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Research article

Practical fixed-time consensus via intermittent dynamic event-based control

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Abstract: This paper investigates the practical fixed-time consensus problem for multi-agent systems under intermittent dynamic event-triggered communication. First, unlike traditional fixed-time controllers that rely on linear and nonlinear power terms, the proposed controller incorporates an exponential function, resulting in a more concise and easily implementable control strategy. Next, two auxiliary functions are introduced to determine the working and resting intervals of intermittent control. Finally, we conduct a numerical simulation to validate the proposed method.

Keywords: intermittent control; dynamic event-triggered control; fixed-time consensus; Zeno behavior
Mathematics Subject Classification: 93C10, 93A16, 93C65, 93D40

1. Introduction

In recent decades, multi-agent systems (MASs) have proven highly effective in modeling large-scale and uncertain networked systems. A key advantage of MASs lies in their ability to solve complex tasks beyond the capacity of individual agents, which has attracted extensive research interest across diverse domains, including formation control [1], spacecraft attitude coordination [2], alternating current microgrids, and fault-tolerant control [3,4]. Consensus, as a fundamental collective behavior in MASs, has consistently remained a central research focus. To achieve consensus, researchers have developed a variety of control strategies, such as event-triggered control (ETC) [5], intermittent control [6, 7], sampled-data control [8], and fuzzy control [9].

Intermittent control alternates between working and resting intervals. This method significantly reduces control costs while maintaining system performance. It has been extensively applied to consensus problems of MASs [10–12]. The concept of intermittent control was first introduced in [10]. Subsequently, Wang et al. employed intermittent control to achieve fixed-time consensus (FTC) of MASs [11], and Azarbahram et al. extended it to tracking consensus of uncertain nonlinear MASs under denial-of-service attacks [12]. Notably, these studies mainly focused on periodic intermittent control. However, aperiodic intermittent control is more general and has broader practical potential [13–15]. For instance, a containment control algorithm for heterogeneous MASs was developed using intermittent control in [13]. Later, He et al. adopted aperiodic intermittent control to realize finite-time consensus of MASs [14], and Liu et al. further addressed the consensus of MASs via aperiodically intermittent ETC [15]. It should be emphasized that in the above works, the working instants of intermittent control were artificially predefined. In real-world applications such as wind power generation, these instants need to be determined autonomously, which serves as a crucial motivation for the present study.

To further reduce controller updates and conserve communication resources, ETC has been extensively employed in addressing consensus problems [4, 16–19]. For instance, in the context of AC microgrid secondary control with actuator faults, Zhai et al. proposed an event-triggered fault-tolerant control strategy that achieves voltage regulation. However, the approach relies on event-triggered patterns with intermittent control that do not adapt dynamically to the real-time system state [4]. Zhu et al. investigated general linear MASs within the ETC framework [16], while Cai et al. applied ETC to achieve FTC of MASs subject to uncertain disturbances [17]. Zhang et al. studied general linear MASs by adopting an aperiodic intermittent adaptive ETC strategy [18]. Zhu et al. addressed the problem of achieving optimal consensus control for multi-agent systems with unknown dynamics under limited computational resources by employing an event-triggered mechanism [19]. However, the aforementioned studies primarily relied on static ETC with fixed triggering parameters, which inherently restricts system adaptability to dynamic state changes. To overcome this limitation, dynamic ETC has been proposed and developed [20–22]. Specifically, Chen et al. explored consensus of general linear MASs using dynamic ETC [20], and the observer-based consensus problem of MASs has been similarly addressed via dynamic ETC strategies [21]. Zhou et al. addressed the state estimation problem for complex networks subject to deception and DoS attacks by employing a dynamic event-triggered mechanism, thereby achieving accurate state estimation under hybrid attacks and limited communication resources [22].

The settling time is a key metric for MASs. Consequently, accelerating the convergence process has become a central research objective. Compared with asymptotic convergence methods, finite-time control techniques offer remarkable advantages [23–25]. For instance, Gao et al. investigated the finite-time output consensus of heterogeneous fractional-order MASs via ETC [23], and Wang et al. studied bipartite finite-time consensus of MASs through intermittent ETC [24]. Haripriya et al. studied the finite-time synchronization of sampled-data-controlled complex dynamical networks with a time-varying delay [25].

Nevertheless, a major limitation of finite-time control is its dependence on the system's initial conditions, which undermines its practicality when initial states are unknown or sufficiently large. To circumvent this issue, the fixed-time theory was introduced [26], which guarantees that the settling time remains independent of initial values. Recent advancements in this field have yielded substantial findings on fixed-time control [27, 28]. Specifically, Zuo et al. explored the practical FTC of MASs over undirected topological networks [27], and Zhou et al. addressed the FTC of second-order MASs with uncertain bounded disturbances [28]. Inspired by these developments, this paper proposes an intermittent dynamic ETC scheme to achieve FTC of MASs. The principal contributions of this work are:

(1) Compared with the methods in [14, 15, 18, 39], this work introduces an innovative aperiodic intermittent dynamic ETC mechanism by incorporating auxiliary functions. This mechanism autonomously determines the working and resting instants of intermittent control without relying on predefined thresholds.

(2) In contrast to the methods in [30, 31] that determine the working and resting instants of intermittent control, this paper determines these instants via a dynamic event-triggered control mechanism.

(3) Unlike the controllers in [15, 27, 31, 37, 38] that typically employ linear or power-law terms, the proposed controller adopts an exponential term, resulting in a more concise structure and simpler implementation.

Notation: $\mathbb{R}$ denotes the set of real numbers; $\mathbb{R}^{M\times M}$ for $M \times M$ real matrices. The transpose of a vector x is written x^{T}. A diagonal matrix with entries $d_1, d_2, ..., d_M$ is written as $\mathrm{diag}\{d_1, d_2, ..., d_M\}$. Let $\lambda_{\max}(\cdot)$ and $\lambda_{\min}(\cdot)$ be the maximum and minimum eigenvalues of a matrix. $\kappa \gg 1$ means that κ is far greater than 1. Given $x = (x_1^{\mathrm{T}},\ x_2^{\mathrm{T}},\ ...,\ x_M^{\mathrm{T}})^{\mathrm{T}}$, $x_i = (x_{i1},\ x_{i2},\ ...,\ x_{in})^{\mathrm{T}}$, set $\mathrm{Tanh}(x) = (\mathrm{Tanh}^{\mathrm{T}}(x_1),\ \mathrm{Tanh}^{\mathrm{T}}(x_2),\ ...,\ \mathrm{Tanh}^{\mathrm{T}}(x_M))^{\mathrm{T}}$, where $\mathrm{Tanh}(x_i) = (\tanh(x_{i1}),\ \tanh(x_{i2}),\ ...,\ \tanh(x_{in}))^{\mathrm{T}}$, $\|x\|_m = (|x_1|^m + |x_2|^m + ... + |x_M|^m)^{1/m}$, $m = 1,\ 2$.

We organize the paper as follows. Section 2 provides preliminaries and basic results. Section 3 establishes the main theoretical results. Section 4 provides an illustrative example. Finally, Section 5 contains conclusions and future research.

2. Preliminaries

Consider an undirected graph composed of M nodes, denoted by $G(N, \mathcal{E})$, where each node corresponds to an agent. The edge set is $\mathcal{E}$. A pair of agents (i, j) are neighbors whenever $(i, j) \in \mathcal{E}$. The matrix $A = [a_{ij}] \in \mathbb{R}^{M\times M}$, where $a_{ij} = \begin{cases} 1, & \text{if } (i,j) \in \mathcal{E}, \\ 0, & \text{otherwise,} \end{cases}$ and $a_{ii} = 0$, the degree matrix $D = \mathrm{diag}\{d_1, d_2, ..., d_M\}$ with $d_i = \sum_{j=1, j\neq i}^{M} a_{ij}$, and the matrix $L = D - A$. Define $B = \mathrm{diag}\{b_1, b_2, ..., b_M\}$ with $b_i > 0$ for agents that can access the leader; otherwise $b_i = 0$. Let $\hat{L} = L + B = (c_{ij})_{M\times M}$ be a positive definite matrix.

The MASs under study comprise one leader and M followers, whose dynamics are characterized as follows:

$$\begin{cases} \dot{x}_i(t) = u_i(t) + f(x_i(t), t) + d_i(x_i(t), t), i = 1, 2, ..., M, \\ \dot{x}_0(t) = f(x_0(t), t), \end{cases} \tag{2.1}$$

where $x_i(t), x_0(t) \in \mathbb{R}^n$ are the states of the ith follower and the leader, respectively; $u_i(t)$ is the control input; and $f : \mathbb{R}^n \times \mathbb{R}^+ \to \mathbb{R}^n$ is a continuous nonlinear function. $d_i(x_i(t), t)$ is an uncertain but bounded disturbance.

Assumption 2.1. [6] Let $\mathcal{D}$ be a known positive constant, satisfying $\|d_i(x_i(t), t)\|_2 \leq \mathcal{D}$.

Assumption 2.2. [33] For a constant $h > 0$, we have

$$\|f(z_1,t) - f(z_2,t)\|_2 \leq h\|z_1 - z_2\|_2,$$

where $z_1, z_2 \in \mathbb{R}^n$.

