Letter

Consensus Control for Multiple Euler-Lagrange Systems Based on High-Order Disturbance Observer: An Event-Triggered Approach

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Dear editor,

This letter addresses the leader-following consensus problem (LFCP) for multiple Euler-Lagrange (EL) systems with a directed topology. Firstly, a local high-order disturbance observer (HODO) is put forward to estimate the compound disturbance for each EL system itself, and the estimate error can ultimately achieve zero. Based on this HODO, an event-based distributed sliding mode control protocol is proposed to solve the LFCP of multiple EL systems. Furthermore, the reachability of the sliding mode surface is analyzed. Besides, it should be pointed out that the interval between any two triggering instants is a strictly positive value, hence the well-known Zeno behavior is avoided for the developed event-based protocol. Finally, the effectiveness of the proposed HODO and control protocol is further verified by a numerical simulation.

Related work: The collective behavior of multi-agent systems has been widely applied to many engineering fields, such as intelligent robots, traffic control, as well as sensor networks ([1]−[10]), since its advantages of high efficiency and high fault tolerance. Meanwhile, as a kind of typical collective behavior, distributed cooperative control is one of the hottest research topics. Specially, it can be divided into the following several cases: consensus control, formation control and containment control (see [11]−[13]).

In recent years, multi-agent systems with EL dynamics have received ever-increasing research attention (see [4], [5]) due mainly to the superiority of modeling some typical actual industrial systems, such as multi-arm robots, mobile robots and spacecraft. Notably, the control protocols designed in the above papers need the assumption of continuous communication, which may require sufficient computing resources and an ideal communication environment. However, in practical engineering applications, agents have limited communication bandwidth and on-board energy, so that the above requirements cannot be achieved. Therefore, an event-triggered method is introduced to solve this problem. Specially, for multiple EL systems, two event-triggered strategies, i.e., decentralized and distributed, have been developed in [6] with the help of Barbalat's Lemma. Furthermore, the event-based containment control has been studied in [7] over directed networks. Recently, the same issue has also been investigated in [8], where an event-based observer is proposed to estimate the trajectory inside the convex hull spanned by the leaders' states.

It should be pointed out that, the multi-agent system with EL dynamics has more strong uncertainty and nonlinearity. Unfortunately, the methods used in general linear and nonlinear systems cannot be directly extended to this kind of multi-agent system. As an alternative approach, a disturbance observer (DO) can be employed to estimate the uncertainties consisting of both unmodeled dynamics as well as some external disturbances [14]. In order to improve the observation performance, an HODO has been proposed in [15], and subsequently applied to estimate the mismatched disturbance for a class of underactuated robotic system in [16], under which it has been shown that the higher the order of the disturbance observer, the smaller the norm of the observer error.

As far as the authors know, lots of developed results of multi-agent systems with EL dynamics are based on some simplification on system models, such as the case without uncertain parameters, gravity vector or unknown external disturbances. However, all these cases could occur in practical engineering, which results in an urgent requirement of developing a more general control protocol based on event-triggering communication. In addition, the sliding mode control strategy proposed in this letter can effectively recompense the uncertain parameters and external disturbances of the EL system, of which the algorithm is simple and response speed is fast. Thence, it is more convenient for practical engineering applications. Inspired by the above-mentioned problems, this letter is devoted to studying the LFCP for multiple EL systems over a directed topology. The main contributions are as follows.

● A local HODO is designed to estimate the compound disturbance (including uncertain parameters and external disturbance) of EL systems, and the observer gain matrices are selected to make the observer error ultimately approaches zero.

● An event-based distributed sliding mode control strategy is proposed to handle the LFCP of multiple EL systems in order to reduce the updating frequency and save energy. In addition, by designing an appropriate triggering function, it can be proved that there is no infinite number of triggering events within a finite time.

Communication topology: Consider a class of EL systems with N followers and a leader (labeled as agent 0), whose communication topology is described by a directed graph $\tilde{G}$ with the set of vertices $\tilde{V}=\{0,\ 1,\ \ldots,\ N\}$. The leader can sent information to followers but not receive information reversely. Define $B=\text{diag}\{b_1,\ b_2,\ \ldots,\ b_N\}$, where $b_i>0$ if the information of the leader is available to follower i and $b_i=0$, otherwise.

