Letter

Fixed-Time Cooperative Tracking for Delayed Disturbed Multi-Agent Systems Under Dynamic Event-Triggered Control

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Dear editor,

Recently, researchers have obtained many new results about the multi-agent systems (MASs) [1]–[3]. In [1], the fixed-time cooperative control (FTCC) algorithm of linear MASs with matched disturbances was proposed. The nonholonomic chained-form dynamics case was considered in [2]. In [3], the output tracking problem with data packet dropout was solved for high-order MASs. Moreover, delay frequently occurs because of the non-ideal data transmission [4], and the corresponding FTCC algorithm of MASs with delay was given in [5].

However, the above results required continuous updates of controllers. An event-triggered control (ETC) was presented to solve the consensus problems [6]–[10]. In [7], the lossy sensors and cyber-attacks were considered for the MASs. In [8], a new distributed ETC was developed for the heterogeneous linear MASs. Furthermore, the FTCC problem was solved for the discrete-time nonlinear MASs with constraints via neural-network-based ETC control in [9]. In [10], the output consensus problem was addressed for the nonlinear MASs under unknown control directions. In addition, some follow-up studies have employed a dynamic ETC for FTCC [11]–[17]. In [11], a new formation protocol was proposed as required under the dynamic ETC. In [12], the dynamic ETC algorithm can guarantee the agents converge exponentially to the average consensus. Moreover, the formation-containment control problem was addressed in [13]. Furthermore, a new bandwidth-aware dynamic ETC scheduling algorithm was applied to the automated vehicles in [14]. In [15], a new framework of cooperative control was developed for MASs based on fault-estimation-in-the-loop. In [16], the dynamic ETC algorithm was applied to industrial systems based on reinforcement learning, and more control algorithms and applications of dynamic ETC were given in [17].

Considering the FTCC with the ETC, there are some good results [18], [19]. In [18], the dynamic ETC was considered for the linear MASs to guarantee finite-time consensus. In [19], fixed-time ETC problem of leader-follower MASs was considered, and a new self-triggered scheme was developed. However, the abovementioned studies need continuous listening. Hence, some new ETC strategies were designed in [20]–[23]. In [20], the FTCC consensus was obtained via ETC, and the input delay was considered in [21]. Moreover, the output-based FTCC algorithm was developed in [22]. Furthermore, the dynamic mechanism was adopted in [23]. In addition, the self-triggered scheme was presented in [24], and the dynamic mechanism was not considered both in the ETC and self-triggered scheme, which may lead to more triggering times.

Motivated by these existing literature, we investigate the FTCC problem of delayed leader-follower MASs subject to external disturbances via dynamic ETC. However, the dynamic ETC implies less information exchange. Hence, the difficulty is how to obtain the FTCC when the dynamic ETC is considered. The contributions are listed as follows. First, different from the leaderless FTCC results based on ETC [18], [21]–[23], we additionally consider situations that include a dynamic leader. Second, compared with the triggering mechanism in [19], [20], [24], a new dynamic ETC mechanism is designed herein, which can effectively reduce triggering times under the same convergence rate. Third, the consensus tracking can be reached in a finite time under arbitrary initial conditions even with input delay and external disturbances. Furthermore, few results have been reported for the practical FTCC problem for delayed leader-follower MASs via dynamic ETC hitherto.

Preliminaries: Consider an undirected graph $\mathcal{G}$ with $\mathcal{N}$ nodes. The Laplacian matrix $\mathcal{L}$ and the $\mathcal{H}=\mathcal{L}+\mathcal{B}$ can be seen in [19]. The delayed MASs have $\mathcal{N}$ followers and one leader, and the dynamics models are described as

$$\begin{aligned}&\dot{x}_i(t)=u_i(t-\tau_i)+\omega_i(x_i(t),t), \qquad i\in\{1,\ldots,\mathcal{N}\}\\&\dot{x}_0(t)=u_0(t)\end{aligned}\tag{1}$$

where $x_i(t)$ and $x_0(t)$ are the states; $u_i(t)$ and $u_0(t)$ are the controllers; τ_i is the known delay, and $\omega_i(x_i(t),t)$ is the unknown disturbance.

Assumption 1: There are two non-negative and known constants ϖ and $\bar{u}$ such that $|\omega_i(x_i(t),t)|\le\varpi$ and $|u_0(t)|\le\bar{u}$.