Definition 2.3. [15] The nonlinear MASs (2.1) realize practical FTC tracking if the following inequalities hold for $i = 1, 2, ..., M$:

$$\begin{cases} \lim\limits_{t\to T^*} \|x_i(t) - x_0(t)\|_2 \leq d, \\ \|x_i(t) - x_0(t)\|_2 \leq d, \ \forall t > T^*, \end{cases}$$

where d is a small adjustable constant. The settling time T^* does not rely on initial states.

Definition 2.4. [37] For the intermittent control strategy, there exist $\beta \in (0, 1)$ and $T_\beta \geq 0$ such that

$$T_{con}(t_2, t_1) \geq \beta(t_2 - t_1) - T_\beta, \ \forall t_2 > t_1 \geq 0,$$

where $T_{con}(t_2, t_1)$ is the total control time on $[t_1, t_2)$, and β, T_β are the average control rate and the elasticity number, respectively.

Remark 2.5. Definition 2.4 is derived from the proof of the fixed-time differential inequality in [37]. Adopting the average control rate ensures that the lengths of the working intervals $[T_k,\ S_k)$ and resting intervals $[S_k,\ T_{k+1})$ within each control process $[T_k,\ T_{k+1})$ can be arbitrary, provided that the ratio of the total length of the working intervals to the entire control process equals β. Consequently, β is applicable to a broader class of intermittent control signals.

Lemma 2.6. [6] Suppose a Lyapunov function $W(t)$ satisfies the differential inequality

$$\dot{W}(t) \leq \begin{cases} -\alpha_1 W(t) - \alpha_2 W^p(t) - \alpha_3 W^q(t) + \delta_1, & t \in [T_k,\ S_k), \\ \alpha_4 W(t) + \delta_2, & t \in [S_k,\ T_{k+1}), \end{cases}$$

where $\alpha_1,\ \alpha_2,\ \alpha_3,\ \alpha_4$, and $\delta > 0$, $p > 1$, and $0 < q < 1$. If there exists $\breve{\varepsilon} > 0$, $\alpha_4 - \beta\breve{\varepsilon} \leq 0$ and $(1 - \beta)\breve{\varepsilon} - \alpha_3 < 0$ hold. Additionally, $W(t)$ converges to the residual set

$$\lim_{t\to T^*} W(t) \leq \max\{\xi_1, \xi_2, \xi_3\},$$

where $\xi_1 = \delta_1^{1/p}(\bar{h}\alpha_2)^{-1/p}$, $\xi_2 = \delta_1^{1/q}(\bar{h}\alpha_3)^{-1/q}$, $\xi_3 = \delta_2/(\beta\breve{\varepsilon} - \alpha_4)$, and

$$T^* \leq \frac{1 + \hat{\alpha}_1(p-1)T_\beta}{\hat{\alpha}_1(p-1)\beta} + \frac{1 + \hat{\alpha}_2(1-q)T_\beta}{\hat{\alpha}_2(1-q)\beta},$$

where $\hat{\alpha}_1 = \alpha_1(1 - \bar{h})\exp\{(1-p)\breve{\varepsilon}T_\beta\}$, $\hat{\alpha}_2 = \alpha_2(1 - \bar{h})$, $0 < \bar{h} < 1$.

Lemma 2.7. [6] For any $v \in \mathbb{R}$, we can obtain

$$0 \leq |v| - v\tanh(\kappa v) \leq \frac{\mathcal{L}}{\kappa}, \tag{2.2}$$

where $\kappa \gg 1$ and $\mathcal{L} = 0.2785$.

Lemma 2.8. [34] For any vector $z = (z_1, z_2, ..., z_n) \in \mathbb{R}^n$ and $0 < c_1 < c_2$,

$$\|z\|_{c_2} \leq \|z\|_{c_1} \leq n^{\frac{1}{c_1} - \frac{1}{c_2}}\|z\|_{c_2},$$

where $\|z\|_r = (\sum\limits_{i=1}^{n} |c_i|^r)^{1/r}$, in which $r = c_1, c_2$.

3. Results

The tracking error is denoted as $e_i(t) = x_i(t) - x_0(t)$, and the control input of follower i is as follows:

$$u_i(t) = \begin{cases} -\rho_1 y_i(t_m^{ik}) e^{\|y_i(t_m^{ik})\|_2^{2\alpha-1}} - \rho_2 \mathrm{Tanh}(\kappa y_i(t_m^{ik})), & t \in [t_m^{ik},\ t_{m+1}^{ik}) \cap [T_k, S_k), \\ 0, & t \in [S_k, T_{k+1}), \end{cases} \tag{3.1}$$

where $\rho_1, \rho_2 > 0$, $\alpha > 1/2$. T_k and S_k represent the working and resting instants of intermittent dynamic ETC protocol, respectively. The t_m^{ik} indicates the mth triggering instant of the ith agent in $[T_k, S_k)$, and

$$y_i(t) = \sum_{j=1}^{M} a_{ij}(x_i(t) - x_j(t)) + b_i(x_i(t) - x_0(t)) = \sum_{j=1}^{M} c_{ij} e_j(t), \tag{3.2}$$

thus, $(\hat{L} \otimes I_n)e(t) = (y_1^{\mathrm{T}}(t), y_2^{\mathrm{T}}(t), ..., y_M^{\mathrm{T}}(t))^{\mathrm{T}}$, $y_i(t) = (y_{i1}(t), y_{i2}(t), ..., y_{in}(t))^{\mathrm{T}}$.

Remark 3.1. Unlike the controllers proposed in [15, 27, 31] that are built upon linear and power-law terms, our controller adopts an exponential term, yielding a more streamlined design. Moreover, compared with the method in [29], the proposed controller is not only more practical but also integrates intermittent control with a dynamic ETC mechanism, thereby substantially improving both applicability and operational efficiency.

Remark 3.2. Existing works such as [14, 24, 37, 40] employ the sign function, which is discontinuous at the origin. Although this issue can be addressed by using a saturation function [28, 41], the latter is nondifferentiable and requires separate analysis. To overcome these limitations, this paper adopts the tanh function, which effectively resolves both problems while preserving practical applicability.

We introduce two non-negative, continuously differentiable functions $W_1(t)$ and $W_2(t)$ for the purpose of determining the intermittent control intervals:

$$\begin{cases} \dot{W}_1(t) = -m_1 W_1(t) - m_2 W_1^{\frac{2\alpha+1}{2}}(t) - m_3 W_1^{\frac{1}{2}}(t) + \delta_1, \\ \dot{W}_2(t) = -m_1 W_2(t) - m_2 W_2^{\frac{2\alpha+1}{2}}(t) - m_3 W_2^{\frac{1}{2}}(t) + \delta_1, \end{cases} \tag{3.3}$$

where $0 < m_i < \alpha_i$, $i = 1,\ 2,\ 3$, $\delta_1 > 0$. α_i is the Theorem 2.6. $W_1(0) = h_1(1/2e^T(0)(\hat{L} \otimes I_n)e(0) + \sum_{i=1}^{M} \psi_i(0))$, $W_2(0) = h_2(1/2e^T(0)(\hat{L} \otimes I_n)e(0) + \sum_{i=1}^{M} \psi_i(0))$, $0 < h_2 < 1 < h_1$, $\psi_i(t)$ is an internal dynamic variable, $\psi_i(0) > 0$, and $e(t) = (e_1^{\mathrm{T}}(t),\ e_2^{\mathrm{T}}(t),\ ...,\ e_M^{\mathrm{T}}(t))^{\mathrm{T}}$.

Using the auxiliary functions $W_1(t)$ and $W_2(t)$, we design the following ETC mechanism to determine the working and resting instants:

$$\begin{cases} S_k = \inf\{t > T_k : \frac{1}{2} e^T(t)(\hat{L} \otimes I_n)e(t) + \sum_{i=1}^{M} \psi_i(t) \le W_2(t)\}, \\ T_{k+1} = \inf\{t > S_k : \frac{1}{2} e^T(t)(\hat{L} \otimes I_n)e(t) + \sum_{i=1}^{M} \psi_i(t) \ge W_1(t)\}, \end{cases} \tag{3.4}$$

where $T_0 = 0$.

Remark 3.3. In contrast to [30, 31], we utilize a dynamic ETC mechanism to determine the working and resting instants of intermittent control. Consequently, in Eq (3.4), T_k and S_k are determined by the sum of the two terms.

Remark 3.4. The upper and lower bounds are constructed such that $W_2(t) \leq V(t) \leq W_1(t)$. When $V(t)$ reaches the lower bound, the system automatically enters the resting interval, and when it reaches the upper bound, it automatically enters the working interval, thus achieving autonomous switching between working and resting instants. In contrast, a single auxiliary function cannot simultaneously determine both the start and stop of control.

The positive constant t_m^{ik} satisfies

$$t_{m+1}^{ik} = \inf\{t > t_m^{ik} | H_i(t) \geq \psi_i(t)\}, \tag{3.5}$$

in which $H_i(t)$ is the triggering function, $\psi_i(t)$ is an internal dynamic variable defined in Proposition 3.6, and $t_0^{ik} = T_k$.

Remark 3.5. During the interval $[T_k, S_k)$, it follows from (3.4) and (3.5) that $t_0^{ik} = T_k$, indicating that an event is triggered at T_k [32]. If t_m^{ik} is the last triggering instant in $[T_k, S_k)$, and $t_m^{ik} < S_k$, then (3.5) implies that no event is triggered, and the controller remains unchanged throughout $[t_m^{ik}, S_k)$.