In what follows, the communication among followers is modeled by $G=\{V,\ \varepsilon,\ A\}$, a subgraph of $\tilde{G}$, where $V=\{1,\ 2,\ \ldots,\ N\}$ is the set of vertices and $\varepsilon\subseteq V\times V$ is the set of edges. In such a directed graph, an edge $(j,\ i)\in\varepsilon$ denotes that follower i can receive information from follower j but not vice versa. Furthermore, follower j is regarded as a neighbor of follower i, and the set of all neighbors of follower i is denoted by $N_i=\{j\in V\ :\ (i,\ j)\in\varepsilon\}$. the adjacency matrix is defined as $A=(a_{ij})_{N\times N}$, where $a_{ij}>0$ if $(j,\ i)\in\varepsilon$ and $a_{ij}=0$ otherwise. In this letter, self-loops are excluded, i.e., $a_{ii}=0$ for all $i\in V$. Denote $C=\text{diag}\{c_1,\ c_2,\ \ldots,\ c_N\}$ with $c_i=\sum_{j=1}^{N}a_{ij}$. The Laplacian matrix L of G is defined as $L=C-A$.

The following assumption will be used in the theoretical analysis.

Assumption 1: $\tilde{G}$ contains a directed spanning tree with the leader as a root node, which means there exist at least one directed path from the leader to every follower, and G is directed.

System model: Consider a set of EL systems, whose agent is described by the following dynamic equations:

$$M_i(q_i)\ddot{q}_i+C_i(q_i,\ \dot{q}_i)\dot{q}_i+G_i(q_i)=u_i+\tau_i^*,\quad i\in V \tag{1}$$

where $q_i\in\mathbb{R}^n$ and $\dot{q}_i\in\mathbb{R}^n$ denote the generalized position vector and velocity vector, respectively. $u_i\in\mathbb{R}^n$ is the generalized force

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vector, and $\tau_i^* \in \mathbb{R}^n$ is the unknown external disturbance. Furthermore, $M_i(q_i)$, $C_i(q_i, \dot{q}_i)$ and $G_i(q_i)$, respectively, are the inertia matrix, the Coriolis and centrifugal matrix, and the gravity vector with adequate dimensions.

Considering the parameter uncertainty, the matrix $M_i(q_i)$, $C_i(q_i, \dot{q}_i)$ and $G_i(q_i)$ can be decomposed as

$$M_i(q_i) = \hat{M}_i(q_i) + \Delta M_i(q_i)$$
$$C_i(q_i, \dot{q}_i) = \hat{C}_i(q_i, \dot{q}_i) + \Delta C_i(q_i, \dot{q}_i)$$
$$G_i(q_i) = \hat{G}_i(q_i) + \Delta G_i(q_i)$$

where $\hat{M}_i(q_i)$, $\hat{C}_i(q_i, \dot{q}_i)$ and $\hat{G}_i(q_i)$ are known nominal matrices $\Delta M_i(q_i)$, $\Delta C_i(q_i, \dot{q}_i)$ and $\Delta G_i(q_i)$ represent unmodeled dynamics. Then, the system (1) can be rewritten as

$$\hat{M}_i(q_i)\ddot{q}_i + \hat{C}_i(q_i, \dot{q}_i)\dot{q}_i + \hat{G}_i(q_i) = u_i + \bar{\tau}_i, \quad i \in V \tag{2}$$

where $\bar{\tau}_i = \tau_i^* - (\Delta M_i(q_i)\ddot{q}_i + \Delta C_i(q_i, \dot{q}_i)\dot{q}_i + \Delta G_i(q_i))$.

Normally, we have the following two properties [17] for the dynamics of the EL systems (2).

Property 1: The matrix $\hat{M}_i(q_i)$ is symmetric and uniformly positive definite.

Property 2: There exist some positive constants $\underline{k}_m$, $\bar{k}_m$, k_c and k_g such that $\underline{k}_m I_n \le \hat{M}_i(q_i) \le \bar{k}_m I_n$, $\|\hat{C}_i(q_i, \dot{q}_i)\| \le k_c\|\dot{q}_i\|$ and $\|\hat{G}_i(q_i)\| \le k_g$.

