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事件触发机制下的多速率多智能体系统 非脆弱一致性控制

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摘要: 针对一类多速率多智能体系统, 研究在事件触发机制下的非脆弱 H_∞ -一致性控制问题。为了更符合实际需要, 采用多速率采样策略, 并通过提升技术将多速率采样转化为单速率采样。考虑到智能体间的通信负担, 引入事件触发机制来减少智能体间的通信次数。此外, 考虑到控制器在执行过程中可能出现的不精确性, 本文设计一种可以容忍执行过程中变化/波动的控制器。综上, 本文的目的是设计一种基于观测器的事件触发非脆弱控制器来实现多智能体系统的 H_∞ -一致性控制。利用线性矩阵不等式技术, 得到使系统满足 H_∞ -一致性控制的充分条件, 然后设计控制器参数。最后, 为了说明事件触发控制方法的有效性, 给出一个数值仿真实例。

关键词: 多智能体系统; 多速率采样; 事件触发机制; 非脆弱控制器

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Event-Triggered Mechanism Based Non-Fragile Consensus Control for Multi-Rate Multi-Agent Systems

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Abstract: The research on the non-fragile H_∞ -consensus control problem for a class of multi-rate multi-agent system under the event-triggered (ET) mechanism is focused on. In order to be more in line with actual need, a multi-rate sampling strategy is adopted, which leads to a multi-rate sampling that can be converted into a single-rate sampling via lifting technique. Considering the transmission burden among the agents, an ET mechanism is introduced to reduce the numbers of transmission among the agents. In addition, in view of the possible inaccuracy of the controller implementation, a controller that can tolerate the changes/fluctuations during the implementation is designed to make the multi-agent system more robust. An observer-based ET non-fragile controller is designed to achieve the H_∞ -consensus control of the multi-agent system, in which the controller can tolerate the variations/fluctuations during the implementation. By using the linear matrix inequality technique, the sufficient conditions are obtained that can ensure the H_∞ -consensus control of the considered system, and then the controller parameters are designed. Finally, a numerical simulation example is given to prove the effectiveness of the ET control method.

Key words: multi-agent system; multi-rate sampling; event-triggered mechanism; non-fragile controller

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在过去的几十年里,多智能体系统由于在化学制造业、地质勘探、楼宇自动化以及航空航天等各个领域的广泛应用而吸引了大量学者的目光^[1-4]。作为多智能体系统的主要研究课题之一,一致性控制问题持续受到关注^[5-8],其目标是通过利用邻居节点的信息设计一致性算法(或协议),使多智能体的状态达到某些共同特征(如位置、相位、速度和姿态),目前在该方面已经涌现了大批优秀成果。例如,文献[5]研究了拓扑结构变化的多智能体系统,考虑了在受到模型不确定性和外部扰动影响下的一致性控制问题。文献[7]对离散时间多智能体系统,同时考虑了外部干扰和测量丢失,并深入研究了测量丢失对一致性行为的影响。此外,为了提高通信可靠性,引入了冗余信道,并构建了相应的冗余信道信息传输协议。文献[8]使用相对输出测量的方法解决了具有一般线性节点的动态多智能体系统的分布式 H_∞ 一致性控制问题。

值得注意的是,现有的大多数控制器设计方法都依赖于一个假设,即所设计的控制器可以精确地实现。然而,由于复杂和多变的环境会对控制器执行过程造成一定程度的干扰^[9-13],导致这一假设在现实中并不总是成立的。为了解决这一问题,学者们设计了非脆弱控制器来容忍控制器增益中的扰动项。在文献[9]中,基于切换有向网络拓扑,提出了一种非脆弱控制方案,以确保具有时变输入时滞的线性连续时间多智能体系统实现有限时间一致性控制。文献[10]分别针对有时滞和有时滞的分数阶记忆(Bidirectional Associative Memory, BAM)神经网络,给出了分数阶BAM神经网络的非脆弱状态估计方法,引入了一种新的变换,将分数阶BAM神经网络转换为带有参数不确定的系统。文献[11]研究了连续时间广义多智能体系统在Lipschitz非线性动力学下的非脆弱一致性控制问题。考虑了相关的非线性多智能体在无向图中通信的情况,最终所有智能体的状态通过所设计控制协议达成一致。更多相关结果见文献[12-16]。

