(\varpi)\dot{\varpi} \\ &\quad + |s(t)|\left|\kappa\zeta(t)m(t)\right| + \dot{\varpi} - \dot{\varpi} \\ &\leq s(t)\tilde{\delta}(t)y(t) + (\kappa M(\varpi) + 1)\dot{\varpi} - ks^2(t) \\ &\quad - \frac{s^2(t)\hat{\varphi}^2(t)}{s(t)\tanh\left(\frac{s(t)}{\varrho(t)}\right)\hat{\varphi}(t) + \varrho(t)} + |s(t)||\varphi|\end{aligned} \tag{20}$$

In view of the equality $0 \leq \phi\tanh\left(\frac{\phi}{G}\right) \leq |\phi|$, $\phi \in R$, $G > 0$, $\dot{V}_s$ can be rephrased as

$$\dot{V}_s \leq s(t)\tilde{\delta}(t)y(t) + (\kappa M(\varpi) + 1)\dot{\varpi} - ks^2(t) - \frac{s^2(t)\hat{\varphi}^2(t)}{|s(t)|\,\hat{\varphi}(t) + \varrho(t)} + |s(t)|\,|\varphi| \tag{21}$$

4. **Stability Analysis.** The following is a definition of a compact set:

$$\Omega = \left\{\left[s, \tilde{\delta}, \tilde{\varphi}\right]^T : V = V_s + \frac{1}{2\gamma}\tilde{\delta}^2(t) + \frac{1}{2\beta}\tilde{\varphi}^2(t) \leq J\right\} \tag{22}$$

where $J > 0$ is an arbitrary given constant.

Theorem 4.1. *In consideration of reference model (1) and FLTS (2), the event-triggered control law (17) and adaptive laws (16), (18), and (19), then for any given positive constant P and bounded initial condition $V(0) \leq J$, all signals s, δ, φ, e, y, y_d, u, $\hbar$, and ϖ are bounded, and $e(t)$ converges to the domain of zero when $t \to \infty$.*

Proof: Define the Lyapunov function as below.

$$V = V_s + \frac{1}{2\gamma}\tilde{\delta}^2(t) + \frac{1}{2\beta}\tilde{\varphi}^2(t) \tag{23}$$

Differentiating V for t, we obtain that

$$\dot{V} \leq -ks^2(t) + (\kappa M(\varpi) + 1)\dot{\varpi} - \frac{s^2(t)\hat{\varphi}^2(t)}{|s(t)|\hat{\varphi}(t) + \varrho(t)} + |s(t)|\hat{\varphi} + \mu\tilde{\varphi}\left(\hat{\varphi} - \varphi_0\right)$$

$$+\tau\tilde{\delta}(t)\hat{\delta}(t) \tag{24}$$

Furthermore, according to the inequality $0 \leq \frac{\rho\nu}{\rho+\nu} \leq \nu$, $\forall \rho, \nu > 0$, and together with $\mu\tilde{\varphi}(\hat{\varphi} - \varphi_0) \leq -\frac{1}{2}\mu\tilde{\varphi}^2 + \frac{1}{2}\mu(\varphi - \varphi_0)^2$, we have

$$\dot{V} \leq -ks^2(t) + (\kappa M(\varpi) + 1)\dot{\varpi} - \frac{1}{2}\tau\tilde{\delta}^2(t) - \frac{1}{2}\mu\tilde{\varphi}^2 + \Delta \tag{25}$$

where $\Delta = \frac{1}{2}\tau\delta^2(t) + \frac{1}{2}\mu(\varphi - \varphi_0)^2 + \bar{\varrho}$. Choosing $\Gamma \leq \min\{2k, \gamma\tau, \beta\mu\}$, then we can get

$$\dot{V} \leq -\Gamma V + (\kappa M(\varpi) + 1)\dot{\varpi} + \Delta \tag{26}$$

If $V \leq J$ and $\Gamma \geq \frac{(\kappa M(\varpi)+1)\dot{\varpi}+\Delta}{J}$, we get $\dot{V} \leq 0$. From $V(0) \leq J$, we obtain $V(t) \leq J$, $\forall t > 0$. Multiplying both sides of the inequality by $e^{\Gamma t}$, and then calculating the integral of both sides on $[0, t]$, we have

$$V \leq \frac{\Delta}{\Gamma} + \left[V(0) - \frac{\Delta}{\Gamma}\right]e^{-\Gamma t} + \int_0^t (\kappa M(\varpi) + 1)\dot{\varpi}e^{\Gamma(\xi - t)}d\xi \tag{27}$$

then, all the signals in FLTS are bounded, from $\frac{1}{2}s(t)^2 \leq V$, we get

$$|s(t)| \leq \sqrt{\frac{2\Delta}{\Gamma}} + \sqrt{2\left[V(0) - \frac{\Delta}{\Gamma}\right]e^{-\Gamma t}} + \sqrt{2\int_0^t (\kappa M(\varpi) + 1)\dot{\varpi}e^{\Gamma(\xi - t)}d\xi} \tag{28}$$

By adjusting the appropriate design parameters, $s(t)$ can converge to the domain of zero, then $y(t)$ able to track on $y_d(t)$ asymptotically. To demonstrate that there exists a constant $\epsilon > 0$ such that $|t_{q+1} - t_q| \geq \epsilon$, $\forall q \in Z^+$, as stated by $\psi(t) = \hbar(t) - u(t)$, $\forall t \in [t_q, t_{q+1})$, then, we obtain

$$\frac{d}{dt}|\psi| = \frac{d}{dt}|\psi * \psi|^{\frac{1}{2}} = sign(\psi)\dot{\psi} \leq \left|\dot{\hbar}(t)\right| \tag{29}$$

According to (17), $\dot{\hbar}(t)$ is bounded and continuous. There exists a constant $\bar{\hbar} > 0$ such that $\left|\dot{\hbar}(t)\right| < \bar{\hbar}$. From $\psi(t_q) = 0$ and $\lim_{t \to t_{q+1}} \psi(t) = m > 0$, it yields that the bound of ϵ must satisfy $\frac{m}{\bar{\hbar}}$, and the Zeno-behavior is thence avoided.

