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Leader-following Consensus of Heterogeneous Multi-agent Systems with Packet Dropout

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Abstract: This paper studies the leader-following consensus problem for heterogeneous multi-agent systems composed of linear second-order integrator agents and nonlinear Euler-Lagrange agents in two aspects. The consensus problem of heterogeneous multi-agent systems is discussed with unknown velocities, time-varying disturbances and packet dropout by introducing extended state observer. Sufficient conditions are established to ensure that all following agents could reach consensus with a virtual leader, which provide the allowable upper bound of packet drop rate. Numerical simulations are presented to illustrate the theoretical results.

Keywords: Extended state observer (ESO), heterogeneous multi-agent systems, leader-following consensus, packet dropout.

1. INTRODUCTION

Research on multi-agent consensus has attracted much attentions in the past two decades due to it's broad applications [1-3]. A key problem for the consensus of multi-agent systems is to design a networked control protocol such that all the agents could be able to reach an agreement using the shared data only through local communications. Up to now, the consensus protocols have been obtained for both linear and nonlinear multi-agent systems.

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The consensus problem of first-, second- and high-order linear multi-agent systems is primarily studied, please refer to [4-7] and the references therein. For those linear dynamics, the consensus control under various network environments has been studied in many papers [8-11]. Based on the researches of linear multi-agent systems, there are many literatures focus on the nonlinear agent dynamics [12-14]. It is noted that all the above works deal with homogeneous multi-agent systems, i.e., it is assumed that each subsystem has the same dynamics. Actually, the dynamics of the agents coupled with each other may be different when different kinds of agents share common goals in some practical applications [15]. For example, in the multi-robot systems, due to common goal and dynamic environments, some robots should be modeled by linear second-order integrator equation and others should be modeled by Euler-Lagrange (EL) equation, then new coordination protocols need to be developed [16].

Up to now, the consensus problem of heterogeneous multi-agent system has gained tremendously progress in the literatures [16,17]. However, there are few papers take time-varying disturbances, unknown velocities and packet dropout into consideration for the consensus of heterogeneous multi-agent systems. It is known that the multi-agent systems in the network require intercommunication for sharing knowledge by which to make control decisions. But during the information exchange, packet dropout which may degrade the control performance and even destabilize the entire system inevitably exists [18]. Furthermore, the velocities of agent are not usually measured and the agent is always subject to external disturbances. Both the two issues make it difficult to achieve ideal consensus performance for heterogeneous multi-agent systems. All of these motivated us for the study in this paper.

ESO is a particular observer firstly proposed by Han in [19]. Unlike traditional linear or nonlinear observers, the

ESO estimates the effect of uncertainties, unmodeled dynamics and external disturbances acting on the system as an extended state of the original system, and thus we are able to cancel total disturbances in the controller design [20]. Therefore, we will apply ESO to deal with the unknown velocities and time-varying disturbances. Motivated by the above discussions, the consensus problems for heterogeneous multi-agent systems composed of second-order agents and nonlinear EL agents are considered in this paper. The main contributions of this paper are threefold. First, the consensus case with packet dropout for heterogeneous multi-agent systems composed of second-order agents and nonlinear EL agents is firstly studied in this paper. Second, a particular observer ESO is designed to deal with the problem of consensus control for heterogeneous multi-agent systems with unknown velocities and time-varying disturbances. Finally, in the proof of controller design with packet dropout, the weak infinitesimal operator $\mathscr{L}$ method is introduced to deal with the consensus case with packet dropout.

Notation: In the following, if not explicitly stated, matrices are assumed to have compatible dimensions. The shorthand $\text{diag}\{M_1, M_2, \cdots, M_N\}$ denotes a diagonal matrix with diagonal blocks $M_1, M_2, \ldots, M_N$. $\|\cdot\|$ is the Euclidean norm of a vector. $R := (-\infty, \infty)$, $\mathbb{R}_{>0} := (0, \infty)$, $\mathbb{R}_{\geq 0} := [0, \infty)$. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space. For any function $f : \mathbb{R}_{\geq 0} \to \mathbb{R}^n$, the L_∞-norm is defined as $\| f \| = sup_{t \geq 0} | f |$, and the L_2-norm as $\| f \|_2^2 = \int_0^\infty | f |^2 \, dt$. The L_∞ and L_2 spaces are defined as the sets $\{f : \mathbb{R}_{\geq 0} \to \mathbb{R}^n : \| f \|_\infty < \infty\}$ and $\{f : \mathbb{R}_{\geq 0} \to \mathbb{R}^n : \| f \|_2 < \infty\}$, respectively. $\sigma(\cdot)$ is the set of singular values of a matrix, with the maximum singular value $\bar{\sigma}(\cdot)$ and the minimum singular value $\underline{\sigma}(\cdot)$. $\otimes$ is the standard Kronecker product. I_N is the identity matrix with dimension N. The symmetric terms in a symmetric matrix are denoted by *. The notation $x \to y$ means that there exists a constant ε such that $\| x - y \| \leq \varepsilon$ with $\varepsilon \geq 0$.