Assumption 2: In this paper, we assume that the undirected graph of the followers is connected and at least one $a_{i0}>0$.

Lemma 1 [24]: Consider the system (1), there is a $V(x(t))$ satisfying $\dot{V}(x(t))\le-\eta_1V^{\mu}(x(t))-\eta_2V^{\nu}(x(t))+\iota$, where $\eta_1>0$, $\eta_2>0$, $\iota>0$, $\mu\in(0,1)$, $\nu\in(1,\infty)$ is the ratio of positive odd numbers; in addition, the system (1) is practical fixed-time stable, and we have

$$\left\{\lim_{t\to T}x(t)|V\le\min\left\{\eta_1^{-\frac{1}{\mu}}\left(\frac{\iota}{1-\Theta}\right)^{\frac{1}{\mu}},\eta_2^{-\frac{1}{\nu}}\left(\frac{\iota}{1-\Theta}\right)^{\frac{1}{\nu}}\right\}\right\}$$

with a constant $\Theta\in(0,1)$, and settling time $T\le T_{\max}:=1/(\eta_1\Theta(1-\mu))+1/(\eta_2\Theta(\nu-1))$.

Lemma 2 [24]: For any $X\in\mathbb{R}$, it yields that $0\le|X|-X\tanh(\Psi X)\le\Pi/\Psi$, where $\Psi>>1$ and $\Pi=0.2785$.

Main results: Herein, we investigate how to achieve FTCC via dynamic Zeno-free ETC. Firstly, define the following state error:

$$e_i(t)=\hat{x}_i(t)-x_0(t)\tag{2}$$

where $\hat{x}_i(t)=x_i(t)+\int_{t-\tau_i}^{t}u_i(T)dT$. In addition, the tracking error is written as $\varsigma_i=x_i(t)-x_0(t)$.

We present the controller of follower i as follows:

$$u_i(t)=-\eta_1\gamma_i^{\nu}\left(t_k^i\right)-\eta_2\tanh\left(\Psi\gamma_i\left(t_k^i\right)\right)-\eta_3\gamma_i\left(t_k^i\right)\tag{3}$$

with $\gamma_i(t)=\sum_{j=1}^{\mathcal{N}}a_{ij}(\hat{x}_i(t)-\hat{x}_j(t))+a_{i0}e_i(t)$, where η_1, η_2, and $\nu\in(1,\infty)$ are the same parameters in Lemma 1, $\eta_3>0$, t_k^i is the latest triggering instant of follower i, and $t\in[t_k^i,t_{k+1}^i)$. The measurement error $E_i(t)=\eta_1\gamma_i^{\nu}(t_k^i)+\eta_2\tanh(\Psi\gamma_i(t_k^i))+\eta_3\gamma_i(t_k^i)-\eta_1\gamma_i^{\nu}(t)-\eta_2\tanh(\Psi\gamma_i(t))-\eta_3\gamma_i(t)$.

Define the following triggering function:

$$\Gamma_i(t)=\Theta\left(|E_i(t)|-\epsilon\eta_3|\gamma_i(t)|-\epsilon\eta_2-\epsilon\eta_1\left|\gamma_i^{\nu}(t)\right|\right)\tag{4}$$

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Citation: J. Liu, Y. B. Wu, M. W. Sun, and C. Y. Sun, "Fixed-time cooperative tracking for delayed disturbed multi-agent systems under dynamic event-triggered control," *IEEE/CAA J. Autom. Sinica*, vol. 9, no. 5, pp. 930–933, May 2022.

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Digital Object Identifier 10.1109/JAS.2022.105503

where $\epsilon \in (0,1)$ and $\Theta > 0$. According to our results [24] and motivated by [12], we define a dynamic variable $\Xi_i(t)$, which is written as

$$\begin{aligned}\dot{\Xi}_i(t) = {} & \delta|\gamma_i(t)|\left(\epsilon\eta_1\left|\gamma_i^{\nu}(t)\right| + \epsilon\eta_2 + \epsilon\eta_3|\gamma_i(t)| - |E_i(t)|\right)\\ & -\rho_1\Xi_i^{\frac{\nu+1}{2}}(t) - \rho_2\Xi_i^{\frac{1}{2}}(t) - \rho_3\Xi_i^2(t)\end{aligned} \tag{5}$$

where $\delta \in (0,1)$, $\Xi_i(0)$, ρ_1, ρ_2, and ρ_3 are positive constants.