$H_i(t)$ is defined as follows:

$$H_i(t) = \frac{1}{2}\|\eta_i(t)\|_2^2 - \theta\rho_1\|y_i(t)\|_2^{2\alpha+1} - \theta\rho_2 \tag{3.6}$$

with the triggering parameter $\theta \in (0, 1)$.

Herein, $\eta_i(t)$ is constructed as

$$\eta_i(t) = \rho_1 y_i(t_m^{ik}) e^{\|y_i(t_m^{ik})\|_2^{2\alpha-1}} + \rho_2 \mathrm{Tanh}(\kappa y_i(t_m^{ik})) - \rho_1 y_i(t) e^{\|y_i(t)\|_2^{2\alpha-1}} - \rho_2 \mathrm{Tanh}(\kappa y_i(t)). \tag{3.7}$$

The overall architecture diagram of the closed-loop system is depicted in Figure 1.

Proposition 3.6. Consider the following variable $\psi_i(t)$:

$$\dot{\psi}_i(t) = \begin{cases} \theta\rho_1\|y_i(t)\|_2^{2\alpha+1} + \theta\rho_2 - \frac{1}{2}\|\eta_i(t)\|_2^2 - \gamma_1\psi_i^{\frac{2\alpha+1}{2}}(t) - \gamma_2\psi_i^{\frac{1}{2}}(t), & t \in [t_m^{ik},\ t_{m+1}^{ik}) \cap [T_k, S_k), \\ 0, & t \in [S_k, T_{k+1}), \end{cases} \tag{3.8}$$

where $\gamma_1,\ \gamma_2$ and $\psi_i(0) > 0$. Based on Eq (3.8) and $\psi_i(0) > 0$, it is guaranteed that for all $t > 0$, $\psi_i(t) > 0$.

The proof of Proposition 3.6, which shows that $\psi_i(t) > 0$ for any $t > 0$, is similar to that in [38] and is therefore omitted here.

By the definition of $e_i(t)$, we have

$$\dot{e}_i(t) = \begin{cases} -\rho_1 y_i(t_m^{ik}) e^{\|y_i(t_m^{ik})\|_2^{2\alpha-1}} - \rho_2 \mathrm{Tanh}(\kappa y_i(t_m^{ik})) + F(x_i(t), t) + d_i(x_i(t), t), & t \in [t_m^{ik},\ t_{m+1}^{ik}) \cap [T_k, S_k), \\ F(x_i(t), t) + d_i(x_i(t), t), & t \in [S_k, T_{k+1}), \end{cases} \tag{3.9}$$

where $F(x_i(t), t) = f(x_i(t), t) - f(x_0(t), t)$.

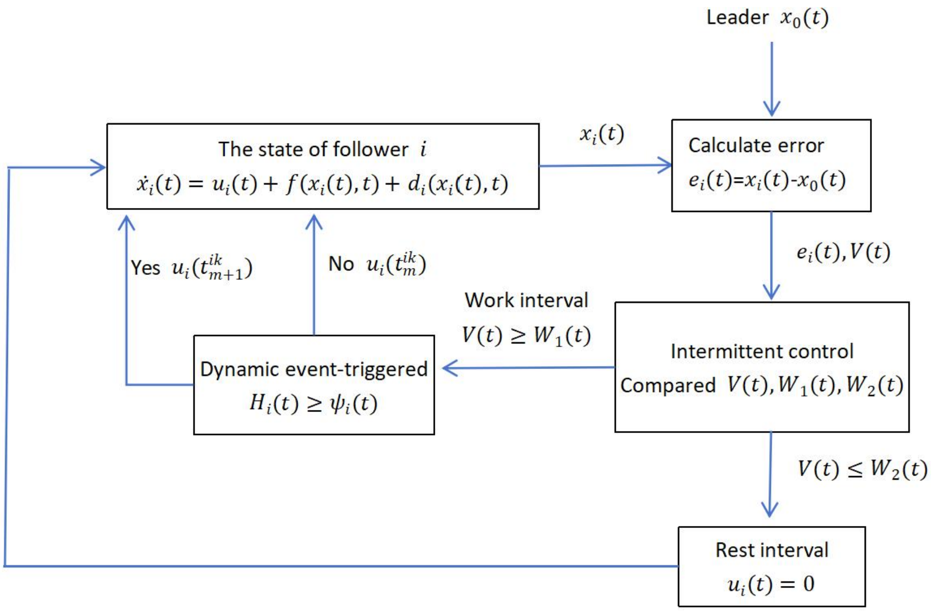

Figure 1. Diagram figure of intermittent dynamic ETC.

Algorithm 1 Intermittent Control Dynamic ETC Parameter Selection Algorithm

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1: Given the system parameters $L, D, \rho_1, \rho_2, m_1, m_2, m_3, \delta_1, \mathcal{D}$;
2: Real-time compute $V(t)$, $W_1(t)$, $W_2(t)$;
if $V(t) \geq W_1(t)$ then
  Goto step 3
else if $V(t) \leq W_2(t)$ then
  $u_i(t) = 0$
3: Choose $\alpha > 1/2$, $\breve{\varepsilon} > 0$, positive parameters $\gamma_1, \gamma_2, \theta, \kappa, \bar{h}$;
4: Calculate $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \delta$ from Theorem 3.9;
5: Calculate the settling time T^* according to Theorem 3.9.

Remark 3.7. Existing intermittent control schemes [6, 14, 18, 23] typically rely on predetermined time sequences, which limits their flexibility. In this study, we propose a novel approach. First, we construct two auxiliary functions that converge within a fixed time. Then, we introduce a dynamic ETC mechanism to autonomously determine the working and resting instants of intermittent control. Consequently, the proposed intermittent dynamic ETC protocol achieves significant improvements in both flexibility and adaptability. A comparison of the controller innovations between this work and previous studies is provided in Table 1.

Table 1. Different controllers.

No.	Controller structure	Triggering mechanism
[14]	$\begin{cases} u_i(t) = \beta sig\left(\sum_{j\in\mathcal{N}_i} a_{ij}(x_j(t)-x_i(t))\right)^{\alpha}, & t\in[t_k, t_k+\delta_k), \\ u_i(t) = 0, & t\in[t_k+\delta_k, t_{k+1}), \quad k=1,2,\ldots \end{cases}$	none
[15]	$u_i(t) = \begin{cases} -\rho_1 y_i^{\alpha}(t_{r_i}^i) - \rho_2 \tanh(\kappa y_i(t_{r_i}^i)) - \rho_3 y_i(t_{r_i}^i), & t\in[t_{r_i}^i, t_{r_i+1}^i)\cap[t_k, s_k), \\ 0, & t\in[s_k, t_{k+1}) \end{cases}$	$t_{r_i+1}^i = \inf\{t > t_{r_i}^i \mid \mathcal{H}_i(t)\geq 0\}$
[18]	$u_i(t) = \begin{cases} c_i(t)K\sum_{j=1}^N a_{ij}(x_j(t)-x_i(t)) + d_i(s_0(t)-x_i(t)), & t\in[t_{i,s}^k, t_{i,s+1}^k)\cap[T_{2k}, T_{2k+1}), \\ 0, & t\in[T_{2k+1}, T_{2k+2}) \end{cases}$	$h_i(t) = e_i^T(t)e_i(t) - \eta_i\delta_i^T(t)\delta_i(t) < 0$
[20]	$u_i = J\chi_i\hat{\xi}_i, \quad \dot{\chi}_i = \begin{cases} 0, & \chi_i\geq\bar{\chi}_i, \\ \kappa_i\hat{\xi}_i^T\Omega\hat{\xi}_i, & \chi_i<\bar{\chi}_i \end{cases}$	$t_{k+1}^i = \min\{t > t_k^i \mid \psi_i(t)\leq 0\}$
[27]	$u_i = c_i\left\{\alpha\left[\sum_{j=1}^N a_{ij}(x_j-x_i)\right]^{2-\frac{p}{q}} + \beta\left[\sum_{j=1}^N a_{ij}(x_j-x_i)\right]^{\frac{p}{q}}\right\}$	none
[35]	$u_i(t) = \begin{cases} -g_i(t)e_i(t) - \varepsilon_i\mathrm{sign}(e_i(t)) - \theta_i\mathrm{sign}(e_i(t))\sum_{j=1}^n \lvert e_j(t-\tau(t))\rvert & \\ \quad -\delta_i\mathrm{sign}(e_i(t))\lvert e_i(t)\rvert^l, & t_k\leq t<s_k, \\ -\theta_i\mathrm{sign}(e_i(t))\sum_{j=1}^n \lvert e_j(t-\tau(t))\rvert - \varepsilon_i\mathrm{sign}(e_i(t)), & s_k\leq t<t_{k+1} \end{cases}$	none
[36]	$u_i(t) = \begin{cases} -d_i z_i(t) - (e^{\alpha z_i^{\varpi}(t)} - e^{-\alpha z_i^{\varpi}(t)})/2, & t\in[t_k, s_k), \\ 0, & t\in[s_k, t_{k+1}) \end{cases}$	none
this paper	$u_i(t) = \begin{cases} -\rho_1 y_i(t_m^{ik})e^{\Vert y_i(t_m^{ik})\Vert_2^{2\alpha-1}} - \rho_2\mathrm{Tanh}(\kappa y_i(t_m^{ik})), & t\in[t_m^{ik}, t_{m+1}^{ik})\cap[T_k, S_k), \\ 0, & t\in[S_k, T_{k+1}) \end{cases}$	$t_{m+1}^{ik} = \inf\{t > t_m^{ik} \mid H_i(t)\geq\psi_i(t)\}$

Remark 3.8. As presented in Table 2, although studies [30, 31] also employ auxiliary functions to determine the working and resting instants of intermittent control, they rely solely on intermittent event-triggered mechanisms to achieve FTC. In contrast, the method proposed in this work integrates intermittent control with a dynamic ETC mechanism to achieve FTC, thereby further reducing controller update frequency and resource consumption.