2. BACKGROUND AND PROBLEM FORMULATION

2.1. Heterogeneous multi-agent systems

Consider a heterogeneous system composed of m second-order agents and $n - m$ EL agents. Suppose that in addition to the n agents, called followers hereafter, there exists a virtual leader, labeled as agent d, with a time-varying position x_d and velocity v_d. We assume that $x_d \in L_\infty$ and $v_d \in L_\infty$. Then, the ith second-order agent is given by

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = \tau_i(t), \quad i \in \mathscr{I}_m, \end{cases} \tag{1}$$

where $\mathscr{I}_m \triangleq \{1, \ldots, m\}$. $x_i(t) \in \mathbb{R}^p$, $v_i(t) \in \mathbb{R}^p$ and $\tau_i(t) \in \mathbb{R}^p$ are the position, velocity and control input, respectively. Furthermore, the dynamics of the ith EL agent is given by

$$\begin{cases} \dot{x}_i(t) = v_i(t), \qquad i \in \mathscr{I}_m / \mathscr{I}_n \\ M_i(x_i)\dot{v}_i + C_i(x_i, v_i)v_i = \tau_i(t) + \tau_{ext,i}(t), \end{cases} \tag{2}$$

where $\mathscr{I}_n \triangleq \{1, \ldots, n\}$, $x_i(t) \in \mathbb{R}^p$, $v_i(t) \in \mathbb{R}^p$, $\tau_i(t) \in \mathbb{R}^p$ and $\tau_{ext,i}(t) \in \mathbb{R}^p$ are the position, velocity, control input and external disturbance, respectively. $M_i(x_i) \in \mathbb{R}^{p \times p}$ is the general inertia matrix and $C_i(x_i, v_i) \in \mathbb{R}^{p \times p}$ is the matrix of Coriolis and centrifugal forces.

2.2. Graph theory

In this paper, we use a graph to describe the information exchanging between followers and the leader. The interaction topology of information exchanged between n followers is usually modeled by a graph $\mathscr{G} = (\mathscr{V}, \mathscr{E})$, where $\mathscr{V} = \{v_1, \cdots, v_N\}$ is a finite nonempty set of nodes and $\mathscr{E} = \mathscr{V} \times \mathscr{V}$ is a set of edges of the graph. $(v_i, v_j) \in \mathscr{E}$ means that node i and node j can exchange information between them. Denote the adjacency or connectivity matrix as $A = [a_{ij}]$ with $a_{ij} > 0$ if $(v_j, v_j) \in E$ and $a_{ij} = 0$ otherwise. Note that $a_{ii} = 0$. The set of neighbors of a node v_i is $N_i = \{v_j : (v_j, v_i) \in E\}$, i.e., the set of nodes with arcs incoming to v_i. Define the in-degree matrix as a diagonal matrix $D = \text{diag}\{d_1 d_2 \cdots d_N\}$ with $d_i = \sum_{j \in N_i} a_{ij}$, which is the weighted in-degree of node i. The graph Laplacian matrix is $L = D - A$, which has all row sums equal to zero. A digraph has a spanning tree, if there is a node (called the root), such that there is a directed path from the root to every other node in the graph. When $\mathscr{G}$ contains a spanning tree, the Laplacian matrix has a single zero eigenvalue and the corresponding eigenvector is the vector of ones $\underline{1}$. Moreover, all the other non-zero eigenvalues are in the open right half plane [21]. Furthermore, define the pinning matrix of graph $\mathscr{G}$ as $B = \text{diag}\{b_1 b_2 \cdots b_N\}$ with $b_i \geq 0$, $b_i > 0$ if and only if there exists an edge from the leader to the ith following node and $b_i > 0$ for at least one i. The leader is represented by vertex d and information is exchanged between the leader and the followers which are in the neighbors of leader. Then, we have a graph $\overline{\mathscr{G}}$, which consists of graph $\mathscr{G}$, vertex d and edges between the leader and its neighbors. In this paper, we make the assumption regarding $\mathscr{G}$ as follows:

Assumption 1: The communication graph $\mathscr{G}$ is fixed, directed and contains a spanning tree.

3. MAIN RESULTS

The consensus control problem confronted in this paper is to design control protocols for all the agents in $\mathscr{G}$ such that the states of all agents are consensus to the leader, i.e., one requires

$$\lim_{t \to \infty} x_i \to x_d \text{ and } \lim_{t \to \infty} v_i \to v_d, \quad \forall i \in 1, \cdots, n. \tag{3}$$

3.1. Consensus with unknown velocities and time-varying disturbances

In this section, we considered the consensus problem for heterogeneous multi-agent systems with unknown velocities and time-varying disturbances. Define the local neighborhood consensus error for the ith agent as

$$e_{i1} = \sum_{j\in N_i} a_{ij}(x_j - x_i) + b_i(x_d - x_i),$$
$$e_{i2} = \sum_{j\in N_i} a_{ij}(v_j - v_i) + b_i(v_d - v_i),$$

where a_{ij} is the element of connectivity matrix A, and $b_i > 0$ is the pinning gains. It satisfies that $b_i > 0$ for at least one i. Then, the global error vector for network $\mathscr{G}$ is

$$\begin{aligned} e_1 &= -((L+B)\otimes I_p)(x - 1_n \otimes x_d), \\ e_2 &= -((L+B)\otimes I_p)(v - 1_n \otimes v_d), \end{aligned} \tag{4}$$

where $e_1 = [e_{11}^T e_{21}^T \cdots e_{n1}^T]^T$, $e_2 = [e_{12}^T e_{22}^T \cdots e_{n2}^T]^T$, L is the graph Laplacian matrix of networked system, $B = \text{diag}\{b_1, b_2, \dots, b_n\}$ and it presents the communication relationship between leader and followers. Under Assumption 1, it is known that all the eigenvalues of matrix $-(L+B)$ have negative real part according to the above discussions in graph theory, i.e., matrix $-(L+B)$ is stable. For the time-varying disturbances of EL agents, the following assumption is presented:

Assumption 2: There exists a function $f(t)$ which is infinite approximate the actual external disturbance torque $\tau_{ext,i}$. Furthermore, the differential of $f(t)$ is assumed to be bounded.