Remark 1: The dynamics models considered in this paper are similar to the case in [24]. However, a new dynamic Zeno-free ETC mechanism is constructed herein, which can effectively reduce triggering times. If the dynamic triggering mechanism is excluded, it will be the result in [24]. In [18], the finite-time consensus was obtained via dynamic ETC for linear MASs. In this paper, the consensus tracking can be reached in a finite time under arbitrary initial conditions even with input delay and external disturbances.

Based on $\Xi_i(t)$, the triggering condition is constructed as

$$t_{k+1}^i = \inf\{t > t_k^i \,|\, \Gamma_i(t) \ge \Xi_i(t)\}. \tag{6}$$

Thus, for follower i, one derives $\Gamma_i(t) \le \Xi_i(t)$, which implies $|E_i(t)| \le \epsilon\eta_1\left|\gamma_i^{\nu}(t)\right| + \epsilon\eta_2 + \epsilon\eta_3|\gamma_i(t)| + \Xi_i(t)/\Theta$.

Based on (5) and (6), we have $\dot{\Xi}_i(t) \ge -\rho_1\Xi_i^{\frac{\nu+1}{2}}(t) - \rho_2\Xi_i^{\frac{1}{2}}(t) - \rho_3\Xi_i^2(t) - (\delta/\Theta)|\gamma_i(t)|\Xi_i(t)$. Thus, we have $\Xi_i(t) \ge \exp(\int_0^t \chi_i(s)\,ds) \times \Xi_i(0) > 0$ with $\chi_i(t) = -\rho_1\Xi_i^{\frac{\nu-1}{2}}(t) - \rho_2\Xi_i^{-12}(t) - \rho_3\Xi_i(t) - (\delta/\Theta)|\gamma_i(t)|$ for all $t \ge 0$.

Theorem 1: For the MASs, if the inequalities $\eta_2(1-\epsilon) > \varpi + \bar{u}$, and $\sqrt{4\eta_3\rho_3(1-\epsilon)} \ge (1-\delta)/\Theta$ hold, the fixed-time cooperative tracking problem is addressed.

Proof: Choose the Lyapunov function as $V(t) = (1/2)e^T(t)\mathcal{H}e(t) + \sum_{i=1}^{\mathcal{N}}\Xi_i(t)$, where $e(t) = [e_1(t), e_2(t), \ldots, e_{\mathcal{N}}(t)]^T$. Utilizing $\hat{x}_i(t) = x_i(t) + \int_{t-\tau_i}^t u_i(T)\,dT$, it yields that $\dot{\hat{x}}_i(t) = u_i(t) + \omega_i(x_i(t), t)$. Then, we have