在复杂的实际系统中,不同的信号往往根据其物理特性采用不同的采样率进行采样,也就是说更多的工程系统实际上是多速率系统^[17-21]。例如,在机器人和制造业系统中,测量是通过图像处理来进行视觉反馈,它们都需要较长的时间才能实现采样,这就导致了大的采样周期。因此,对于不同的元件采用不同的采样率(即多速率采样)能够使系统性能和资源消耗达到一个恰当的平衡状态,所以研究多速率

系统具有很好的理论意义和工业价值。由于多速率采样带来的复杂性,关于多速率系统的分析与综合已经受到了广泛关注,如稳定性分析、 H_∞ 一致性控制、模型预测控制及故障检测^[22-36]。文献[24]讨论了一类时变时滞网络化控制系统的镇定问题,其中随机时滞小于一个传感器周期或大于一个传感器周期但有界。文中提出了一种新的多速率方法来建立短随机时滞和长随机时滞的联合模型。文献[28]针对带有随机噪声、未知输入以及执行器和传感器故障的系统,解决了多速率多传感器融合系统的故障检测问题和最优滤波问题。值得指出的是,虽然多速率采样问题已经被大量研究,但在多智能体系统中少有考虑。因此,本文的第一个研究动机是探索多速率采样对多智能体系统非脆弱一致性控制问题的影响。

众所周知,在恶劣的环境下智能体的通信资源和运算能力通常是被限制的^[37-38],为了降低资源的损耗,基于事件触发的通信方式进入了人们的视野^[39-44]。瑞典学者Åarzén于20世纪90年代末第一次提出了基于事件触发机制的PID控制策略^[45],并对事件触发机制进行了详细的分析。与时间触发机制不同,事件触发机制的核心思想是“按需”触发,而不再是“按时”触发。根据实际需求预先设定触发条件,只有系统的当前信息满足触发条件,才执行当前触发任务。显而易见,事件触发机制的应用会降低资源的消耗。在文献[39]中,作者清楚地描述了时间触发和事件触发的区别,并阐述了事件触发在节约通信资源方面的优势。值得注意的是,目前基于事件触发机制的多智能体系统一致性控制问题的研究大多数聚焦于单速率采样,本文将研究事件触发机制对多速率多智能体系统一致性控制问题的影响,并提出相应的一致性控制方案。

基于以上讨论,本文将针对多速率多智能体系统,研究其在事件触发机制下的非脆弱 H_∞ 一致性控制问题。具体贡献如下:(1) 首次研究了一类多速率多智能体系统的非脆弱 H_∞ 一致性控制问题;(2) 与时间触发机制相比,引入的事件触发机制在节约通信资源方面更具优势并且采用了相对触发的形式来动态调整阈值,使系统的性能和资源的消耗达到恰当的平衡;(3) 获得了增广系统渐近稳定且满足给定 H_∞ 一致性控制约束的充分条件。

1 预备知识

1.1 图论

首先,通过使用有向图 $G_Q(V_Q, S_Q, Q_Q)$ 表示智能

体之间的拓扑结构,其中 $V_Q = \{v_1, v_2, \dots, v_N\}$ 是 N 个节点的集合, $S_Q = V_Q \times V_Q$ 表示边的集合, $Q_Q = [q_{ij}] \in \mathbb{R}^{N \times N}$ 表示邻接矩阵。边 $q_{ij} \in S_Q$ 并且当且仅当 $q_{ij} > 0$ 时,意味着智能体 j 可以将其信息发送给智能体 i ,其中智能体 j 称为智能体 i 的邻居。相邻智能体的集合表示为 $\mathbb{N}_i = \{v_i \in V_Q : q_{ij} \in S_Q, j \neq i\}$,如果每对顶点之间存在一条路径,那么有向图是连通的。矩阵 $R_Q = \text{diag}\{r_i\} \in \mathbb{R}^{N \times N}$ 为度矩阵且 $r_i = \sum_{j \in \mathbb{N}_i} q_{ij}$, $L = R_Q - Q_Q$ 为拉普拉斯矩阵。