Table 2. Determining the work instants and rest instants of intermittent control.

No.	Triggering mechanism	The work and rest instants of intermittent control
[30]	none	$\begin{cases} s_k = \inf\{t > t_k : x^T(t)x(t)\leq\mathscr{W}_2(t)\}, \\ t_{k+1} = \inf\{t > s_k : x^T(t)x(t)\geq\mathscr{W}_1(t)\} \end{cases}$
[31]	$t_{l+1}^k = \inf\{t > t_l^k : \Vert e(t)\Vert - \frac{\gamma}{2}\Vert z(t)\Vert > 0\}$	$\begin{cases} S_k = \inf\{t > T_k : \frac{1}{2}x^T(t)(L^T\Gamma\otimes I_n)x(t)\leq W_2(t)\}, \\ T_{k+1} = \inf\{t > S_k : \frac{1}{2}x^T(t)(L^T\Gamma\otimes I_n)x(t)\geq W_1(t)\} \end{cases}$
This paper	$t_{m+1}^{ik} = \inf\{t > t_m^{ik} : H_i(t)\geq\psi_i(t)\}$	$\begin{cases} S_k = \inf\{t > T_k : \frac{1}{2}e^T(t)(\hat{L}\otimes I_n)e(t) + \sum_{i=1}^M\psi_i(t)\leq W_2(t)\}, \\ T_{k+1} = \inf\{t > S_k : \frac{1}{2}e^T(t)(\hat{L}\otimes I_n)e(t) + \sum_{i=1}^M\psi_i(t)\geq W_1(t)\} \end{cases}$

Theorem 3.9. Assume that the intermittent control generated by (3.4) satisfies Definition 2.4 with some constants $0 < \beta < 1$ and $T_\beta > 0$. Under the controller (3.1) and triggering function (3.6), the MASs (2.1) realizes practical FTC tracking if $\breve{\varepsilon} > 0$, $\alpha_4 - \beta\breve{\varepsilon} \leq 0$, $(1-\beta)\breve{\varepsilon} - \alpha_3 < 0$, and $0 < \bar{h} < 1$. The settling time

$$T^* \leq \frac{1 + \hat{\alpha}_1(p-1)T_\beta}{\hat{\alpha}_1(p-1)\beta} + \frac{1 + \hat{\alpha}_2(1-q)T_\beta}{\hat{\alpha}_2(1-q)\beta},$$

where $\hat{\alpha}_1 = \alpha_1(1-\bar{h})\exp\{(1-p)\breve{\varepsilon}T_\beta\}$, $\hat{\alpha}_2 = \alpha_2(1-\bar{h})$. $\alpha_1 = 2\lambda_{\min}(\hat{L})(\rho_1 - 1/2 - h/\lambda_{\min}(\hat{L}))$, $\alpha_2 = 2^{(1-2\alpha)/2}\beta_2$, $\beta_2 = \min\{[(2\lambda_{\min}^2(\hat{L}))/\lambda_{\max}(\hat{L})]^{(2\alpha+1)/2}\rho_1(M^{(1-2\alpha)/2} - \theta),\ \gamma_1 M^{(1-2\alpha)/2}\}$, $\alpha_3 = \min\{(2\lambda_{\min}(\hat{L}))^{1/2}(\rho_2 - \mathcal{D}M^{\frac{1}{2}}), \gamma_2\}$, $\alpha_4 = 2h\lambda_{\max}(\hat{L})/\lambda_{\min}(\hat{L})$, h is the constant in Assumption 2.2. $T_{con}(t_2, t_1)$ is the total control time on $[t_1, t_2)$; β and T_β are the average control rate and the elasticity number, respectively.

Meanwhile, the function $V(t)$ converges to the following region:

$$\lim_{t\to T^*} V(t) \le \max\{\xi_1, \xi_2, \xi_3\},$$

where $\xi_1 = \delta_1^{1/p}(\bar{h}\alpha_2)^{-1/p}$, $\xi_2 = \delta_1^{1/q}(\bar{h}\alpha_3)^{-1/q}$, $\xi_3 = \delta_2/(\beta\breve{\varepsilon} - \alpha_4)$. □

Proof. Let the Lyapunov function be defined as

$$V(t) = V_1(t) + V_2(t), \tag{3.10}$$

in which

$$V_1(t) = \frac{1}{2}e^{\mathrm{T}}(t)(\hat{L}\otimes I_n)e(t),\ V_2(t) = \sum_{i=1}^{M}\psi_i(t).$$

When $t \in [t_m^{ik},\ t_{m+1}^{ik}) \cap [T_k, S_k)$, according to the definition of $\eta_i(t)$, we have

$$\begin{aligned}
\dot{V}_1(t) =& e^{\mathrm{T}}(t)(\hat{L}\otimes I_n)\dot{e}(t)\\
=& \sum_{i=1}^{M} y_i^{\mathrm{T}}(t)\dot{e}_i(t)\\
=& \sum_{i=1}^{M} y_i^{\mathrm{T}}(t)(-\eta_i(t) - \rho_2\mathrm{Tanh}(\kappa y_i(t)) + F(x_i(t),t) - \rho_1 y_i(t)e^{\|y_i(t)\|_2^{2\alpha-1}} + d_i(x_i(t),t))\\
=& -\sum_{i=1}^{M} y_i^{\mathrm{T}}(t)\eta_i(t) - \rho_2\sum_{i=1}^{M} y_i^{\mathrm{T}}(t)\mathrm{Tanh}(\kappa y_i(t)) - \rho_1\sum_{i=1}^{M} y_i^{\mathrm{T}}(t)y_i(t)e^{\|y_i(t)\|_2^{2\alpha-1}}\\
&+\sum_{i=1}^{M} y_i^{\mathrm{T}}(t)F(x_i(t),t) + \sum_{i=1}^{M} y_i^{\mathrm{T}}(t)d_i(x_i(t),t).
\end{aligned}$$

Based on Lemma 2.7, the following inequality can be yielded:

$$\begin{aligned}
-\rho_2 y_i^{\mathrm{T}}(t)\mathrm{Tanh}(\kappa y_i(t)) &= -\rho_2\sum_{j=1}^{n} y_{ij}(t)\tanh(\kappa y_{ij}(t))\\
&\le \sum_{j=1}^{n}(\frac{\rho_2\mathcal{L}}{\kappa} - \rho_2|y_{ij}(t)|)\\
&= \frac{\rho_2\mathcal{L}n}{\kappa} - \rho_2\|y_i(t)\|_1.
\end{aligned}$$

Moreover, we have

$$-\rho_2\sum_{i=1}^{M} y_i^{\mathrm{T}}(t)\mathrm{Tanh}(\kappa y_i(t)) \le \frac{\rho_2\mathcal{L}Mn}{\kappa} - \rho_2\|(\hat{L}\otimes I_n)e(t)\|_1.$$

Under Assumption 2.2, we obtain

$$\sum_{i=1}^{M} y_i^{\mathrm{T}}(t)F(x_i(t),t) = y^{\mathrm{T}}(t)F(x(t),t)$$

$$
\begin{aligned}
&\leq \|y(t)\|_2 \|F(x(t), t)\|_2 \\
&\leq h\|y(t)\|_2 \|e(t)\|_2 \\
&= h\|y(t)\|_2 \|(\hat{L} \otimes I_n)^{-1} (\hat{L} \otimes I_n) e(t)\|_2 \\
&\leq \lambda_{\max}((\hat{L} \otimes I_n)^{-1}) h \|(\hat{L} \otimes I_n) e(t)\|_2^2 \\
&= \frac{h}{\lambda_{\min}(\hat{L})} \|(\hat{L} \otimes I_n) e(t)\|_2^2,
\end{aligned}
$$

where $F(x(t), t) = (F^{\mathrm{T}}(x_1(t), t), F^{\mathrm{T}}(x_2(t), t), ..., F^{\mathrm{T}}(x_M(t), t))^{\mathrm{T}}$. Then, based on Assumption 2.1, we have

$$
\begin{aligned}
\dot{V}_1(t) \leq &\frac{1}{2} \sum_{i=1}^{M} \|y_i(t)\|_2^2 + \frac{1}{2} \sum_{i=1}^{M} \|\eta_i(t)\|_2^2 - \rho_2 \|(\hat{L} \otimes I_n) e(t)\|_1 - \rho_1 \sum_{i=1}^{M} y_i^{\mathrm{T}}(t) y_i(t) e^{\|y_i(t)\|_2^{2\alpha-1}} \\
&+ \frac{\rho_2 \mathcal{L} M n}{\kappa} + \sum_{i=1}^{M} y_i^{\mathrm{T}}(t) d_i(x_i(t), t) + \frac{h}{\lambda_{\min}(\hat{L})} \|(\hat{L} \otimes I_n) e(t)\|_2^2 \\
\leq &\frac{1}{2} \sum_{i=1}^{M} \|y_i(t)\|_2^2 + \frac{1}{2} \sum_{i=1}^{M} \|\eta_i(t)\|_2^2 - \rho_2 \|(\hat{L} \otimes I_n) e(t)\|_1 - \rho_1 \sum_{i=1}^{M} y_i^{\mathrm{T}}(t) y_i(t) e^{\|y_i(t)\|_2^{2\alpha-1}} \\
&+ \frac{\rho_2 \mathcal{L} M n}{\kappa} + \mathcal{D} \sum_{i=1}^{M} \|y_i(t)\|_2 + \frac{h}{\lambda_{\min}(\hat{L})} \|(\hat{L} \otimes I_n) e(t)\|_2^2 \\
\leq &\frac{1}{2} \|(\hat{L} \otimes I_n) e(t)\|_2^2 + \frac{1}{2} \sum_{i=1}^{M} \|\eta_i(t)\|_2^2 - \rho_2 \|(\hat{L} \otimes I_n) e(t)\|_2 - \rho_1 \sum_{i=1}^{M} y_i^{\mathrm{T}}(t) y_i(t) e^{\|y_i(t)\|_2^{2\alpha-1}} \\
&+ \frac{\rho_2 \mathcal{L} M n}{\kappa} + \mathcal{D} M^{\frac{1}{2}} \|(\hat{L} \otimes I_n) e(t)\|_2 + \frac{h}{\lambda_{\min}(\hat{L})} \|(\hat{L} \otimes I_n) e(t)\|_2^2.
\end{aligned}
$$