$$\begin{aligned}\dot{V}(t) = {} & \sum_{i=1}^{\mathcal{N}}\gamma_i(t)(u_i(t) + \omega_i(x_i(t),t) - u_0(t))\\ & + \sum_{i=1}^{\mathcal{N}}\delta|\gamma_i(t)|\left(\epsilon\eta_1\left|\gamma_i^{\nu}(t)\right| + \epsilon\eta_2 + \epsilon\eta_3|\gamma_i(t)| - |E_i(t)|\right)\\ & -\rho_1\sum_{i=1}^{\mathcal{N}}\Xi_i^{\frac{\nu+1}{2}}(t) - \rho_2\sum_{i=1}^{\mathcal{N}}\Xi_i^{\frac{1}{2}}(t) - \rho_3\sum_{i=1}^{\mathcal{N}}\Xi_i^2(t)\\ \le {} & (1-\delta)\sum_{i=1}^{\mathcal{N}}|\gamma_i(t)||E_i(t)| - \eta_1(1-\epsilon\delta)\sum_{i=1}^{\mathcal{N}}\gamma_i^{\nu+1}(t)\\ & - \eta_2(1-\epsilon\delta)\sum_{i=1}^{\mathcal{N}}|\gamma_i(t)| + \left(\varpi + \bar{u}\right)\sum_{i=1}^{\mathcal{N}}|\gamma_i(t)|\\ & + \frac{\eta_2\Pi\mathcal{N}}{\Psi} - \rho_3\sum_{i=1}^{\mathcal{N}}\Xi_i^2(t) - \rho_2\left(\sum_{i=1}^{\mathcal{N}}\Xi_i(t)\right)^{\frac{1}{2}}\\ & - \rho_1\mathcal{N}^{\frac{1-\nu}{2}}\left(\sum_{i=1}^{\mathcal{N}}\Xi_i(t)\right)^{\frac{\nu+1}{2}} - \eta_3(1-\epsilon\delta)\sum_{i=1}^{\mathcal{N}}\gamma_i^2(t)\\ \le {} & -\eta_1(1-\epsilon)\mathcal{N}^{\frac{1-\nu}{2}}\left(\sum_{i=1}^{\mathcal{N}}\gamma_i^2(t)\right)^{\frac{\nu+1}{2}} + \frac{\eta_2\Pi\mathcal{N}}{\Psi}\\ & - \left(\eta_2(1-\epsilon) - \varpi - \bar{u}\right)\left(\sum_{i=1}^{\mathcal{N}}\gamma_i^2(t)\right)^{\frac{1}{2}}\\ & - \rho_1\mathcal{N}^{\frac{1-\nu}{2}}\left(\sum_{i=1}^{\mathcal{N}}\Xi_i(t)\right)^{\frac{\nu+1}{2}} - \rho_2\left(\sum_{i=1}^{\mathcal{N}}\Xi_i(t)\right)^{\frac{1}{2}}.\end{aligned} \tag{7}$$

From the definition of $\gamma_i(t)$, we have $\lambda_{\max}e^T(t)\mathcal{H}e(t) \ge \sum_{i=1}^{\mathcal{N}}\gamma_i^2(t) \ge \lambda_{\min}e^T(t)\mathcal{H}e(t)$, where $\lambda_{\min}$ and $\lambda_{\max}$ are the smallest and the largest eigenvalues of $\mathcal{H}$. Hence, the $\dot{V}(t)$ can be written as $\dot{V}(t) \le -(\eta_2(1-\epsilon) - \varpi - \bar{u})(2\lambda_{\min})^{\frac{1}{2}}((1/2)e^T(t)\mathcal{H}e(t))^{\frac{1}{2}} - \mathcal{N}^{\frac{1-\nu}{2}}\eta_1(1-\epsilon)$ $(2\lambda_{\min})^{\frac{\nu+1}{2}}((1/2)e^T(t)\mathcal{H}e(t))^{\frac{\nu+1}{2}} - \rho_1\mathcal{N}^{\frac{1-\nu}{2}}(\sum_{i=1}^{\mathcal{N}}\Xi_i(t))^{\frac{\nu+1}{2}} - \rho_2(\sum_{i=1}^{\mathcal{N}}\Xi_i(t))^{\frac{1}{2}} + \frac{\eta_2\Pi\mathcal{N}}{\Psi} \le -\alpha V^{\frac{1}{2}}(t) - 2^{\frac{1-\nu}{2}}\beta V^{\frac{\nu+1}{2}}(t) + \frac{\eta_2\Pi\mathcal{N}}{\Psi}$, where $\alpha = \min\{\rho_2, (\eta_2(1-\epsilon) - \varpi - \bar{u})(2\lambda_{\min})^{\frac{1}{2}}\}$ and $\beta = \min\{\rho_1\mathcal{N}^{\frac{1-\nu}{2}}, \mathcal{N}^{\frac{1-\nu}{2}}\eta_1(1-\epsilon) \times (2\lambda_{\min})^{\frac{\nu+1}{2}}\}$.