To achieve consensus expressed as (3), ESO is introduced to estimate the unknown disturbances and unknown velocity information of agents. Let $x_{i1} = x_i$, $x_{i2} = v_i$. Then, design the observer for ith second-order agent as

$$\begin{cases} r_{i1} = \hat{x}_{i1} - x_{i1}, \\ \dot{\hat{x}}_{i1} = \hat{x}_{i2} - \beta_{i1} r_{i1}, \\ \dot{\hat{x}}_{i2} = -\beta_{i2} r_{i1} + \tau_i. \end{cases}$$

where $\hat{x}_{i1}$ and $\hat{x}_{i2}$ are estimations of states x_{i1} and x_{i2}, respectively, parameters β_{i1} and β_{i2} are the regulable gain constants. For the EL agents, let $x_{i1} = x_i$, $x_{i2} = v_i$ and the extended state variable $x_{i3} = M_i^{-1}(x_i)[-C_i(x_i, v_i)v_i + \tau_{ext,i}]$. Under Assumption 2, assuming $\dot{x}_{i3} = h_i$, the system (2) is rewritten as

$$\begin{cases} \dot{x}_{i1} = x_{i2}, \\ \dot{x}_{i2} = x_{i3} + M_i^{-1}(x_{i1})\tau_i, \\ \dot{x}_{i3} = h_i. \end{cases} \tag{5}$$

Note that h_i is bounded according to Properties 1 and 4 in [22] under Assumption 2, i.e., there exists a constant α_i such that $\| h_i \| \le \alpha_i$. From (5), the ESO designed for ith EL system (2) is given as

$$\begin{cases} r_{i1} = \hat{x}_{i1} - x_{i1}, \\ \dot{\hat{x}}_{i1} = \hat{x}_{i2} - \beta_{i1} r_{i1}, \\ \dot{\hat{x}}_{i2} = \hat{x}_{i3} - \beta_{i2} r_{i1} + M_i^{-1}(x_{i1})\tau_i, \\ \dot{\hat{x}}_{i3} = -\beta_{i3} r_{i1}, \end{cases} \tag{6}$$

where $\hat{x}_{i1}$, $\hat{x}_{i2}$ and $\hat{x}_{i3}$ are estimations of states x_{i1}, x_{i2} and x_{i3}, respectively, parameters β_{i1}, β_{i2} and β_{i3} are the regulable gain constants. Through regulating β_{i1}, β_{i2} and β_{i3} appropriately, $\hat{x}_{i1}$, $\hat{x}_{i2}$ and $\hat{x}_{i3}$ can be considered as the approximations of the corresponding states x_{i1}, x_{i2} and x_{i3}, respectively. Letting $r_{i2} = \hat{x}_{i2} - x_{i2}$, $r_{i3} = \hat{x}_{i3} - x_{i3}$, and differentiating r_{i1}, r_{i2} and r_{i3} with respect to time, the following dynamical equation is obtained according to (5) and (6),

$$\begin{cases} \dot{r}_{i1} = r_{i2} - \beta_{i1} r_{i1}, \\ \dot{r}_{i2} = r_{i3} - \beta_{i2} r_{i1}, \\ \dot{r}_{i3} = -\beta_{i3} r_{i1} - h_i. \end{cases}$$

With the estimate information, define the synchronization signal of the ith agent as

$$\eta_i = \frac{1}{\rho_i}\left(\hat{e}_{i2} + \Xi_i e_{i1}\right), \tag{7}$$

where $\rho_i = \sum_{j\in N_i} a_{ij} + b_i$, Ξ_i is a positive p-dimensional diagonal matrix and

$$\hat{e}_{i2} = \sum_{j\in N_i} a_{ij}(\hat{x}_{j2} - \hat{x}_{i2}) + b_i(v_d - \hat{x}_{i2}).$$

Based on the above discussions, the control protocols for heterogeneous multi-agent systems composed of (1) and (2) are designed as follows:

$$\begin{aligned} \tau_i(t) &= \frac{1}{\rho_i}\left(\Xi_i \hat{e}_{i2} + \sum_{j\in N_i} a_{ij}\dot{\hat{v}}_j + b_i \dot{v}_d \right) + \tilde{K}_i \eta_i, \quad i \in \mathscr{I}_m, \\ \tau_i(t) &= M_i(x_i)\left[\frac{1}{\rho_i}\left(\Xi_i \hat{e}_{i2} + \sum_{j\in N_i} a_{ij}\dot{\hat{v}}_j + b_i \dot{v}_d \right) \right] \\ &\quad + M_i(x_i)[-\hat{x}_{i3} + \tilde{K}_i \eta_i], \quad i \in \mathscr{I}_m / \mathscr{I}_n, \end{aligned} \tag{8}$$

where $\tilde{K}_i$ is a positive p-dimensional matrix and $\hat{v}_j = \hat{x}_{j2}$. Note that the derivative of $\hat{v}_j$ can be calculated by numerical differentiation. Then, it is obtained that

$$\begin{aligned} \dot{\eta}_i &= \frac{1}{\rho_i}\Xi_i\left[-\sum_{j\in N_i} a_{ij}(r_{j2} - r_{i2}) + b_i r_{i2} \right] \\ &\quad + \beta_{i2} r_{i1} - K_i \eta_i \quad i \in \mathscr{I}_n. \end{aligned} \tag{9}$$

For (9), we construct the following Lyapunov candidate function as

$$V = y^T N y, \tag{10}$$

where $y = [\eta^T\ r_1^T\ r_2^T\ r_{1m}^T\ r_{2m}^T\ r_{3m}^T]^T$ and

$$N=\begin{bmatrix} \frac{1}{2}P & 0 & 0 & 0 & 0 & 0 \\ * & \frac{1}{2}C & -\frac{1}{2}F & 0 & 0 & 0 \\ * & * & \frac{1}{2}G & 0 & 0 & 0 \\ * & * & * & \frac{1}{2}H_m & -\frac{1}{2}J_m & \frac{1}{2}Q_m \\ * & * & * & * & \frac{1}{2}R_m & -\frac{1}{2}S_m \\ * & * & * & * & * & \frac{1}{2}W_m \end{bmatrix}$$