1.2 引理

引理1^[46] 给定3个适当维数的矩阵 S_1, S_2 和 S_3 ,其中 $S_1 = S_1^T$ 和 $S_2 = S_2^T$,那么 $S_1 - S_3^T S_2^{-1} S_3 < 0$ 成立当且仅当

$$\begin{bmatrix} S_1 & S_3^T \\ S_3 & S_2 \end{bmatrix} < 0 \text{ 或 } \begin{bmatrix} S_2 & S_3 \\ S_3^T & S_1 \end{bmatrix} < 0 \quad (1)$$

成立。

对于具有 n_u 个非零奇异值($O_1, \dots, O_{n_u}$)的全列秩矩阵 $W \in \mathbb{R}^{n_x \times n_u} (n_x \geq n_u)$,通过奇异值分解,存在两个正交矩阵 $U \in \mathbb{R}^{n_x \times n_x}$ 和 $V \in \mathbb{R}^{n_u \times n_u}$ 使得式(2)成立。

$$W = U \begin{bmatrix} \theta \\ 0 \end{bmatrix} V^T = [U_1 \ U_2] \begin{bmatrix} \theta \\ 0 \end{bmatrix} V^T = U_1 \theta V^T \quad (2)$$

式中: $\theta = \text{diag}\{O_1, \dots, O_{n_u}\}, U_1 \in \mathbb{R}^{n_x \times n_u}, U_2 \in \mathbb{R}^{n_x \times (n_x - n_u)}$ 。

根据式(2)可得以下引理:

引理2^[47] 如果矩阵 B_Q 具有以下结构

$$B_Q = [U_1 \ U_2] \text{diag}\{B_{Q1}, B_{Q2}\} [U_1 \ U_2]^T = U_1 B_{Q1} U_1^T + U_2 B_{Q2} U_2^T \quad (3)$$

式中: $B_{Q1} \in \mathbb{R}^{n_u \times n_u} > 0, B_{Q2} \in \mathbb{R}^{(n_x - n_u) \times (n_x - n_u)} > 0$,那么存在一个非奇异矩阵 $B_p \in \mathbb{R}^{n_u \times n_u}$ 使得 $W B_p = B_Q W$,其中, $B_p = V \theta^{-1} B_{Q1} \theta V^T$ 。

引理3^[46] 给定适当维数的实矩阵 Φ, Γ 及 Z 且 $\Phi = \Phi^T$,矩阵 Υ 满足 $\Upsilon \Upsilon^T \leq I$,那么

$$\Phi + \Gamma \Upsilon Z + Z^T \Upsilon^T \Gamma^T < 0$$

当且仅当存在一个常数 $\varepsilon > 0$ 使得式(4)成立。

$$\Phi + \varepsilon \Gamma \Gamma^T + \varepsilon^{-1} Z^T Z < 0 \quad (4)$$

2 问题描述

2.1 模型描述

首先,考虑由以下状态空间模型描述的多智能体系统

$$\begin{cases} \dot{x}_i(T_m) = A x_i(T_m) + B u_i(T_m) + E w_i(T_m) \\ \dot{z}_i(T_m) = D x_i(T_m) \end{cases} \quad (5)$$

式中: $x_i(T_m) \in \mathbb{R}^{n_x}, u_i(T_m) \in \mathbb{R}^{n_u}$ 和 $z_i(T_m) \in \mathbb{R}^{n_z}$ 分别为第

i 个智能体的状态、控制输入和控制输出, $w_i(T_m) \in L_2([0, \infty); \mathbb{R}^{n_w})$ 为过程噪声; $A \in \mathbb{R}^{n_x \times n_x}, B \in \mathbb{R}^{n_x \times n_u}, E \in \mathbb{R}^{n_x \times n_w}$ 和 $D \in \mathbb{R}^{n_z \times n_x}$ 为已知常矩阵;系统状态 $x_i(T_m)$ 和控制输出 $z_i(T_m)$ 在 T_m 时刻更新,其中 $T_{m+1} - T_m \triangleq h$ 且 $m = 0, 1, 2, \dots, \mathbb{R}^a$ 表示 a 维欧几里得空间, $\mathbb{R}^{a \times c}$ 表示所有 $a \times c$ 实矩阵的集合。