5. **Simulation.** The efficiency of the proposed event-triggered MRASMC mechanism is demonstrated through the first-order FLTS with unknown direction control gain as

$$E(s) = -\frac{2}{s+3} \tag{30}$$

$$Q(s) = \frac{3}{s+3} \tag{31}$$

The FLTS and reference model can be rephrased as $\dot{y}(t) = -3y(t) - 2u(t)$ and $\dot{y}_d(t) = -3y_d(t) + 3r(t)$, respectively. Nussbaum-type function is $M(\varpi) = \exp\left(\varpi^2\right)\cos(\pi\varpi)$. The reference input is chosen as $r(t) = 0.5\sin(0.5t)$.

The parameters involved in designing (16)-(19) are selected as $\beta = 30$, $\mu = 5$, $\varphi_0 = 0.1$, $\kappa_d = 2$, $b_d = 3$, $\lambda = 1$, $\alpha = 0.8$, $k = 15$, $\varrho = 20$, $\gamma = 25$, $\tau = 10$. The initial values are selected as $y(0) = 0.15$, $y_d(0) = 0.05$, $\hat{\varphi}(0) = 0.2$, $\varpi(0) = 0.15$, $\hat{\delta}(0) = 0.15$.

It can be seen from Figure 1 that the proposed approach described in this paper can produce good tracking performance, and the control objective can be successfully achieved. Figure 2 displays the difference between event-triggered control and intermediate continuous input.

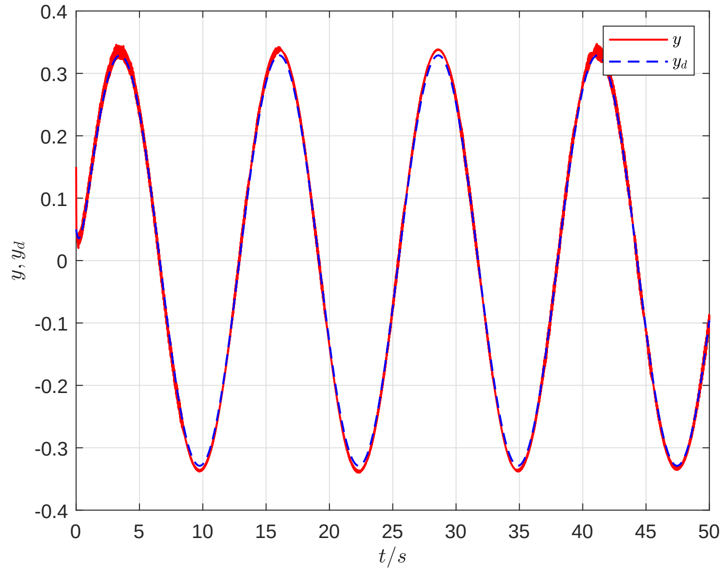

Figure 1. Curves of output y and desired trajectory y_d

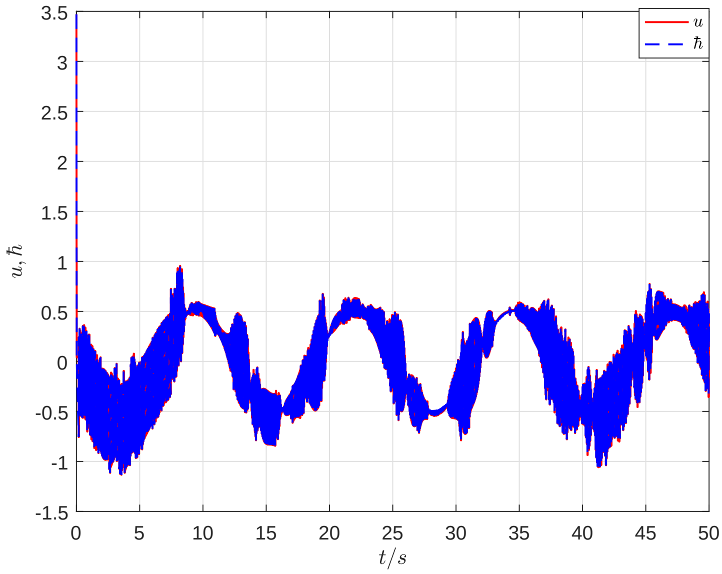

Figure 2. Curves of event-triggered control u and intermediate input $\hbar$

6. **Conclusions.**

The event-triggered MRASMC has been proposed for a class of first-order FLTS with unknown direction control gain in this paper. The integral sliding mode control strategy, including the sign function, is designed to alleviate the chattering problem. An additional adaptive law is introduced to eliminate uncertainty caused by unknown direction control gain and triggering event. The Nussbaum-type function handles the unknown control gain. The tracking error e can then be converged to a limited domain of zero by building an appropriate event-triggered MRASMC. In the future, the results of FLTS obtained will be further improved for a class of high-order linear multi-agent systems.

Acknowledgment. This work was supported in part by the National Natural Science Foundation of China under Grant 61833007, Grant 61991402 and Grant 62073154, and in part by the Postgraduate Research & Practice Innovation Program of Jiangsu Province under Grant KYCX22_2304.

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