with $r_1=[r_{11}^T r_{21}^T \cdots r_{n1}^T]^T$, $r_2=[r_{12}^T r_{22}^T \cdots r_{n2}^T]^T$ and

$$\begin{aligned} & r_{1m}=[r_{(m+1)1}^T \cdots r_{n1}^T]^T, \quad r_{2m}=[r_{(m+1)2}^T \cdots r_{n2}^T]^T, \\ & P=\mathrm{diag}\{P_1,P_2,\cdots,P_n\}, \quad G=\mathrm{diag}\{G_1,G_2,\cdots,G_n\}, \\ & C=\mathrm{diag}\{C_1,C_2,\cdots,C_n\}, \quad F=\mathrm{diag}\{F_1,F_2,\cdots,F_n\}, \\ & J_m=\mathrm{diag}\{J_{m+1},J_{m+2},\cdots,J_n\}, \quad \eta=[\eta_1^T \eta_2^T \cdots \eta_n^T]^T, \\ & S_m=\mathrm{diag}\{S_{m+1},\cdots,S_n\}, \quad H_m=\mathrm{diag}\{H_{m+1},\cdots,H_n\}, \\ & Q_m=\mathrm{diag}\{Q_{m+1},\cdots,Q_n\}, \quad R_m=\mathrm{diag}\{R_{m+1},\cdots,R_n\}, \\ & W_m=\mathrm{diag}\{W_{m+1},W_{m+2},\cdots,W_n\}, \end{aligned}$$

in which P_i, C_i, F_i, G_i, H_i, J_i, Q_i, R_i, S_i and W_i for $i=1,\cdots,n$ are positive p-dimensional matrices. Therefore, V is positive definite when $N>0$ is satisfied. Taking the derivative of V with respect to t, we have

$$\begin{aligned} \dot{V} = & \sum_{i=1}^n \eta_i^T P_i \left[\frac{1}{\rho_i}\Xi_i \left[-\sum_{j\in N_i} a_{ij}(r_{j2}-r_{i2})+b_i r_{i2} \right]\right] \\ & +\sum_{i=1}^n \eta_i^T P_i[\beta_{i2}r_{i1}-\tilde{K}_i\eta_i]-\sum_{i=1}^n r_{i1}^T(C_i\beta_{i1}-F_i\beta_{i2})r_{i1} \\ & -\sum_{i=1}^n r_{i2}^T F_i r_{i2}+\sum_{i=1}^n r_{i1}^T(C_i-G_i\beta_{i2}+F_i\beta_{i1})r_{i2} \\ & -\sum_{i=m+1}^n r_{i1}^T(H_i\beta_{i1}+Q_i\beta_{i3}-J_i\beta_{i2})r_{i1}-\sum_{i=m+1}^n r_{i2}^T J_i r_{i2} \\ & +\sum_{i=m+1}^n r_{i1}^T(H_i+J_i\beta_{i1}+S_i\beta_{i3}-R_i\beta_{i2})r_{i2} \\ & -\sum_{i=m+1}^n r_{i3}^T S_i r_{i3}-\sum_{i=m+1}^n r_{i2}^T S_i h_i-\sum_{i=m+1}^n r_{i3}^T W_i h_i \\ & +\sum_{i=m+1}^n r_{i1}^T(-F_i-J_i-Q_i\beta_{i1}+S_i\beta_{i2}-W_i\beta_{i3})r_{i3} \\ & +\sum_{i=m+1}^n r_{i2}^T(G_i+Q_i+R_i)r_{i3}-\sum_{i=m+1}^n r_{i1}^T Q_i h_i. \end{aligned}$$

It follows that

$$\dot{V}=-y^T My-y^T l_m, \tag{11}$$

where

$$l_m=\begin{bmatrix}0 & 0 & 0 & (Q_m h_m)^T & (S_m h_m)^T & (W_m h_m)^T\end{bmatrix}^T,$$

$$M=\begin{bmatrix} P\tilde{K} & -\frac{1}{2}P\beta_2 & (1,3) & 0 & 0 & 0 \\ * & (2,2) & (2,3) & 0 & 0 & 0 \\ * & * & F & 0 & 0 & 0 \\ * & * & * & (4,4) & (4,5) & (4,6) \\ * & * & * & * & J_m & (5,6) \\ * & * & * & * & * & S_m \end{bmatrix}$$

with $h_m=[h_{m+1}^T h_{m+2}^T \cdots h_n^T]^T$ and

$$\begin{aligned} & (1,3)=-\frac{1}{2}P(D+B)^{-1}\Xi(L+B), \\ & (2,2)=C\beta_1-F\beta_2, \quad (2,3)=-\frac{1}{2}(C-G\beta_2+F\beta_1), \\ & (4,4)=H_m\beta_{1m}+Q_m\beta_{3m}-J_m\beta_{2m}, \\ & (4,5)=-\frac{1}{2}(H_m+J_m\beta_{1m}+S_m\beta_{3m}-R_m\beta_{2m}), \\ & (4,6)=-\frac{1}{2}(-F_m-J_m-Q_m\beta_{1m}+S_m\beta_{2m}-W_m\beta_{3m}), \\ & (5,6)=-\frac{1}{2}(G_m+Q_m+R_m), \\ & \tilde{K}=\mathrm{diag}\{\tilde{K}_1,\tilde{K}_2,\cdots,\tilde{K}_n\}, \quad \Xi=\mathrm{diag}\{\Xi_1,\Xi_2,\cdots,\Xi_n\}, \\ & \beta_1=\mathrm{diag}\{\beta_{11},\cdots,\beta_{n1}\}, \quad \beta_2=\mathrm{diag}\{\beta_{12},\cdots,\beta_{n2}\} \end{aligned}$$

with $F_m=\mathrm{diag}\{F_{m+1},\cdots,F_n\}$ and

$$\begin{aligned} & \beta_{1m}=\mathrm{diag}\{\beta_{(m+1)1},\beta_{(m+2)1},\cdots,\beta_{n1}\}, \\ & \beta_{2m}=\mathrm{diag}\{\beta_{(m+1)2},\beta_{(m+2)2},\cdots,\beta_{n2}\}, \\ & \beta_{3m}=\mathrm{diag}\{\beta_{(m+1)3},\beta_{(m+2)3},\cdots,\beta_{n3}\}. \end{aligned}$$