在采样时刻 t_m ,第 i 个智能体的测量模型为

$$y_i(t_m) = C x_i(t_m) + F v_i(t_m) \quad (6)$$

式中: $y_i(t_m) \in \mathbb{R}^{n_y}$ 为测量输出, $t_{m+1} - t_m \triangleq bh$ 且 b 为正整数; $v_i(t_m) \in L_2([0, \infty); \mathbb{R}^{n_v})$ 为能量有界的测量噪声; $C \in \mathbb{R}^{n_y \times n_x}$ 和 $F \in \mathbb{R}^{n_y \times n_v}$ 为已知常矩阵。

通过提升技术,将式(5)提升为时间尺度为 t_m 的系统,如式(7)所示。

$$\begin{cases} x_i(t_{m+1}) = A^b x_i(t_m) + \bar{B}_1 \bar{u}_i(t_m) + \bar{E}_1 \bar{w}_i(t_m) \\ x_i(t_{m+1} - h) = A^{b-1} x_i(t_m) + \bar{B}_2 \bar{u}_i(t_m) + \bar{E}_2 \bar{w}_i(t_m) \\ \vdots \\ x_i(t_{m+1} - (b-1)h) = A x_i(t_m) + \bar{B}_b \bar{u}_i(t_m) + \bar{E}_b \bar{w}_i(t_m) \end{cases} \quad (7)$$

式中:

$$\begin{aligned} \bar{B}_l &\triangleq [\bar{B}_{1l} \ 0], \bar{E}_l \triangleq [\bar{E}_{1l} \ 0], 0 \triangleq [0 \ \dots \ 0] \\ \bar{B}_{1l} &\triangleq [A^{b-l} B \ \dots \ AB \ B], l \triangleq 1, 2, \dots, b \\ \bar{E}_{1l} &\triangleq [A^{b-l} E \ \dots \ AE \ E] \end{aligned}$$

接下来,定义:

$$\bar{x}_i(t_m) \triangleq \text{col}_1^b \{x_i(t_m - (l-1)h)\}$$

$$\bar{u}_i(t_m) \triangleq \text{col}_1^b \{u_i(t_m + (l-1)h)\}$$

$$\bar{w}_i(t_m) \triangleq \text{col}_1^b \{w_i(t_m + (l-1)h)\}$$

$$\bar{v}_i(t_m) \triangleq \text{col}_1^b \{v_i(t_m + (l-1)h)\}$$

$$\bar{z}_i(t_m) \triangleq \text{col}_1^b \{z_i(t_m - (l-1)h)\}$$

得到一个新的采样时刻为 t_m 的多智能体系统如式(8)所示。

$$\begin{cases} \bar{x}_i(t_{m+1}) = \hat{A} \bar{x}_i(t_m) + \hat{B} \bar{u}_i(t_m) + \hat{E} \bar{w}_i(t_m) \\ y_i(t_m) = \bar{C} \bar{x}_i(t_m) + \bar{F} \bar{v}_i(t_m) \\ \bar{z}_i(t_m) = \bar{D} \bar{x}_i(t_m) \end{cases} \quad (8)$$

式中:

$\bar{A} \triangleq \text{col}_b^1\{A^i\}$, $\hat{A} \triangleq [\bar{A} \quad \underbrace{0 \cdots 0}_{b-1}]$, $\hat{B} \triangleq \text{col}_1^b\{\bar{B}_i\}$,
 $\hat{E} \triangleq \text{col}_1^b\{\bar{E}_i\}$, $\bar{C} \triangleq [C \quad \underbrace{0 \cdots 0}_{b-1}]$, $\bar{D} \triangleq \text{diag}_b\{D\}$, $\bar{F} \triangleq [F$
 $\underbrace{0 \cdots 0}_{b-1}]$ 。其中, $\text{col}_1^b\{d_i\}$ 表示向量 $[d_1^T \ d_2^T \ \cdots \ d_b^T]^T$, $\text{diag}_b\{\cdots\}$
表示一个 $b \times b$ 的对角矩阵。