For the purpose of performance analysis, introducing the coordinate transformation $x_{i1} = q_i$ and $x_{i2} = \dot{q}_i$ $\left(i \in \tilde{V}\right)$, the above system (2) can be transformed into

$$\begin{cases} \dot{x}_{i1} = x_{i2} \\ \dot{x}_{i2} = f_i(x_{i1}, x_{i2}) + g_i(x_{i1})u_i + \tau_i, \quad i \in V \end{cases} \tag{3}$$

where

$$f_i(x_{i1}, x_{i2}) = -\hat{M}_i^{-1}(x_{i1})\left(\hat{C}_i(x_{i1}, x_{i2})x_{i2} + \hat{G}_i(x_{i1})\right)$$
$$g_i(x_{i1}) = \hat{M}_i^{-1}(x_{i1})$$
$$\tau_i = \hat{M}_i^{-1}(x_{i1})\bar{\tau}_i.$$

The following assumptions are needed for the EL system.

Assumption 2: The disturbance τ_i and its derivative are both bounded, and τ_i is m times differentiable, and satisfies $\frac{d^m\tau_i}{dt^m} \in L_2$.

Assumption 3: All elements of the matrices $\hat{M}_i(q_i)$, $\hat{C}_i(q_i, \dot{q}_i)$ and $\hat{G}_i(q_i)$ are differentiable and locally Lipschitz.

Assumption 4: For the leader, there exist two positive constants ϕ_{02} and φ_{02} such that $\|x_{02}\| \le \phi_{02}$ and $\|\dot{x}_{02}\| \le \varphi_{02}$.

Problem statement: This letter will focus on investigating the LFCP of multiple EL systems, where the framework of addressed systems is shown in Fig. 1. In particular, the objectives of this letter are as follows:

- A local HODO is proposed to estimate the compound disturbance of EL systems, where the observer error ultimately approaches zero;

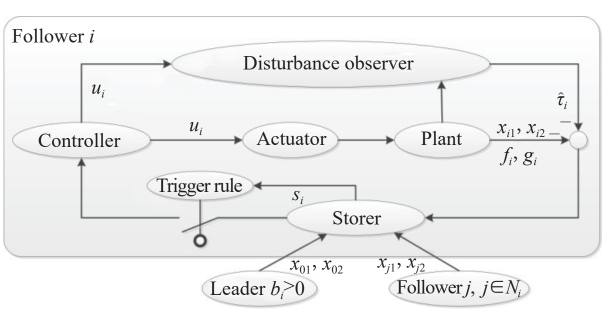

Fig. 1. Schematic of the proposed event-based control strategy.

- An event-based distributed sliding mode control strategy is designed to make the EL systems achieve consensus. i.e., for all $i \in V$, one has

$$\begin{cases} \lim\limits_{t\to\infty}(x_{i1} - x_{01}) = 0 \\ \lim\limits_{t\to\infty}(x_{i2} - x_{02}) = 0. \end{cases} \tag{4}$$

The following lemmas will be used in the theoretical analysis.

Lemma 1 [18]: Based on Assumption 1, the matrix $H = L + B$ is nonsingular. Define

$$T = (t_1\ t_2\ \cdots\ t_N)^T = H^{-1}1_N$$
$$W = \text{diag}\{w_1, w_2, \ldots, w_N\} = \text{diag}\left\{\frac{1}{t_1}, \frac{1}{t_2}, \ldots, \frac{1}{t_N}\right\}.$$

Then, W is positive definite and $R = WH + H^T W$ is also positive definite.

Lemma 2 [19]: Let x be a differentiable function, if x, $\dot{x} \in L_\infty$ and $x \in L_p$ for some value of $p \in [1, \infty)$, then $\lim_{t\to\infty} x = 0$.