Theorem 1: Considering the heterogeneous multi-agent systems composed of second-order system (1) and EL system (2) under Assumptions 1 and 2, by choosing τ_i as (8), if there exist appropriate ESO parameters β_{i1}, β_{i2}, β_{i3} and positive matrices P_i, C_i, F_i, G_i, H_i, J_i, Q_i, R_i, S_i and $W_i, \forall i \in 1,\cdots,n$ such that the LMIs $N>0$ and $M>0$ given by (10) and (11), respectively, are satisfied, then the consensus in the sense of (3) is achieved.

Proof: According to (11), we have $\dot{V}\le 0$ if M is positive definite and $\|y\|>\|l_m\|_{max}\,\underline{\sigma}(M)=B_d$. Furthermore, from (10), it is obtained that

$$\frac{1}{2}\|y\|^2\,\underline{\sigma}(N)\le V\le\frac{1}{2}\|y\|^2\,\bar{\sigma}(N).$$

Following [23], one can draw the conclusion that for any initial value $y(t_0)$, there exists a time T_0 such that

$$\|y(t)\|\le\sqrt{\bar{\sigma}(N)/\underline{\sigma}(N)}Bd, \quad \forall t\ge t_0+T_0. \tag{12}$$

By definition of $y(t)$, (12) implies that $\eta(t)$ and $r_2(t)$ are uniformly ultimately bounded (UUB). According to

(4) and (7), as $-(L+B)$ is stable, we have $\lim_{t\to\infty} v_i(t) \to v_d(t)$ and $\lim_{t\to\infty} x_i(t) \to x_d(t)$, i.e., the consensus in the sense of (3) is reached.

3.2. Consensus with unknown velocities, time-varying disturbances and packet dropout

During information transmission among agents, the data packet dropout is inevitably exists and it might be potential sources to the instability and poor performance of multi-agent systems. Therefore, the consensus problem for heterogeneous multi-agent systems with unknown velocities, time-varying disturbances and packet dropout is considered in this section. Specifically, the consensus protocols for heterogeneous multi-agent systems (1)-(2) under the influences of packet dropout are rewritten as follows:

$$\begin{aligned} \tau_i(t) &= \Delta_i \hat{e}_{i2\gamma} + \Pi_i e_{i1\gamma}, & i \in \mathscr{I}_m, \\ \tau_i(t) &= M_i(x_i)[-\hat{x}_{i3} + \Delta_i \hat{e}_{i2\gamma} + \Pi_i e_{i1\gamma}], & i \in \mathscr{I}_m / \mathscr{I}_n, \end{aligned} \tag{13}$$

where Δ_i and Π_i are positive p-dimensional matrices, and

$$e_{i1\gamma} = \sum_{j=1}^{n} \gamma_{ij}(t) a_{ij}(x_j - x_i) + \gamma_{id}(t) b_i (x_d - x_i),$$

$$\hat{e}_{i2\gamma} = \sum_{j=1}^{n} \gamma_{ij}(t) a_{ij}(\hat{v}_j - \hat{v}_i) + \gamma_{id}(t) b_i (v_d - \hat{v}_i)$$

in which $\gamma_{ij}(t)$ is a binary random variable characterizing the fading property of the channel $(i,j) \in \varepsilon$. It is assumed that $\gamma_{ij}(t)$ is independent of both the time index t and spatial index i, j, and identically distributed for each t and $(i,j) \in \varepsilon$. Note that the distribution of $\gamma_{ij}(t)$ is given by $\mathbb{P}(\gamma_{ij}(t)=1) = \lambda = 1 - \mathbb{P}(\gamma_{ij}(t)=0)$ for all $(i,j) \in \varepsilon$ and t. λ is called recovery rate in the rest of the paper. For the consensus case with packet dropout in this section, we construct the Lyapunov candidate function $V = V_1 + V_2$ with

$$\begin{aligned} V_1 &= \frac{1}{2} e_1^T \bar{Z} e_1 + \frac{1}{2} e_2^T \bar{P} e_2 + e_1^T \bar{E} e_2, \\ V_2 &= \frac{1}{2}\sum_{i=1}^{n} r_{i1}^T \bar{C}_i r_{i1} - \sum_{i=1}^{n} r_{i1}^T \bar{F}_i r_{i2} + \frac{1}{2}\sum_{i=1}^{n} r_{i2}^T \bar{G}_i r_{i2} \\ &\quad + \frac{1}{2}\sum_{i=m+1}^{n} r_{i1}^T \bar{H}_i r_{i1} - \sum_{i=m+1}^{n} r_{i1}^T \bar{J}_i r_{i2} \\ &\quad + \sum_{i=m+1}^{n} r_{i1}^T \bar{Q}_i r_{i3} + \frac{1}{2}\sum_{i=m+1}^{n} r_{i2}^T \bar{R}_i r_{i2} \\ &\quad - \sum_{i=m+1}^{n} r_{i2}^T \bar{S}_i r_{i3} + \frac{1}{2}\sum_{i=m+1}^{n} r_{i3}^T \bar{W}_i r_{i3}, \end{aligned}$$

where $\bar{Z}$, $\bar{P}$, $\bar{E}$, $\bar{C}_i$, $\bar{F}_i$, $\bar{G}_i$, $\bar{H}_i$, $\bar{J}_i$, $\bar{Q}_i$, $\bar{R}_i$, $\bar{S}_i$ and $\bar{W}_i$ are positive definite matrices with appropriate dimension. Then the Lyapunov function V can be changed as