为了表述方便,进一步表示 $k \triangleq t_m$ 。

2.2 控制器设计

本部分将基于系统状态设计控制器,因此,首先针对多智能体 i 设计相应的状态观测器。

$$\xi_i(k+1) = \hat{A}\xi_i(k) + \hat{B}\bar{u}_i(k) + H(y_i(k) - \bar{C}\xi_i(k)) \quad (9)$$

式中: $\xi_i(k)$ 为 $\bar{x}_i(k)$ 的估计值, H 为需要设计的观测器增益。

考虑到智能体之间的通信受限情况,采用事件触发机制决定它们之间的通信时刻,其中触发时刻由式(10)决定。

$$k_{s+1}^i = \inf\{k > k_s^i \mid [\hat{\xi}_i(k) - \xi_i(k)]^T [\hat{\xi}_i(k) - \xi_i(k)] \geq \sigma_i \xi_i^T(k) \xi_i(k)\} \quad (10)$$

式中: $\sigma_i (i = 1, 2, \cdots, N)$ 为预先设定的标量, k_s^i 为智能体 i 的第 s 个触发时刻。当 $k \in [k_s^i, k_{s+1}^i)$ 时, $\hat{\xi}_i(k) = \xi_i(k_s^i)$, 其中 $\{k_s^i\}_{s \geq 0}$ 为智能体 i 的一个触发时间序列。

基于事件触发机制,为智能体 i 构造分布式非脆弱控制器

$$\bar{u}_i(k) = \hat{K} \sum_{j \in \mathbb{N}_i} q_{ij} (\hat{\xi}_j(k) - \hat{\xi}_i(k)) \quad (11)$$

式中: $\hat{\xi}_j(k) = \xi_j(k_{s'}^j)$, $k_{s'}^j$ 为智能体 j 的第 s' 个触发时刻且 $k_{s'}^j = \max\{k_s^j \mid k_s^j < k\}$, $\sum_{j \in \mathbb{N}_i} q_{ij}$ 在图论中已给出说明。 $\hat{K} = K + \Delta K$, 其中 K 为需要设计的控制器增益, ΔK 为控制器增益的扰动项, 满足

$$\Delta K = KH_1 F_1 G_1 \quad (12)$$

式中: H_1 及 G_1 为给定矩阵, F_1 满足 $F_1 F_1^T \leq I$ 。

注解1 在触发时刻 k_s^i , 对于智能体 i , 为其构造状态观测器, 并将 $\xi_i(k_s^i)$ 传输到其相邻智能体 j 并更新其控制协议 $\bar{u}_i(k)$ 。对于邻居智能体 $j (j \in \mathbb{N}_i)$, 在触发时刻 k_s^i 收到来自智能体 i 的观测器信息 $\xi_i(k_s^i)$, 然后智能体 j 利用最新的信息 $\xi_j(k_{s'}^j)$ 更新其控制信号 $\bar{u}_j(k)$ 。因此, 控制信号 $\bar{u}_i(k)$ 在其相邻智能体及其自身的触发时刻更新。

2.3 系统增广

为方便以下分析, 先做出如下定义:

$$\delta_i(k) \triangleq \xi_i(k) - \bar{x}_i(k)$$

$$e_i(k) \triangleq \hat{\xi}_i(k) - \xi_i(k)$$

$$\bar{x}(k) \triangleq [\bar{x}_1^T(k) \ \bar{x}_2^T(k) \ \cdots \ \bar{x}_N^T(k)]^T$$

$$\xi(k) \triangleq [\xi_1^T(k) \ \xi_2^T(k) \ \cdots \ \xi_N^T(k)]^T$$

$$\hat{\xi}(k) \triangleq [\hat{\xi}_1^T(k) \ \hat{\xi}_2^T(k) \ \cdots \ \hat{\xi}_N^T(k)]^T$$