Based on the Taylor expansion, we can obtain

$$
\begin{aligned}
&-\rho_1 \sum_{i=1}^{M} y_i^{\mathrm{T}}(t) y_i(t) e^{\|y_i(t)\|_2^{2\alpha-1}} \\
\leq &-\rho_1 \sum_{i=1}^{M} y_i^{\mathrm{T}}(t) y_i(t) - \rho_1 \sum_{i=1}^{M} \|y_i(t)\|_2^{2\alpha+1} \\
\leq &-\rho_1 \|y(t)\|_2^2 - \rho_1 M^{\frac{1-2\alpha}{2}} \|y(t)\|_2^{2\alpha+1} \\
= &-\rho_1 \|(\hat{L} \otimes I_n) e(t)\|_2^2 - \rho_1 M^{\frac{1-2\alpha}{2}} \|(\hat{L} \otimes I_n) e(t)\|_2^{2\alpha+1}.
\end{aligned}
$$

From this, we derive

$$
\begin{aligned}
\dot{V}_1(t) \leq &\frac{1}{2} \|(\hat{L} \otimes I_n) e(t)\|_2^2 - (\rho_2 - \mathcal{D} M^{\frac{1}{2}}) \|(\hat{L} \otimes I_n) e(t)\|_2 - \rho_1 \|(\hat{L} \otimes I_n) e(t)\|_2^2 \\
&- \rho_1 M^{\frac{1-2\alpha}{2}} \|(\hat{L} \otimes I_n) e(t)\|_2^{2\alpha+1} + \frac{h}{\lambda_{\min}(\hat{L})} \|(\hat{L} \otimes I_n) e(t)\|_2^2 + \frac{\rho_2 \mathcal{L} M n}{\kappa} + \frac{1}{2} \sum_{i=1}^{M} \|\eta_i(t)\|_2^2 \\
\leq &-(\rho_1 - \frac{1}{2} - \frac{h}{\lambda_{\min}(\hat{L})}) \|(\hat{L} \otimes I_n) e(t)\|_2^2 - (\rho_2 - \mathcal{D} M^{\frac{1}{2}}) \|(\hat{L} \otimes I_n) e(t)\|_2
\end{aligned}
$$

$$-\rho_1 M^{\frac{1-2\alpha}{2}}\|(\hat{L}\otimes I_n)e(t)\|_2^{2\alpha+1}+\frac{\rho_2\mathcal{L}Mn}{\kappa}+\frac{1}{2}\sum_{i=1}^{M}\|\eta_i(t)\|_2^2.$$

Based on (3.8),

$$\begin{aligned}
\dot{V}_2(t)=&\sum_{i=1}^{M}\dot{\psi}_i(t)\\
=&\theta\rho_1\sum_{i=1}^{M}\|y_i(t)\|_2^{2\alpha+1}-\frac{1}{2}\sum_{i=1}^{M}\|\eta_i(t)\|_2^2-\gamma_1\sum_{i=1}^{M}\psi_i^{\frac{2\alpha+1}{2}}(t)-\gamma_2\sum_{i=1}^{M}\psi_i^{\frac{1}{2}}(t)\\
\leq&\theta\rho_1(\sum_{i=1}^{M}\|y_i(t)\|_2^2)^{\frac{2\alpha+1}{2}}-\frac{1}{2}\sum_{i=1}^{M}\|\eta_i(t)\|_2^2-\gamma_1 M^{\frac{1-2\alpha}{2}}(\sum_{i=1}^{M}\psi_i(t))^{\frac{2\alpha+1}{2}}-\gamma_2(\sum_{i=1}^{M}\psi_i(t))^{\frac{1}{2}}.
\end{aligned}$$

From this, we derive

$$\begin{aligned}
\dot{V}(t)=&\dot{V}_1(t)+\dot{V}_2(t)\\
\leq&-(\rho_1-\frac{1}{2}-\frac{h}{\lambda_{\min}(\hat{L})})\|(\hat{L}\otimes I_n)e(t)\|_2^2+\frac{1}{2}\sum_{i=1}^{M}\|\eta_i(t)\|_2^2-\rho_1 M^{\frac{1-2\alpha}{2}}\|(\hat{L}\otimes I_n)e(t)\|_2^{2\alpha+1}\\
&-(\rho_2-\mathcal{D}M^{\frac{1}{2}})\|(\hat{L}\otimes I_n)e(t)\|_2+\frac{\rho_2\mathcal{L}Mn}{\kappa}+\theta\rho_1\|(\hat{L}\otimes I_n)e(t)\|_2^{2\alpha+1}-\frac{1}{2}\sum_{i=1}^{M}\|\eta_i(t)\|_2^2\\
&-\gamma_1 M^{\frac{1-2\alpha}{2}}(\sum_{i=1}^{M}\psi_i(t))^{\frac{2\alpha+1}{2}}-\gamma_2(\sum_{i=1}^{M}\psi_i(t))^{\frac{1}{2}}\\
\leq&-(\rho_1-\frac{1}{2}-\frac{h}{\lambda_{\min}(\hat{L})})\|(\hat{L}\otimes I_n)e(t)\|_2^2-\rho_1(M^{\frac{1-2\alpha}{2}}-\theta)\|(\hat{L}\otimes I_n)e(t)\|_2^{2\alpha+1}\\
&-(\rho_2-\mathcal{D}M^{\frac{1}{2}})\|(\hat{L}\otimes I_n)e(t)\|_2-\gamma_1 M^{\frac{1-2\alpha}{2}}(\sum_{i=1}^{M}\psi_i(t))^{\frac{2\alpha+1}{2}}-\gamma_2(\sum_{i=1}^{M}\psi_i(t))^{\frac{1}{2}}+\frac{\rho_2\mathcal{L}Mn}{\kappa}\\
\leq&-2\lambda_{\min}(\hat{L})(\rho_1-\frac{1}{2}-\frac{h}{\lambda_{\min}(\hat{L})})V_1(t)-(\frac{2\lambda_{\min}^2(\hat{L})}{\lambda_{\max}(\hat{L})})^{\frac{2\alpha+1}{2}}\rho_1(M^{\frac{1-2\alpha}{2}}-\theta)V_1^{\frac{2\alpha+1}{2}}(t)\\
&-(2\lambda_{\min}(\hat{L}))^{\frac{1}{2}}(\rho_2-\mathcal{D}M^{\frac{1}{2}})V_1^{\frac{1}{2}}(t)-\gamma_1 M^{\frac{1-2\alpha}{2}}(\sum_{i=1}^{M}\psi_i(t))^{\frac{2\alpha+1}{2}}-\gamma_2(\sum_{i=1}^{M}\psi_i(t))^{\frac{1}{2}}+\frac{\rho_2\mathcal{L}Mn}{\kappa}\\
\leq&-2\lambda_{\min}(\hat{L})(\rho_1-\frac{1}{2}-\frac{h}{\lambda_{\min}(\hat{L})})V_1(t)-(\frac{2\lambda_{\min}^2(\hat{L})}{\lambda_{\max}(\hat{L})})^{\frac{2\alpha+1}{2}}\rho_1(M^{\frac{1-2\alpha}{2}}-\theta)V_1^{\frac{2\alpha+1}{2}}(t)\\
&-(2\lambda_{\min}(\hat{L}))^{\frac{1}{2}}(\rho_2-\mathcal{D}M^{\frac{1}{2}})V_1^{\frac{1}{2}}(t)-\gamma_1 M^{\frac{1-2\alpha}{2}}V_2^{\frac{2\alpha+1}{2}}(t)-\gamma_2 V_2^{\frac{1}{2}}(t)+\frac{\rho_2\mathcal{L}Mn}{\kappa}\\
\leq&-\beta_1 V(t)-\beta_2(V_1^{\frac{2\alpha+1}{2}}(t)+V_2^{\frac{2\alpha+1}{2}}(t))-\beta_3(V_1^{\frac{1}{2}}(t)+V_2^{\frac{1}{2}}(t))+\frac{\rho_2\mathcal{L}Mn}{\kappa}\\
\leq&-\beta_1 V(t)-\beta_2 2^{\frac{1-2\alpha}{2}}V^{\frac{2\alpha+1}{2}}(t)-\beta_3 V^{\frac{1}{2}}(t)+\frac{\rho_2\mathcal{L}Mn}{\kappa},
\end{aligned}$$

where $\beta_1=2\lambda_{\min}(\hat{L})(\rho_1-1/2-h/\lambda_{\min}(\hat{L}))$, $\beta_2=\min\{[(2\lambda_{\min}^2(\hat{L}))/\lambda_{\max}(\hat{L})]^{(2\alpha+1)/2}\rho_1(M^{(1-2\alpha)/2}-\theta),\ \gamma_1 M^{(1-2\alpha)/2}\}$, $\beta_3=\min\{(2\lambda_{\min}(\hat{L}))^{1/2}(\rho_2-\mathcal{D}M^{1/2}),\gamma_2\}$.