$$V = V_1 + V_2 = \bar{y}^T \bar{N}^* \bar{y}, \tag{14}$$

where $\bar{y} = [e_1^T\ e_2^T\ r_1^T\ r_2^T\ r_{1m}^T\ r_{2m}^T\ r_{3m}^T]^T$ and

$$\bar{N}^* = \begin{bmatrix} \frac{1}{2}\bar{Z} & \frac{1}{2}\bar{E} & 0 & 0 & 0 & 0 & 0 \\ * & \frac{1}{2}\bar{P} & 0 & 0 & 0 & 0 & 0 \\ * & * & \frac{1}{2}\bar{C} & -\frac{1}{2}\bar{F} & 0 & 0 & 0 \\ * & * & * & \frac{1}{2}\bar{G} & 0 & 0 & 0 \\ * & * & * & * & \frac{1}{2}\bar{H}_m & -\frac{1}{2}\bar{J}_m & \frac{1}{2}\bar{Q}_m \\ * & * & * & * & * & \frac{1}{2}\bar{R}_m & -\frac{1}{2}\bar{S}_m \\ * & * & * & * & * & * & \frac{1}{2}\bar{W}_m \end{bmatrix}$$

with $\bar{W}_m = \mathrm{diag}\{\bar{W}_{m+1}, \bar{W}_{m+2}, \cdots, \bar{W}_n\}$ and

$$\begin{aligned} &\bar{C} = \mathrm{diag}\{\bar{C}_1, \bar{C}_2, \cdots, \bar{C}_n\}, \quad \bar{F} = \mathrm{diag}\{\bar{F}_1, \bar{F}_2, \cdots, \bar{F}_n\}, \\ &\bar{G} = \mathrm{diag}\{\bar{G}_1, \bar{G}_2, \cdots, \bar{G}_n\}, \quad \bar{H}_m = \mathrm{diag}\{\bar{H}_{m+1}, \cdots, \bar{H}_n\}, \\ &\bar{J}_m = \mathrm{diag}\{\bar{J}_{m+1}, \cdots, \bar{J}_n\}, \quad \bar{Q}_m = \mathrm{diag}\{\bar{Q}_{m+1}, \cdots, \bar{Q}_n\}, \\ &\bar{R}_m = \mathrm{diag}\{\bar{R}_{m+1}, \cdots, \bar{R}_n\}, \quad \bar{S}_m = \mathrm{diag}\{\bar{S}_{m+1}, \cdots, \bar{S}_n\}. \end{aligned}$$

From (14), V is positive definite if $\bar{N}^* > 0$ is satisfied. Then, the weak infinitesimal operator $\mathscr{L}$ of (14) with packet dropout process is given by

$$\begin{aligned} \mathscr{L}(V) &= \lim_{h\to 0} \frac{1}{h}\{E[V(t+h) \mid V(t)] - V(t)\} \\ &= -\bar{y}^T \bar{M} \bar{y} + \bar{y}^T \bar{l}_m, \end{aligned} \tag{15}$$

$$\bar{l}_m = \Big[-(\bar{E}(L+B)\dot{v}_d)^T \quad -(\bar{P}(L+B)\dot{v}_d)^T \quad 0 \quad 0 \quad (\bar{Q}_m h_m)^T \quad (\bar{S}_m h_m)^T \quad (\bar{W}_m h_m)^T\Big]^T,$$

$$\bar{M} = \begin{bmatrix} (1,1) & (1,2) & 0 & (1,4) & 0 & 0 & 0 \\ * & (2,2) & 0 & (2,4) & 0 & 0 & 0 \\ * & * & (3,3) & -\frac{1}{2}(\bar{C} - \bar{G}\beta_2 + \bar{F}\beta_1) & 0 & 0 & 0 \\ * & * & * & \bar{F} & 0 & 0 & 0 \\ * & * & * & * & (5,5) & (5,6) & (5,7) \\ * & * & * & * & * & \bar{J}_m & (6,7) \\ * & * & * & * & * & * & (\bar{S}_m - I) \end{bmatrix}, \tag{16}$$

where $\bar{l}_m$ and $\bar{M}$ are shown as (16) with

$$(1,1) = \lambda \bar{E}(L+B)\Pi - 1/2(\bar{E}(L+B))^T(\bar{E}(L+B)),$$
$$(1,2) = -1/2(\bar{Z} - \lambda \bar{P}(L+B)\Pi - \lambda \bar{E}(L+B)\Delta),$$
$$(1,4) = -1/2(\lambda \bar{E}(L+B)^T(L+B)\Delta),$$
$$(2,2) = \lambda \bar{P}(L+B)\Delta - \bar{E} - \frac{1}{2}(\bar{P}(L+B))^T(\bar{P}(L+B)),$$
$$(2,4) = \lambda \bar{P}(L+B)^T(L+B)\Delta,$$
$$(3,3) = \bar{C}\beta_1 - \bar{F}\beta_2,$$
$$(5,5) = \bar{H}_m\beta_{1m} + \bar{Q}_m\beta_{3m} - \bar{J}_m\beta_{2m},$$
$$(5,6) = -1/2(\bar{H}_m + \bar{J}_m\beta_{1m} + \bar{S}_m\beta_{3m} - \bar{R}_m\beta_{2m}),$$
$$(6,7) = -1/2(\bar{G}_m + \bar{Q}_m + \bar{R}_m),$$
$$(5,7) = -1/2(-\bar{F}_m - \bar{J}_m - \bar{Q}_m\beta_{1m} + \bar{S}_m\beta_{2m} - \bar{W}_m\beta_{3m})$$

with

$$\bar{G}_m = \mathrm{diag}\{\bar{G}_{m+1}, \cdots, \bar{G}_n\}, \quad \bar{F}_m = \mathrm{diag}\{\bar{F}_{m+1}, \cdots, \bar{F}_n\}.$$