HODO for EL system: In this subsection, we propose the following mth order disturbance observer to estimate the compound disturbance of the ith follower:

$$\begin{cases} \hat{\tau}_i^{(j-1)} = z_{ij} + K_{ij}x_{i2} \\ \dot{z}_{ij} = -K_{ij}(f_i + g_iu_i + \hat{\tau}_i) + \hat{\tau}_i^{(j)}, \quad j = 1, \ldots, m-1 \\ \hat{\tau}_i^{(m-1)} = z_{im} + K_{im}x_{i2} \\ \dot{z}_{im} = -K_{im}(f_i + g_iu_i + \hat{\tau}_i) \end{cases} \tag{5}$$

where $K_{ij} \in \mathbb{R}^{n\times n}$ $(j = 1, \ldots, m)$ are the observer gain matrices to be designed, and $\hat{\tau}_i^{(j-1)}$ are the estimates of $\frac{d^{(j-1)}\tau_i}{dt^{(j-1)}}$ $(j = 1, \ldots, m)$.

Define the observer errors $\tilde{\tau}_i^{(j-1)} = \frac{d^{(j-1)}\tau_i}{dt^{(j-1)}} - \hat{\tau}_i^{(j-1)}$. Then, they can be represented as a vector form

$$\dot{e}_i = A_ie_i + B_i\omega_i \tag{6}$$

where $e_i = \left(\tilde{\tau}_i^T\ \tilde{\dot{\tau}}_i^T\ \cdots\ \tilde{\tau}_i^{(m-1)T}\right)^T$, $\omega_i = \dfrac{d^m\tau_i}{dt^m}$

$$A_i = \begin{pmatrix} -K_{i1} & I_n & 0 & \cdots & 0 \\ -K_{i2} & 0 & I_n & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -K_{i(m-1)} & 0 & 0 & \cdots & I_n \\ -K_{im} & 0 & 0 & \cdots & 0 \end{pmatrix}, \quad B_i = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ I_n \end{pmatrix}.$$

Next, we draw the following conclusion.

Theorem 1: Consider the proposed mth order disturbance observer (5) for the ith follower. Under Assumption 2, if the observer gain matrices K_{ij} are selected such that A_i is Hurwitz, and the inequality $\underline{\lambda}_{Q_i} - \bar{\lambda}_{P_i}^2 > 0$ holds, where the matrices P_i and Q_i are the solution of matrix equation $P_iA_i + A_i^TP_i = -Q_i$. Then, the observer error ultimately approaches zero.

Distributed sliding mode controller based on event-triggering mechanism: Before moving on, denote the local differences as

$$\begin{cases} x_{i1r} = \sum\limits_{j=1}^{N} a_{ij}\left(x_{i1} - x_{j1}\right) + b_i(x_{i1} - x_{01}) \\ x_{i2r} = \sum\limits_{j=1}^{N} a_{ij}\left(x_{i2} - x_{j2}\right) + b_i(x_{i2} - x_{02}) \end{cases} \tag{7}$$

then, construct the following sliding surface

$$s_i = x_{i2r} + \kappa x_{i1r} \tag{8}$$

where κ is a positive constant.

On the other hand, in order to reduce the communication burden, an event-triggering scheme is exploited to the data exchange. To proceed further, denote t_k^i with $t_0^i = 0$ $(k = 0, 1, \ldots)$ as the triggering instant at which the controller updates. Then, introducing the errors:

$$\begin{cases} e_{i1}(t) = g_i^{-1}(t_k^i)x_{i2}(t_k^i) - g_i^{-1}(t)x_{i2}(t) \\ e_{i2}(t) = g_i^{-1}(t_k^i)s_i(t_k^i) - g_i^{-1}(t)s_i(t) \\ e_{i3}(t) = g_i^{-1}(t_k^i)\mathrm{sign}(s_i(t_k^i)) - g_i^{-1}(t)\mathrm{sign}(s_i(t)) \\ e_{i4}(t) = g_i^{-1}(t_k^i)f_i(t_k^i) - g_i^{-1}(t)f_i(t) \\ e_{i5}(t) = g_i^{-1}(t_k^i)\hat{\tau}_i(t_k^i) - g_i^{-1}(t)\hat{\tau}_i(t) \end{cases} \quad (9)$$

the event-triggered function is presented by

$$h_i(t) = \frac{\|WH\|}{\underline{k}_m}(\kappa\|e_{i1}(t)\| + k_1\|e_{i2}(t)\| + k_2\|e_{i3}(t)\| + \|e_{i4}(t)\| + \|e_{i5}(t)\|) - \frac{\sigma_i}{2}\|s_i(t)\| - a_i e^{-c_i t} \quad (10)$$

where $0 < \sigma_i < 1$, $a_i > 0$ and $0 < c_i < 1$ are three predetermined positive parameters, the matrix W is defined in Lemma 1 and $\underline{k}_m$ satisfies Property 2. In fact, the event is triggered only when $h_i(t) \ge 0$, hence the condition $h_i(t) < 0$ always holds as long as $t \in [t_k^i, t_{k+1}^i)$.