Then, it follows that $\lim_{t\to T(\hat{x})}V(t) \le Y = \min\{\alpha^{-2}(\frac{\eta_2\Pi\mathcal{N}}{\Psi(1-\Theta)})^2, 2^{\frac{\nu-1}{\nu+1}}(\frac{\eta_2\Pi\mathcal{N}}{\beta\Psi(1-\Theta)})^{\frac{2}{\nu+1}}\}$, and we can derive $T(\hat{x}) \le T_{\max} = \frac{2}{\alpha\Theta} + \frac{2}{\beta\Theta(\nu-1)}$, which means that $\sum_{i=1}^{\mathcal{N}}\gamma_i^2(t) \le 2\lambda_{\max}(Y - \sum_{i=1}^{\mathcal{N}}\Xi_i(t)) \le 2\lambda_{\max}Y$ when $t = T(\hat{x})$, and $|\int_{t-\tau_i}^t u_i(T)dT| \le \bar{Y} = \tau_i((2\mathcal{N}\lambda_{\max}Y)^{\frac{\nu}{2}} + \eta_2\tanh(\Psi\sqrt{2\lambda_{\max}Y}))$ when $t = T(\hat{x}) + \tau_i$. Because of $\lim_{t\to T(x)}\hat{x}_i(t) = x_i(t) + \int_{t-\tau_i}^t u_i(T)dT$ and $|\hat{x}_i(t) - x_0(t)| \le 2\mathrm{Y}/\lambda_{\min}$, we can derive $|x_i(t) - x_0(t)| \le 2\mathrm{Y}/\lambda_{\min} + \bar{Y}$ when $t = T(x) \le T_{\max} + \max\{\tau_1, \ldots, \tau_{\mathcal{N}}\}$. The practical fixed-time cooperative tracking is reached, and it follows that $T(x) \le 2/(\alpha\Theta) + 2/(\beta\Theta(\nu-1)) + \max\{\tau_1, \ldots, \tau_{\mathcal{N}}\}$. ■

Remark 2: Compared with the results in [23], we consider the input delay and external disturbances simultaneously herein. First, the model reduction method was adopted in the state error to solve the input delay problem. Then, the upper bound of the convergence time can be obtained, which is related to the input delay. Furthermore, a dynamic leader is considered.

Remark 3: Different from the triggering mechanism in [24], an improved dynamic ETC mechanism is constructed herein, which can effectively reduce triggering times under the same convergence rate. Due to the existence of the new dynamic variable, the form of our controller and measurement error have also become more complicated to ensure the fixed-time convergence of the MASs. If the variable $\Xi_i(t) = 0$, it will be the case in [24].

Theorem 2: Under the abovementioned studies, the dynamic ETC is Zeno-free.

Proof: We have $D^+|E_i(t)| \le (\eta_1\nu|\gamma_i^{\nu-1}(t)| + \eta_3 + \eta_2\Psi(1 - \tanh^2(\Psi\gamma_i(t))))|\dot{\gamma}_i(t)| \le (\eta_1\nu(2\lambda_{\max}V(0))^{\frac{\nu-1}{2}} + \eta_2\Psi + \eta_3)|\dot{\gamma}_i(t)| \le \Lambda_1|\sum_{j=1}^{\mathcal{N}}a_{ij} \times (\dot{\hat{x}}_i(t) - \dot{\hat{x}}_j(t)) + a_{i0}\dot{e}_i(t)| \le \Lambda_1(|\sum_{j=1}^{\mathcal{N}}l_{ij}u_j(t)| + a_{i0}\bar{u} + 2h_{ii}\varpi) \le \Lambda_1\Lambda_{i,2}$, where $\Lambda_1 = \eta_1\nu(2\lambda_{\max}V(0))^{\frac{\nu-1}{2}} + \eta_2\Psi + \eta_3$, $\Lambda_{i,2} = \sum_{j=1}^{\mathcal{N}}|l_{ij}|(\eta_1 \times (2\lambda_{\max}V(0))^{\frac{\nu}{2}} + \eta_2 + \eta_3(2\lambda_{\max}V(0))^{\frac{1}{2}}) + a_{i0}\bar{u} + 2h_{ii}\varpi$. We obtain $|E_i(t)| \le \int_{t_k^i}^t \Lambda_1\Lambda_{i,2}\mathrm{d}s$, and the $|E_i(t_{k+1}^i)| = \epsilon\eta_3|\gamma_i(t_{k+1}^i)| + \epsilon\eta_2 + \epsilon\eta_1|\gamma_i^{\nu}(t_{k+1}^i)| + \Xi_i(t_{k+1}^i)/\Theta \le \int_{t_k^i}^{t_{k+1}^i}\Lambda_1\Lambda_{i,2}ds$. Hence, it is easy to obtain $t_{k+1}^i - t_k^i \ge \epsilon\eta_2/(\Lambda_1\Lambda_{i,2}) > 0$. ■

Simulation results: We will give a simple simulation example to demonstrate the effectiveness of the algorithm. According to Fig. 1, we have $\lambda_{\min} = 0.1308$ and $\lambda_{\max} = 5.4256$.