Utilizing Schur complement, $\bar{M} > 0$ is equal to

$$\bar{M}^* = \begin{bmatrix} \bar{M}_{11}^* & \bar{M}_{12}^* \\ * & \bar{M}_{22}^* \end{bmatrix}, \tag{17}$$

where $\bar{M}_{11}^* = \bar{M}$, $\bar{M}_{22}^* = I_{99\times 99}$ and

$$\bar{M}_{12}^* = \begin{bmatrix} (1,1)^* & 0 & 0 & 0 & 0 & 0 & 0 \\ * & (2,2)^* & 0 & 0 & 0 & 0 & 0 \\ * & * & 0 & 0 & 0 & 0 & 0 \\ * & * & * & 0 & 0 & 0 & 0 \\ * & * & * & * & 0 & 0 & 0 \\ * & * & * & * & * & 0 & 0 \\ * & * & * & * & * & * & 0 \end{bmatrix}$$

with $(1,1)^* = \frac{1}{\sqrt{2}}\left(\bar{R}(L+B)\right)$, $(2,2)^* = \frac{1}{\sqrt{2}}\left(\bar{P}(L+B)\right)$.

Theorem 2: Consider the heterogeneous multi-agent systems composed of second-order system (1) and EL system (2) under Assumptions 1 and 2. Design τ_i as (13). If there exist appropriate ESO parameters β_{i1}, β_{i2}, β_{i3} and positive matrices $\bar{Z}$, $\bar{P}$, $\bar{E}$, $\bar{C}_i$, $\bar{F}_i$, $\bar{G}_i$, $\bar{H}_i$, $\bar{J}_i$, $\bar{Q}_i$, $\bar{R}_i$, $\bar{S}_i$ and $\bar{W}_i, \forall i \in 1, \cdots, n$ such that the LMIs $\bar{N}^* > 0$ and $\bar{M}^* > 0$ given by (14) and (17), respectively, are satisfied, then the consensus in the sense of (3) is achieved.

Proof: From (15) and (17), we have $\mathscr{L}(V) \le 0$ if $\bar{M}^*$ is positive definite and $\| \bar{y} \| > \| \bar{l}_m \|_{max}\, \underline{\sigma}(\bar{M}) = \bar{B}_d$. Furthermore, according to (14), we have

$$\frac{1}{2}\| \bar{y} \|^2\, \underline{\sigma}(\bar{N}^*) \le V \le \frac{1}{2}\| \bar{y} \|^2\, \bar{\sigma}(\bar{N}^*).$$

Following [23], one can draw the conclusion that for any initial value $\bar{y}(t_0)$. There exists a time T_0 such that

$$\| \bar{y}(t) \| \le \sqrt{\bar{\sigma}(\bar{N}^*)/\underline{\sigma}(\bar{N}^*)}\bar{B}d, \quad \forall t \ge t_0 + T_0. \tag{18}$$

By definition of $\bar{y}(t)$, (18) implies that $e_1(t)$ and $e_2(t)$ are UUB. According to (4), as $-(L+B)$ is stable, it is obtained that $\lim_{t\to\infty} v_i(t) \to v_d(t)$ and $\lim_{t\to\infty} x_i(t) \to x_d(t)$, i.e., the consensus in the sense of (3) is reached. This completes the proof.

4. NUMERICAL EXAMPLES

In this section, we give an example to illustrate the effectiveness of the theoretical results in Theorem 2. It is noticed that the result of Theorem 1 is a special case of Theorem 2 without packet dropout. Consider the heterogeneous systems composed of three second-order integrator agents and three EL agents with a virtual leader, and the model is shown as

$$\begin{cases} \dot{x}_i(t) = v_i(t), \\ \dot{v}_i(t) = \tau_i(t), \quad i \in \{1,2,3\}, \end{cases}$$

and

$$\begin{cases} \dot{x}_i(t) = v_i(t), & i \in \{4,5,6\}, \\ M_i(x_i)\dot{v}_i + C_i(x_i, v_i)v_i = \tau_i(t) + \tau_{ext,i}(t). \end{cases} \tag{19}$$

Note that the dynamics of EL agents is similar to those in [22]. Therefore, we chose inertial matrices $J_{s/c,i}$ $\mathrm{kg}\cdot\mathrm{m}^2$ and the external disturbances $d_{ext,i}$ $\mathrm{N}\cdot\mathrm{m}$, $\forall i = 4,5,6$ which are the parameters of (19) as

$$J_{s/c,4} = \mathrm{diag}\{17,12,9\}, \quad d_{ext,4} = [2.22.22.2]^T,$$
$$J_{s/c,5} = \mathrm{diag}\{14,13,10\}, \quad d_{ext,5} = [1.41.41.4]^T,$$
$$J_{s/c,6} = \mathrm{diag}\{20,10,9\}, \quad d_{ext,6} = [0.80.80.8]^T.$$

All of these parameters are set to be 10%-80% of accuracy of spacecrafts' real values [22] and the agents considered herein are 3-dimensional systems. Moreover, $x_{ij}, v_{ij}, \forall j = 1,2,3$ are the jth elements of x_i and v_i, respectively.

The communication topology is shown in Fig. 1. It is noted that the directed graph for all followers 1 to 6 is connected and the virtual leader is a neighbor of follower 1. In this section, the leader's reference is set to be $x_d = [\sin(0.1t),\ \sin(0.1t),\ \sin(0.1t)]^T$ rad. In the following, we use x_{ij} and v_{ij} to denote the jth element of x_i and v_i, respectively. For simplicity, only tracking trajectories of first and second elements of states x_i and v_i are given out. Note that it is enough to illustrate the theorem results in this paper.