In light of the constructed sliding surface (8) as well as the event-triggered condition (10), a distributed controller is adopted

$$u_i(t) = g_i^{-1}\left(t_k^i\right)\left(-\kappa x_{i2}\left(t_k^i\right) - k_1 s_i\left(t_k^i\right) - k_2\mathrm{sign}\left(s_i\left(t_k^i\right)\right) - f_i\left(t_k^i\right) - \hat{\tau}_i\left(t_k^i\right)\right),\ t \in \left[t_k^i,\ t_{k+1}^i\right) \quad (11)$$

where k_1 and k_2 are two positive scalars to be designed.

Based on the above analysis, we draw the main result of this letter as follows.

Theorem 2: Consider the multiple EL systems (3) with the HODO (5). Under Assumptions 1, 2 and 4, and the predetermined scalars $\kappa > 0$, $0 < \sigma_i < 1$, $a_i > 0$ and $0 < c_i < 1$, such a system with the sliding surface (8) and the event-triggered scheme (10) achieves consensus if the parameters in the distributed controller (11) are selected as

$$k_1 > \frac{2\sigma + \|WH\|^2}{\lambda_R},\quad k_2 > \varphi_{02} + \kappa\phi_{02}$$

where the matrices W and R are defined in Lemma 1, and $\sigma = \max\{\sigma_1, \sigma_2, \ldots, \sigma_N\}$.

It is worthwhile to note that the desirable control effect is difficult to achieve in the actual engineering system when the Zeno behavior, particular concern, occurs for the designed event-triggered scheme. To this end, we propose the following theorem.

Theorem 3: Under Assumption 3, consider the multiple EL systems (3) with the HODO (5) and the sliding mode controller (11). Each agent with the event-triggered scheme (10) excludes the famous Zeno behavior in any finite operation time interval.

Simulation: Consider a group of two-link robot arms with one leader and four followers, whose communication topology with the given weights is shown in Fig. 2. In what follows, we select the position vector of the leader as $q_0 = (\sin(t), \cos(t))^T$. Similar to [15], the system dynamic of follower i are modeled by (1). Furthermore, the addressed arms are subject to the following four different external disturbances:

$$\tau_{11}^* = 0.1\sin(0.3t) + 0.04\cos(0.6t)$$
$$\tau_{12}^* = 0.2\sin(0.5t) + 0.2\sin(0.3t + 0.5)$$
$$\tau_{21}^* = 0.2\cos(0.5t)\,\tau_{22}^* = 0.05\cos(0.53t) + 0.1\cos(0.1t)$$
$$\tau_{31}^* = 0.75\sin(0.5t + 0.12)\,\tau_{32}^* = 0.1\cos(0.1t)$$
$$\tau_{41}^* = 0.3\cos(0.1t) + 0.4\sin(0.45t + 0.7)$$
$$\tau_{42}^* = 0.2\sin(0.5t) + 0.4\cos(0.5t).$$

It should be noticed that, the actual physical parameters of four robot arms are not accurately known for the design of both the HODO and the controller, hence the nominal parameters have to be employed (see [16]). The parameters of the HODO, controller and event-triggered function are selected as $\kappa = 0.1$, $k_1 = 0.9$, $k_2 = 1.2$, $\sigma_i = 0.3$, $c_i = 0.5$, $a_i = 1$, $K_{i1} = 20I_2$, $K_{i2} = 100I_2$ and $K_{i3} = 50I_2$. In addition, the initial positions and velocities of the four followers are set to be $q_i(0) = (-1.1,\ 1.1)^T$ and $\dot{q}_i(0) = (-0.8, 0.8)^T$, respectively.