When $t \in [S_k, T_{k+1})$, we have

$$\begin{aligned}\dot{V}(t) &= \sum_{i=1}^{M} y_i^{\mathrm{T}}(t)\dot{e}_i(t)\\ &= \sum_{i=1}^{M} y_i^{\mathrm{T}}(t)(F(x_i(t),t) + d_i(x_i(t),t))\\ &\leq \frac{2h\lambda_{\max}(\hat{L})}{\lambda_{\min}(\hat{L})}V(t) + \mathcal{D}\sum_{i=1}^{M}\|y_i(t)\|_2\\ &\leq \frac{2h\lambda_{\max}(\hat{L})}{\lambda_{\min}(\hat{L})}V(t) + \mathcal{D}(2M\lambda_{\max}(\hat{L}))^{\frac{1}{2}}V^{\frac{1}{2}}(t)\\ &\leq \frac{2h\lambda_{\max}(\hat{L})}{\lambda_{\min}(\hat{L})}V(t) + \mathcal{D}(2M\lambda_{\max}(\hat{L}))^{\frac{1}{2}}V_{\max}^{\frac{1}{2}}\\ &= \frac{2h\lambda_{\max}(\hat{L})}{\lambda_{\min}(\hat{L})}V(t) + \delta_2.\end{aligned}$$

Therefore, we have

$$\dot{V}(t) \leq \begin{cases}-\alpha_1 V(t) - \alpha_2 V^{\frac{2\alpha+1}{2}}(t) - \alpha_3 V^{\frac{1}{2}}(t) + \delta_1, & t \in [t_m^{ik},\ t_{m+1}^{ik}) \cap [T_k, S_k),\\ \alpha_4 V(t) + \delta_2, & t \in [S_k,\ T_{k+1}),\end{cases} \tag{3.11}$$

where $\alpha_1 = \beta_1$, $\alpha_2 = 2^{(1-2\alpha)/2}\beta_2$, $\alpha_3 = \beta_3$, $\alpha_4 = 2h\lambda_{\max}(\hat{L})/\lambda_{\min}(\hat{L})$, $p = (2\alpha+1)/2$, $q = 1/2$, $\delta_1 = \rho_2\mathcal{L}Mn/\kappa$, $\delta_2 = \mathcal{D}(2M\lambda_{\max}(\hat{L}))^{1/2}V_{\max}^{1/2}$. $V(t) \leq V_{\max}$ for $t \geq 0$.

Based on Lemma 2.6, the system (2.1) can achieve FTC, and T^* satisfies

$$T^* \leq \frac{1 + \hat{\alpha}_1(p-1)T_\beta}{\hat{\alpha}_1(p-1)\beta} + \frac{1 + \hat{\alpha}_2(1-q)T_\beta}{\hat{\alpha}_2(1-q)\beta},$$

where $\hat{\alpha}_1 = \alpha_1(1-\bar{h})\exp\{(1-p)\breve{\varepsilon}T_\beta\}$, $\hat{\alpha}_2 = \alpha_2(1-\bar{h})$, $0 < \bar{h} < 1$. Additionally, the function $V(t)$ converges to the following region:

$$\lim_{t\to T^*} V(t) \leq \max\{\xi_1, \xi_2, \xi_3\},$$

where $\xi_1 = \delta_1^{1/p}(\bar{h}\alpha_2)^{-1/p}$, $\xi_2 = \delta_1^{1/q}(\bar{h}\alpha_3)^{-1/q}$, $\xi_3 = \delta_2/(\beta\breve{\varepsilon} - \alpha_4)$. □

Based on system (3.3) and the condition (3.4), we have $V(T_k) = W_1(T_k)$. Moreover, according to (3.11), it follows that $V(t) \leq W_1(t)$, $\forall t \in [T_k,\ S_k)$. Additionally, by the event-triggered mechanism (3.4), $V(t) < W_1(t)$ holds for $t \in [S_k,\ T_{k+1})$. From the definition of $W_2(t)$, we obtain $V(t) > W_2(t)$ and $\dot{V}(t) > \dot{W}_2(t)$ for $t \in [T_k,\ S_k)$; consequently, $V(S_k) = W_2(S_k)$. For $t \in [S_k, T_{k+1})$, it is clear that $V(t) \geq W_2(t)$. Therefore, $W_2(t) \leq V(t) \leq W_1(t), \forall t > 0$.

Since $\lim_{t\to T_1^*} W_1(t) \leq d$ and $\lim_{t\to T_1^*} W_2(t) \leq d$, there is a positive constant $T^* < T_1^*$ such that

$$\lim_{t\to T^*} V(t) \leq d,$$

where T_1^* is the convergence time of $W_1(t)$ and $W_2(t)$, $d > 0$.

Remark 3.10. In system (3.3), we have $\dot{W}_i(t) = -m_1 W_i(t) - m_2 W_i^{(2\alpha+1)/2}(t) - m_3 W_i^{1/2}(t) + \delta_1 \leq -m_2 W_i^{(2\alpha+1)/2}(t) - m_3 W_i^{1/2}(t) + \delta_1$. As shown in [6], $W_i(t)$ converges to a residual set whose size depends on m_2, m_3, α, δ_1. Since $W_2(t) \leq V(t) \leq W_1(t)$, the quantity d is less than or equal to this residual set.

Remark 3.11. The controller is given by $u_i(t) = -\rho_1 y_i(t_m^{ik}) e^{\|y_i(t_m^{ik})\|_2^{2\alpha-1}} - \rho_2 \mathrm{Tanh}(\kappa y_i(t_m^{ik}))$, where ρ_1 is the control gain of the exponential term, which adjusts the convergence rate, and ρ_2 is the gain of the hyperbolic tangent term, which enhances robustness. As ρ_1 and ρ_2 increase, the settling time T^* decreases. The triggering condition (3.6) involves parameters θ, γ_1, γ_2. Here, θ is the triggering threshold coefficient: A larger θ increases the triggering threshold, thereby enlarging the interval between two successive triggering instants and making it easier to avoid Zeno phenomenon. The parameters γ_1 and γ_2 are decay coefficients of the dynamic variable $\psi(t)$, ensuring its non-negativity and excluding the Zeno phenomenon. By Lemma 2.6 and Theorem 3.9, we have $\rho_1 > 1/2 + h/\lambda_{\min}(\hat{L})$ and $\rho_2 > \mathcal{D}M^{1/2}$. For γ_1 and γ_2, it is required that they be greater than zero and satisfy $\beta_2 = \min\{[(2\lambda_{\min}^2(\hat{L}))/\lambda_{\max}(\hat{L})]^{(2\alpha+1)/2}\rho_1(M^{(1-2\alpha)/2} - \theta), \gamma_1 M^{(1-2\alpha)/2}\}$, and $\alpha_3 = \min\{(2\lambda_{\min}(\hat{L}))^{1/2}(\rho_2 - \mathcal{D}M^{1/2}), \gamma_2\}$ with $\theta \in (0, 1)$.

Theorem 3.12. For the intermittent dynamic ETC process, Zeno behavior can be excluded under (3.1) and (3.7).

Proof. To estimate $t_{m+1}^{ik} - t_m^{ik}$ from below, we compute the derivative of $\|\eta_i(t)\|_2$.