Then, we set $\tau_i = 0.06$, $\omega_i(x_i(t), t) = 1.5\sin(x_i(t))$, $u_0(t) = 10\cos(60t)$, which satisfy Assumption 1 with $\varpi = 1.5$ and $\bar{u} = 10$. Moreover, we assume that $x(0) = [24\ \ -8\ \ 12\ \ 2\ \ -20\ \ -7]^T$ and $x_0(0) = 2$. Furthermore, the parameters are that $\eta_1 = 1$, $\eta_2 = 15$, $\eta_3 = 2$, $\rho_1 = 0.6$, $\rho_2 = 0.7$, $\rho_3 = 1$, $\epsilon = 0.2$, $\nu = 7/5$, $\Theta = 0.5$, $\delta = 0.5$, $\Xi_i(0) = 30$, $\Psi = 100$.

Fig. 2 shows the trajectories of the MASs under the dynamic ETC, and the FTCC is obtained in 0.4 s. The evolutions of the tracking errors are given in Fig. 3. The triggering instants under the dynamic Zeno-free ETC of the six followers are depicted in Fig. 4. Moreover, Fig. 5 shows the evolution of $\Xi_i(t)$. According to Fig. 5, it is easy to find that the dynamic variable $\Xi_i(t) > 0$, which implies the validity

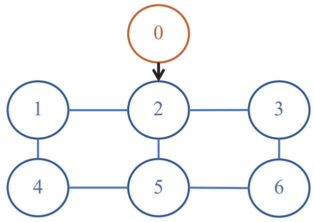

Fig. 1. The communication graph.

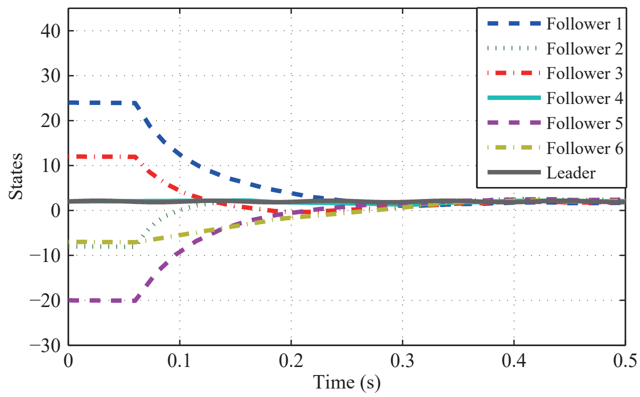

Fig. 2. Trajectories of the MASs.

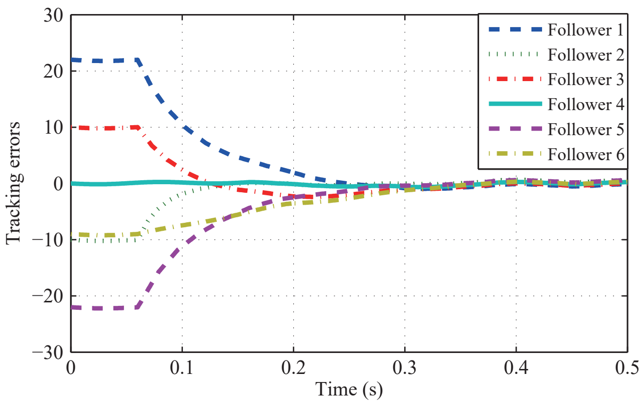

Fig. 3. Tracking errors under the dynamic Zeno-free ETC.

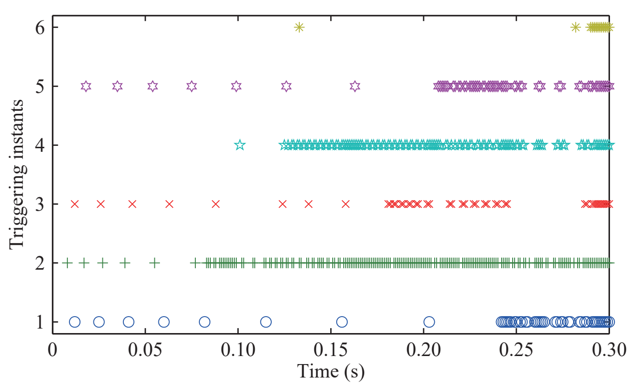

Fig. 4. Triggering instants of six followers.

of our theoretical results in Theorem 1.