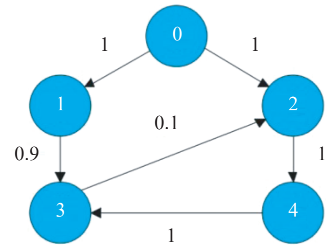

Fig. 2. Communication topology of one leader and four followers.

Without loss of generality, only τ_{11} is analyzed here. Then, the simulation results are shown in Figs. 3−5. Specifically, Fig. 3 plots the estimate errors under first-orders, second-order and third-order disturbance observer, respectively, as well as the trajectory of disturbance τ_{11} and disturbance observer $\hat{\tau}_{11}$. It is not difficult to see from Fig. 3 that the designed disturbance observer can effectively observe the compound disturbance, and the higher the order of the disturbance observer, the better the observation effect. Fig. 4 plots the position tracking errors and velocity tracking errors, and it can be observed from Fig. 4 that both the position and the velocity tracking errors can converge to zero, and due to the existence of sliding mode control, oscillation will occur near the zero point of the error trajectories. Fig. 5 shows the triggering times of each agent during the time interval $[0,\ 100\ \mathrm{s}]$. Note from Fig. 5 that there exist a finite number of triggering instants within 0 to 100 s, and the controller input will be updated in any triggering instants, thus excluding undesirable Zeno behavior. In addition, since continuous-time sampling is avoided, the update frequency can be reduced and energy can be saved. Consequently, the LFCP can be solved by applying the event-based distributed sliding mode controller (11) together with the proposed disturbance observer (5).

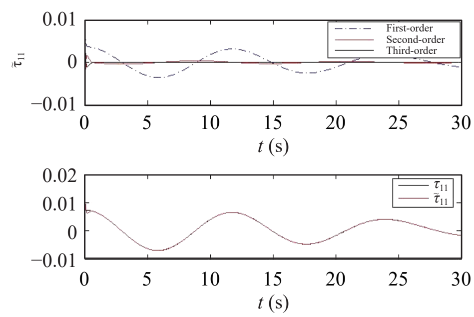

Fig. 3. Estimate error and trajectory of disturbance observer.

Conclusions: The LFCP for multiple EL systems has been addressed in this letter. Firstly, a local HODO is designed to observe the compound disturbance of each EL system. Based on the HODO, an event-based distributed sliding mode controller is proposed to solve the LFCP for multiple EL systems. Furthermore, we prove that each EL system with the event-triggered scheme excludes the famous Zeno behavior in any finite operation time interval. Finally, the simulation results of two-link robot arms system show the effectiveness of the proposed observer and controller. Our future work will focus on the finite-time and fixed-time consensus of multiple EL systems.

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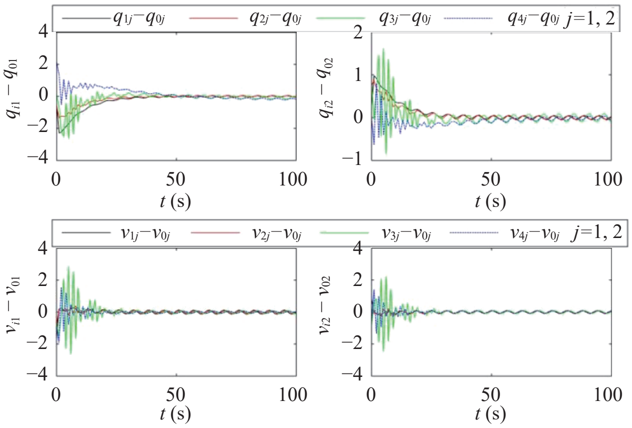

Fig. 4. Position tracking errors and velocity tracking errors.

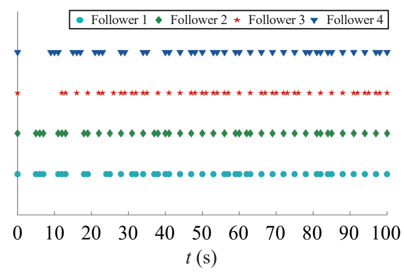

Fig. 5. Triggering times during the time interval [0, 100 s].

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