When $t \in [t_m^{ik}, t_{m+1}^{ik}) \cap [T_k, S_k)$, we have

$$
\begin{aligned}
D^+\|\eta_i(t)\|_2 \leq& \|\dot{\eta}_i(t)\|_2 \\
\leq& (\rho_1 e^{\|y_i(t)\|_2^{2\alpha-1}} + \rho_1(2\alpha-1)\|y_i(t)\|_2^{2\alpha-1} e^{\|y_i(t)\|_2^{2\alpha-1}} + \rho_2\kappa \mathrm{sech}^2(\kappa y_i(t)))\|\dot{y}_i(t)\|_2 \\
\leq& (\rho_1 e^{\|y_i(t)\|_2^{2\alpha-1}} + \rho_1(2\alpha-1)\|y_i(t)\|_2^{2\alpha-1} e^{\|y_i(t)\|_2^{2\alpha-1}} + \rho_2\kappa)\|\dot{y}_i(t)\|_2 \\
\leq& (\rho_1 e^{(2\lambda_{\max}(\hat{L})V_{\max})^{\frac{2\alpha-1}{2}}} + \rho_1(2\alpha-1)(2\lambda_{\max}(\hat{L})V_{\max})^{\frac{2\alpha-1}{2}} e^{(2\lambda_{\max}(\hat{L})V_{\max})^{\frac{2\alpha-1}{2}}} + \rho_2\sqrt{n})\|\dot{y}_i(t)\|_2.
\end{aligned}
$$

Based on (3.2), one has

$$
\begin{aligned}
\|\dot{y}_i(t)\|_2 =& \|\sum_{i=1}^{M} a_{ij}(\dot{x}_i(t) - \dot{x}_j(t)) + b_i(\dot{x}_i(t) - \dot{x}_0(t))\|_2 \\
=& \|\sum_{j=1}^{M} a_{ij}(f(x_i(t),t) + u_i(t) + d_i(x_i(t),t) - f(x_j(t),t) - u_j(t) - d_j(x_j(t),t)) \\
&+ b_i(f(x_i(t),t) + u_i(t) + d_i(x_i(t),t) - f(x_0(t),t))\|_2 \\
=& \|\sum_{j=1}^{M} a_{ij}(f(x_i,t) - f(x_j,t)) + b_i(f(x_i,t) - f(x_0,t))\|_2 \\
&+ \|\sum_{j=1}^{M} a_{ij}(u_i(t) - u_j(t)) + b_i u_i(t)\|_2 \\
&+ \|\sum_{j=1}^{M} a_{ij}(d_i(x_i(t),t) - d_j(x_j(t),t)) + b_i d_i(x_i(t),t)\|_2
\end{aligned}
$$

$$
\begin{aligned}
&\le \| \sum_{j=1}^{M} a_{ij}(e_i(t) - e_j(t)) + b_i e_i(t)\|_2 + \| \sum_{j=1}^{M} a_{ij}(u_i(t) - u_j(t)) + b_i u_i(t)\|_2 \\
&\quad + (2\mathcal{D} \sum_{j=1}^{M} a_{ij} + b_i \mathcal{D}) \\
&\le \| \sum_{j=1}^{M} c_{ij} u_j(t)\|_2 + h \sum_{j=1}^{M} a_{ij}(\|e_i(t)\|_2 + \|e_j(t)\|_2) + h b_i \|e_i(t)\|_2 + \mathcal{D}(2l_{ii} + b_i).
\end{aligned}
$$

Since (3.1), we have

$$
\begin{aligned}
\| \sum_{j=1}^{M} c_{ij} u_j(t)\|_2 &= \| \sum_{j=1}^{M} c_{ij}(-\rho_1 y_j(t_m^{jk}) e^{\|y_j(t_m^{jk})\|_2^{2\alpha-1}} - \rho_2 \mathrm{Tanh}(\kappa y_j(t_m^{jk})))\|_2 \\
&\le \sum_{j=1}^{M} c_{ij}(\rho_1 (2\lambda_{\max}(\hat{L}) V_{\max})^{\frac{1}{2}} e^{(2\lambda_{\max}(\hat{L}) V_{\max})^{\frac{2\alpha-1}{2}}} + \rho_2 \sqrt{n}) \\
&= \omega_1.
\end{aligned}
$$

Therefore, we have

$$
\begin{aligned}
\|\dot{y}_i(t)\|_2 &\le \omega_1 + h \sum_{j=1}^{M} a_{ij}(\|e_i(t)\|_2 + \|e_j(t)\|_2) + h b_i \|e_i(t)\|_2 + \mathcal{D}(2l_{ii} + b_i) \\
&\le \omega_1 + h(2l_{ii} + b_i)(\frac{2V_{\max}}{\lambda_{\min}(\hat{L})})^{\frac{1}{2}} + \mathcal{D}(2l_{ii} + b_i) \\
&\le \omega_1 + \omega_2.
\end{aligned}
$$

Therefore, we have

$$
\|\dot{\eta}_i(t)\|_2 \le (\rho_1 e^{(2\lambda_{\max}(\hat{L}) V_{\max})^{\frac{2\alpha-1}{2}}} + \rho_1(2\alpha - 1)(2\lambda_{\max}(\hat{L}) V_{\max})^{\frac{2\alpha-1}{2}} e^{(2\lambda_{\max}(\hat{L}) V_{\max})^{\frac{2\alpha-1}{2}}} + \rho_2 \sqrt{n})(\omega_1 + \omega_2).
$$

Based on $\eta_i(t_m^{ik}) = 0$, we can deduce that

$$
\|\eta_i(t)\|_2 \le \int_{t_m^{ik}}^{t} \omega_3 ds + \|\eta_i(t_m^{ik})\|_2 = \int_{t_m^{ik}}^{t} \omega_3 ds,
$$

where $\omega_3 = (\rho_1 e^{(2\lambda_{\max}(\hat{L}) V_{\max})^{(2\alpha-1)/2}} + \rho_1(2\alpha - 1)(2\lambda_{\max}(\hat{L}) V_{\max})^{(2\alpha-1)/2} e^{(2\lambda_{\max}(\hat{L}) V_{\max})^{(2\alpha-1)/2}} + \rho_2 \sqrt{n})(\omega_1 + \omega_2)$. Therefore,

$$
\|\eta_i(t)\|_2^2 \le (\omega_3(t - t_m^{ik}))^2.
$$

According to (3.6), we have

$$
\|\eta_i(t_{m+1}^{ik})\|_2^2 = 2\theta\rho_1 \|y_i(t_{m+1}^{ik})\|_2^{2\alpha+1} + 2\theta\rho_2, \tag{3.12}
$$

which implies that

$$
(\omega_3(t_{m+1}^{ik} - t_m^{ik}))^2 \ge 2\theta\rho_2.
$$

A lower bound for the intertriggering interval is obtained as

$$t_{m+1}^{ik} - t_m^{ik} \geq \frac{\sqrt{2\theta\rho_2}}{\omega_3}.$$

When $t \in [S_k,\ T_{k+1})$, event is not triggered. Therefore, Zeno behavior is excluded. The proof is completed. □

4. Simulation results

We conduct a simulation on a nonlinear MAS consisting of ten followers and one leader. The dynamic of each agent is $\dot{x}_i(t) = u_i(t) + f(x_i(t), t) + d_i(x_i(t), t)$, where $f(x_i(t), t) = 0.5(|x_{i1}(t) + 1| - |x_{i1}(t) - 1|, |x_{i2}(t) + 1| - |x_{i2}(t) - 1|)^{\mathrm{T}}$ [30]. From Assumption 2.2, it follows that $h = 0.5$.

Figure 2 illustrates the undirected communication topology, from which we obtain $\lambda_{\min}(\hat{L})$=1, $\lambda_{\max}(\hat{L})$=6.8. The initial states $x_i(0)$ and $x_0(0)$ are selected uniformly at random from $[-0.5, 0.5]$.

We further compare our aperiodic intermittent dynamic ETC scheme with the numerical simulation reported in [30].

Since the control intervals of intermittent control are [0.00, 0.10], [0.44, 0.56], [0.90, 0.99], [1.33, 1.42], [1.76, 1.87], [2.20, 2.22], we can obtain $\beta = 0.27$ and $T_{con}(t_2, t_1) = 0.43$. Let $T_\beta = 0.15$ be such that Definition 2.4 is satisfied. By setting $\rho_1 = 3.7$, $\rho_2 = 15$, $\mathcal{D} = 0.1$, $\alpha = 1.1$, $\theta = 0.3$, $\gamma_1 = 1.6$, and $\gamma_2 = 22$, we obtain $\alpha_1 = 5.4$, $\alpha_2 = 0.26$, $\alpha_3 = 22$, and $\alpha_4 = 6.8$.

Let $\breve{\varepsilon} = 30$ and $\bar{h} = 0.9$ be used to obtain $\xi_1 = 0.91$, $\xi_2 = 0.0002$ and $\xi_3 = 0.9$ in Theorem 3.9. Then $V \leq 0.91$ indicates that practical consensus is achieved. Based on (3.11) and $\kappa = 300$, we can obtain $\delta_1 = 0.09$. Choosing $m_1 = 0.3$, $m_2 = 0.2$, $m_3 = 3.2$ ensures $m_i < \alpha_i,\ i = 1, 2, 3$. The state of $V(t)$, $W_1(t)$ and $W_2(t)$ are given in Figure 3.

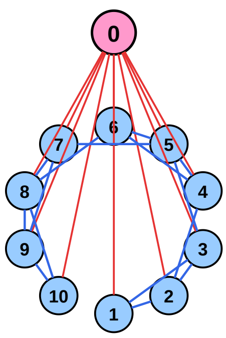

Figure 2. The communication graph.

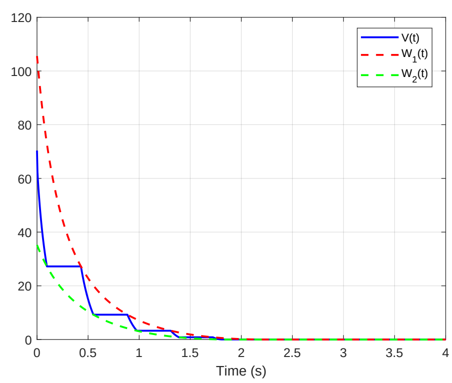

Figure 3. The relation of $V(t)$, $W_1(t)$ and $W_2(t)$.

Figures 4 and 5 show the tacking error and control of system (2.1).