Conclusions: The FTCC problem is addressed for the delayed disturbed leader-follower MASs under dynamic ETC. For the FTCC,

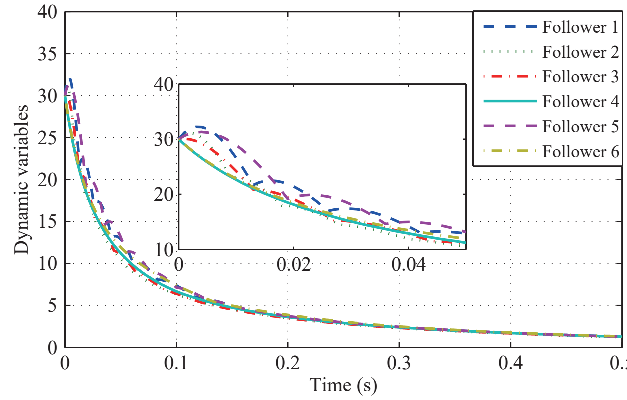

Fig. 5. The evolution of $\Xi_i(t)$.

the upper bound of the convergence time can be specified by choosing appropriate controller parameters, which is independent of the initial conditions. Compared with the traditional static ETC, the dynamic ETC can effectively reduce triggering times.

Acknowledgments: This work was supported in part by the National Natural Science Foundation of China (62103099, 61921004), and the Natural Science Foundation of Jiangsu Province of China (BK20210214).

References

[1] Z. Zuo, B. Tian, M. Defoort, and Z. Ding, "Fixed-time consensus tracking for multiagent systems with high-order integrator dynamics," *IEEE Trans. Automatic Control*, vol. 63, no. 2, pp. 563–570, 2018.

[2] B. Ning and Q.-L. Han, "Prescribed finite-time consensus tracking for multi-agent systems with nonholonomic chained-form dynamics," *IEEE Trans. Automatic Control*, vol. 64, no. 4, pp. 1686–1693, 2019.

[3] J. Ni, P. Shi, Y. Zhao, and Z. Wu, "Fixed-time output consensus tracking for high-order multi-agent systems with directed network topology and packet dropout," *IEEE/CAA J. Autom, Sinica*, vol. 8, no. 4, pp. 817–836, 2021.

[4] X.-M. Zhang, Q.-L. Han, and X. Ge, "Novel stability criteria for linear time-delay systems using Lyapunov-Krasovskii functionals with a cubic polynomial on time-varying delay," *IEEE/CAA J. Autom, Sinica*, vol. 8, no. 1, pp. 77–85, 2021.

[5] J. Ni, L. Liu, C. Liu, and J. Liu, "Fixed-time leader-following consensus for second-order multi-agent systems with input delay," *IEEE Trans. Industrial Electronics*, vol. 64, no. 11, pp. 8635–8646, 2017.

[6] D. Dimarogonas, E. Frazzoli, and K. Johansson, "Distributed event-triggered control for multi-agent systems," *IEEE Trans. Automatic Control*, vol. 57, no. 5, pp. 1291–1297, 2012.

[7] D. Ding, Z. Wang, D. W. Ho, and G. Wei, "Observer-based event-triggering consensus control for multiagent systems with lossy sensors and cyber-attacks," *IEEE Trans. Cybernetics*, vol. 47, no. 8, pp. 1936–1947, 2017.

[8] W. Hu, L. Liu, and G. Feng, "Output consensus of heterogeneous linear multi-agent systems by distributed event-triggered/self-triggered strategy," *IEEE Trans. Cybernetics*, vol. 47, no. 8, pp. 1914–1924, 2017.

[9] D. Ding, Z. Wang, and Q.-L. Han, "Neural-network-based consensus control for multiagent systems with input constraints: The event-triggered case," *IEEE Trans. Cybernetics*, vol. 50, no. 8, pp. 3719–3730, 2020.