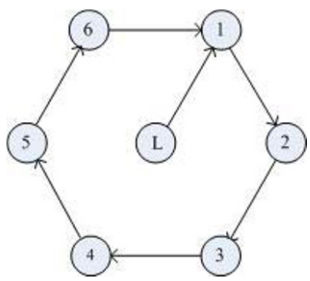
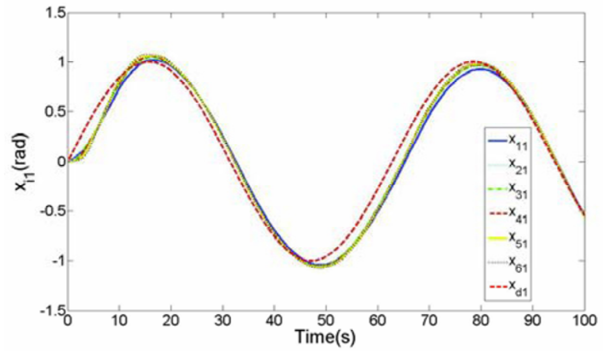
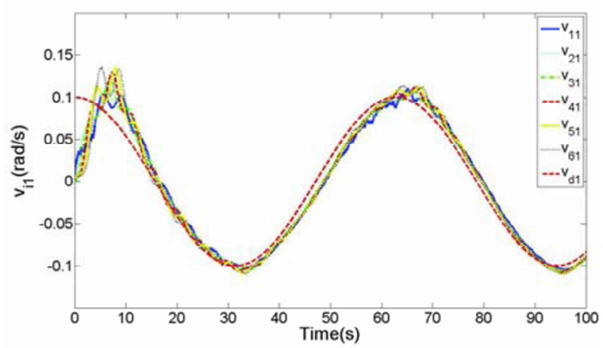


Fig. 1. Communication topology.

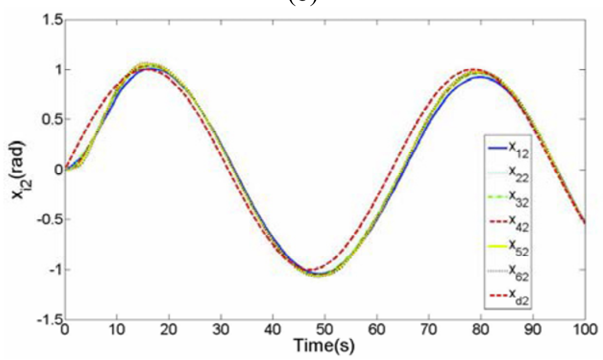
Remark 1: In this paper, we select the same reference signals in 3-dimensional space for the simplicity of simulation. Note that according to the proof of Theorems above, the leader's reference x_d can be in any form as long as it satisfies $x_d \in L_\infty$ and it's differential $v_d \in L_\infty$. Therefore, the reference signals in 3-dimensional space can be also different.



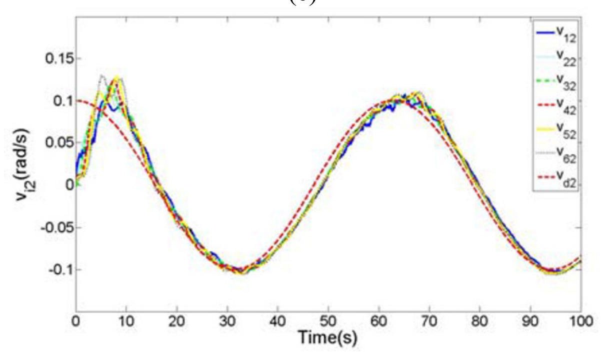
(a)



(b)



(c)



(d)

Fig. 2. Consensus with unknown velocities, time-varying disturbances and packet dropout.

Simulation results regarding the consensus case with packet dropout are implemented in this section. According to the proposed results in Theorem 2, we choose $\Delta_i = \text{diag}\{2,2,2\}$, $\Pi_i = \text{diag}\{2,2,2\}$, $i \in 1,2,3,4,5,6$ and the ESO parameters are chosen as $\beta_{i1} = \text{diag}\{20, 20, 20\}$, $\beta_{i2} = \text{diag}\{150,150,150\}$, $\beta_{i3} = \text{diag}\{500,500, 500\}$, $i \in 4,5,6$. Moreover, we obtain the allowable minimum recovery rate $\lambda = 0.6$ in network $\mathcal{G}$. Figs. 2(a) and 2(b) show the first elements of states x_i and v_i for all the agents, respectively. Similar results are shown in Figs. 2(c) and 2(d) for the second elements of states x_i and v_i.

From Fig. 2, we know that the heterogeneous multi-agent system (1)-(3) with consensus protocol (13) can solve the consensus problem with unknown velocities, time varying disturbances and packet dropout. For the chattering occurs in simulation results, it is due to the existence of packet dropout, which cause the loss of information in communication links and thus deteriorate the controller's performance. It is important to note that with the minimum recovery rate $\lambda = 0.6$, the consensus of heterogeneous multi-agent systems are still achieved. Then, it implies that the controller proposed in Theorem 2 has capability to deal with the problem of packet dropout.

5. CONCLUSION

In this paper, we have studied the leader-following consensus problem for heterogeneous multi-agent systems composed of linear second-order integrator agents and nonlinear EL agents. By introducing ESO, the consensus protocols which allow for unknown velocities and time-varying disturbances have been proposed for the both cases with and without packet dropout in this paper. Sufficient conditions which provide the allowable upper bound of packet drop rate have been obtained to ensure that all following agents could reach consensus asymptotically with a leader. Finally, simulation results have been shown to illustrate the effectiveness of the proposed results. Up to now, little attention has been paid on the consensus problem for heterogeneous multi-agent systems with time-varying delays, which is an common problem need to be solved. Therefore, our future work will focus on the consensus control for heterogeneous multi-agent systems with time delays.

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