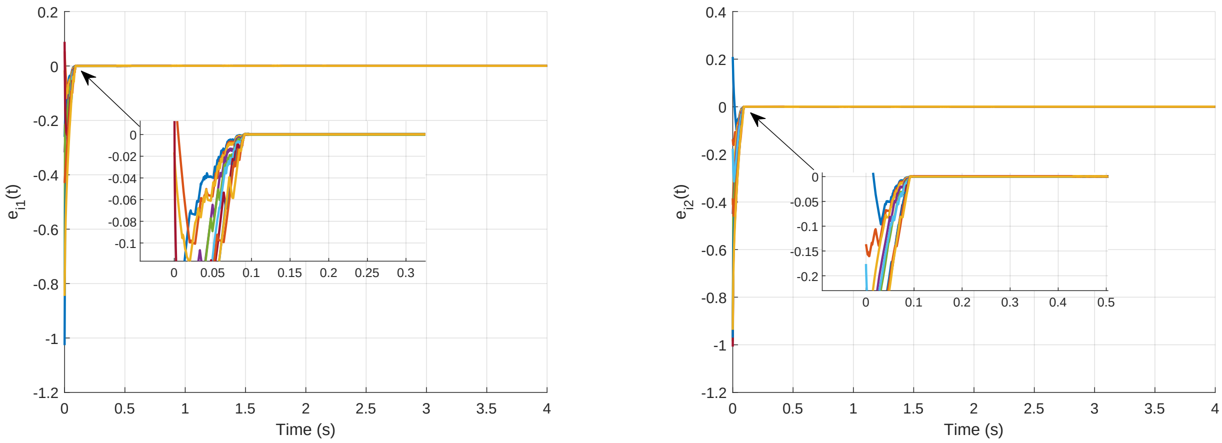

Figure 4. The evolution of $e_i(t)$.

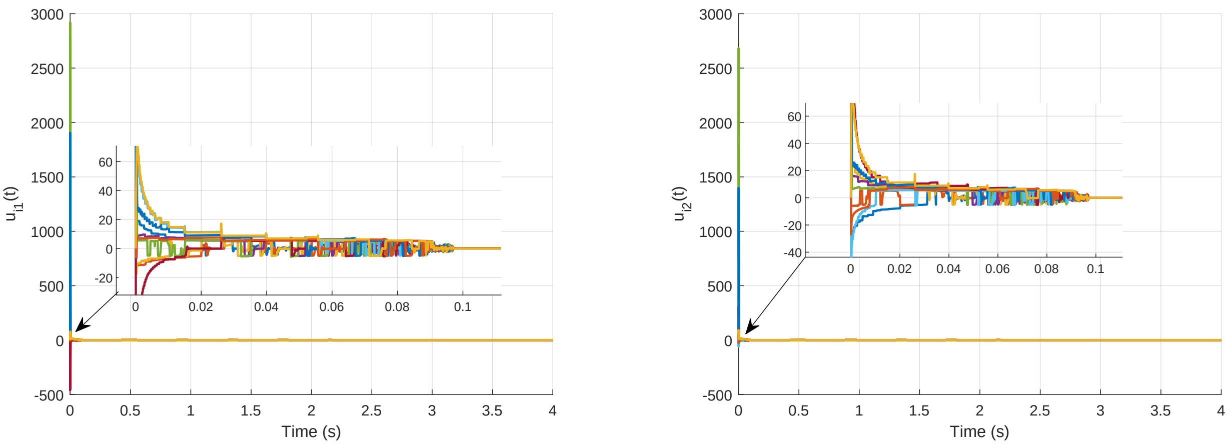

Figure 5. The evolution of $u_i(t)$.

When the initial values of the agents are larger, the results are as follows. The initial states $x_i(0)$ and $x_0(0)$ are selected uniformly at random from $[-5, 5]$.

Figures 6 and 7 show the relevant plots for initial values in the range $[-5, 5]$. It can be observed that consensus can be achieved regardless of the initial values. The results demonstrate that, despite a tenfold increase in the initial deviation, the convergence still completes strictly before the prescribed bound T^*.

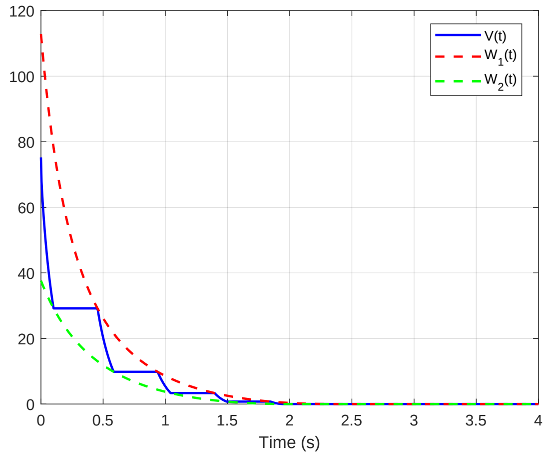

Figure 6. The relation of $V(t)$, $W_1(t)$ and $W_2(t)$.

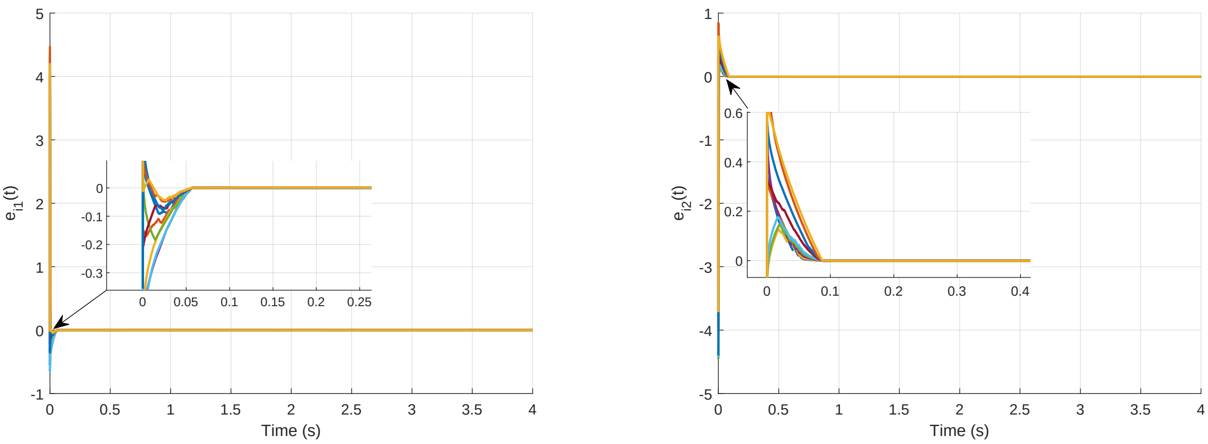

Figure 7. The evolution of $e_i(t)$.

The numerical simulation from [30] is presented as Figures 8 and 9.

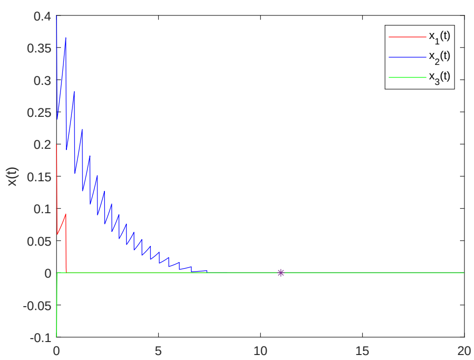

Figure 8. The state of $x(t)$.

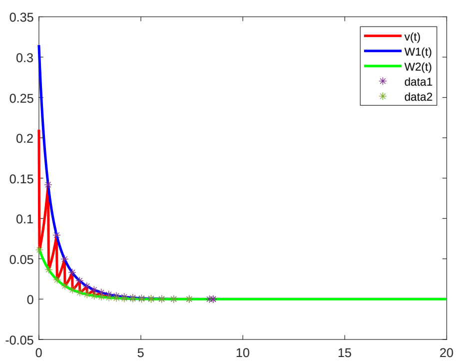

Figure 9. The relation of $V(t)$, $W_1(t)$ and $W_2(t)$.

The same controller and parameters are used in both [30] and this paper. From the convergence times shown in Figures 3 and 9, it can be seen that the method proposed in this paper achieves consensus in a shorter time.

It should be acknowledged that the enlarged initial error inevitably produces a higher instantaneous control signal during the initial transient, which serves as a practical reminder of the trade-off between fast fixed-time convergence and actuator constraints.

5. Discussion

This paper proposed an aperiodic intermittent ETC scheme to address the practical FTC problem of nonlinear MASs with external disturbances. First, a control input incorporating an exponential term and a hyperbolic tangent function was introduced, which was more concise than previous control input forms and better aligned with practical engineering applications. Next, by introducing two auxiliary functions that converged in fixed-time, an aperiodic intermittent ETC strategy was designed to determine the working and resting instants of the intermittent control. Subsequently, based on this framework, several sufficient conditions for achieving practical FTC of MASs with external disturbances were derived. Finally, numerical examples verified the effectiveness of the theoretical results. The controller is constructed with exponential error terms, which accelerate the consensus process, particularly under large initial conditions, by amplifying the control response for large initial deviations. Nevertheless, this amplification effect may push the control input into the saturation region, imposing a practical constraint on the proposed scheme. As a prospective improvement, we intend to introduce a saturation-compensated exponential term in future work to balance the trade-off between convergence speed and actuator limits. In addition, we will demonstrate how two auxiliary functions guarantee the average control rate condition.

Author contributions

Nan Li: Writing-original draft, software, investigation, formal analysis; Na Li: Writing-original draft, supervision, methodology, conceptualization; Shuaibing Zhu: Visualization, resources, software; Jianwen Feng: Visualization, conceptualization. All authors have read and approved the final version of the manuscript for publication.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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