[10] Y.-W. Wang, Y. Lei, T. Bian, and Z.-H. Guan, "Distributed control of nonlinear multiagent systems with unknown and nonidentical control directions via event-triggered communication," *IEEE Trans. Cybernetics*, vol. 50, no. 5, pp. 1820–1832, 2020.

[11] X. Ge and Q.-L. Han, "Distributed formation control of networked multi-agent systems using a dynamic event-triggered communication mechanism," *IEEE Trans. Industrial Electronics*, vol. 64, no. 10, pp. 8118–8127, 2017.

[12] X. Yi, K. Liu, D. V. Dimarogonas, and K. H. Johansson, "Dynamic event-triggered and self-triggered control for multi-agent systems,"

IEEE Trans. Automatic Control, vol. 64, no. 8, pp. 3300–3307, 2019.

[13] A. Amini, A. Asif, and A. Mohammadi, "Formation-containment control using dynamic event-triggering mechanism for multi-agent systems," *IEEE/CAA J. Autom*, *Sinica*, vol. 7, no. 5, pp. 1235–1248, 2020.

[14] X. Ge, S. Xiao, Q.-L. Han, X.-M. Zhang, and D. Ding, "Dynamic event-triggered scheduling and platooning control co-design for automated vehicles over vehicular ad-hoc networks," *IEEE/CAA J. Autom*, *Sinica*, vol. 9, no. 1, pp. 31–46, 2022.

[15] Y. Ju, D. Ding, X. He, Q.-L. Han, and G. Wei, "Consensus control of multi-agent systems using fault-estimation-in-the-loop: Dynamic event-triggered case," *IEEE/CAA J. Autom, Sinica*, DOI: 10.1109/JAS.2021.1004386, 2021.

[16] C. Mu, K. Wang, and C. Sun, "Learning control supported by dynamic event communication applying to industrial systems," *IEEE Trans. Industrial Informatics*, vol. 17, no. 4, pp. 2325–2335, 2021.

[17] X. Ge, Q.-L. Han, L. Ding, Y.-L. Wang, and X.-M. Zhang, "Dynamic event-triggered distributed coordination control and its applications: A survey of trends and techniques," *IEEE Trans. Systems*, *Man*, *and Cybernetics*: *Systems*, vol. 50, no. 9, pp. 3112–3125, 2020.

[18] L. Wen, S. Yu, Y. Zhao, and Y. Yan, "Finite-time dynamic event-triggered consensus of multi-agent systems with disturbances via integral sliding mode," *Int. Journal of Control*, DOI: 10.1080/00207179.2021.1989045, 2021.

[19] J. Liu, Y. Zhang, Y. Yu, and C. Sun, "Fixed-time leader-follower consensus of networked nonlinear systems via event/self-triggered control," *IEEE Trans. Neural Networks and Learning Systems*, vol. 31, no. 11, pp. 5029–5037, 2020.

[20] T. Xu, G. Lv, Z. Duan, Z. Sun, and J. Yu, "Distributed fixed-time triggering-based containment control for networked nonlinear agents under directed graphs," *IEEE Trans. Circuits and Systems I*: *Regular Papers*, vol. 67, no. 10, pp. 3541–3552, 2020.

[21] X. Ai and L. Wang, "Distributed fixed-time event-triggered consensus of linear multi-agent systems with input delay," *Int. Journal of Robust and Nonlinear Control*, vol. 31, no. 7, pp. 2526–2545, 2021.

[22] J. Ni, P. Shi, Y. Zhao, Q. Pan, and S. Wang, "Fixed-time event-triggered output consensus tracking of high-order multiagent systems under directed interaction graphs," *IEEE Trans. Cybernetics*, DOI: 10.1109/TCYB.2020.3034013, 2020.

[23] J. Liu, G. Ran, Y. Wu, L. Xue, and C. Sun, "Dynamic event-triggered practical fixed-time consensus for nonlinear multi-agent systems," *IEEE Trans. Circuits and Systems II*: *Express Briefs*, vol. 69, no. 4, pp. 2156–2160, 2022.

[24] J. Liu, Y. Zhang, Y. Yu, H. Liu, and C. Sun, "A Zeno-free self-triggered approach to practical fixed-time consensus tracking with input delay," *IEEE Trans. Systems, Man, and Cybernetics: Systems*, DOI: 10.1109/TSMC.2021.3063117, 2021.