$$e(k) \triangleq [e_1^T(k) \ e_2^T(k) \ \cdots \ e_N^T(k)]^T$$

$$\bar{w}(k) \triangleq [\bar{w}_1^T(k) \ \bar{w}_2^T(k) \ \cdots \ \bar{w}_N^T(k)]^T$$

$$v(k) \triangleq [v_1^T(k) \ v_2^T(k) \ \cdots \ v_N^T(k)]^T$$

$$\delta(k) \triangleq [\delta_1^T(k) \ \delta_2^T(k) \ \cdots \ \delta_N^T(k)]^T$$

$$\bar{z}(k) \triangleq [\bar{z}_1^T(k) \ \bar{z}_2^T(k) \ \cdots \ \bar{z}_N^T(k)]^T$$

那么系统(8)可重写为

$$\begin{cases} \bar{x}(k+1) = [I_N \otimes \hat{A} - L \otimes (\hat{B}\hat{K})] \bar{x}(k) - [L \otimes (\hat{B}\hat{K})] e(k) - \\ \quad [L \otimes (\hat{B}\hat{K})] \delta(k) + (I_N \otimes \hat{E}) \bar{w}(k) \\ \delta(k+1) = [I_N \otimes \hat{A} - I_N \otimes (H\bar{C})] \delta(k) + [I_N \otimes (H\bar{F})] v(k) - \\ \quad (I_N \otimes \hat{E}) \bar{w}(k) \\ \bar{z}(k) = (I_N \otimes \bar{D}) \bar{x}(k) \end{cases} \quad (13)$$

式中: I_N 表示一个 $N \times N$ 的单位矩阵。

通过定义变量 $\eta(k) \triangleq [\bar{x}^T(k) \ \delta^T(k)]^T$, $\omega(k) \triangleq [\bar{w}^T(k) \ v^T(k)]^T$, 得到增广系统如下

$$\begin{cases} \eta(k+1) = A_1 \eta(k) + B_1 e(k) + E_1 \omega(k) \\ \bar{z}(k) = D_1 \eta(k) \end{cases} \quad (14)$$

式中:

$$A_1 \triangleq \bar{A}_1 + \Delta \bar{A}_1, \quad B_1 \triangleq \bar{B}_1 + \Delta \bar{B}_1$$

$$\begin{aligned} \bar{A}_1 &\triangleq \begin{bmatrix} I_N \otimes \hat{A} - L \otimes (\hat{B}K) & -L \otimes (\hat{B}K) \\ \mathbf{0} & I_N \otimes \hat{A} - I_N \otimes (H\bar{C}) \end{bmatrix} \\ \Delta \bar{A}_1 &\triangleq \begin{bmatrix} -L \otimes (\hat{B}\Delta K) & -L \otimes (\hat{B}\Delta K) \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \\ E_1 &\triangleq \begin{bmatrix} I_N \otimes \hat{E} & \mathbf{0} \\ -I_N \otimes \hat{E} & I_N \otimes (H\bar{F}) \end{bmatrix}, \quad \bar{B}_1 \triangleq \begin{bmatrix} -L \otimes (\hat{B}K) \\ \mathbf{0} \end{bmatrix} \\ \Delta \bar{B}_1 &\triangleq \begin{bmatrix} -L \otimes (\hat{B}\Delta K) \\ \mathbf{0} \end{bmatrix}, \quad D_1 \triangleq [I_N \otimes \bar{D} \quad \mathbf{0}] \end{aligned}$$

由以上结果可知, 式(10)中的事件触发条件为

$$\mathbf{e}^T(k)\mathbf{e}(k) < \boldsymbol{\eta}^T(k)\mathbf{M}\boldsymbol{\eta}(k) \quad (15)$$

式中:

$$\mathbf{M} \triangleq \begin{bmatrix} \mathbf{I}_{bNn_x} & \mathbf{I}_{bNn_x} \end{bmatrix}^T (\boldsymbol{\Lambda} \otimes \mathbf{I}_{bn_x}) \begin{bmatrix} \mathbf{I}_{bNn_x} & \mathbf{I}_{bNn_x} \end{bmatrix}$$

$$\boldsymbol{\Lambda} \triangleq \text{diag}\{\sigma_1, \sigma_2, \dots, \sigma_N\}$$

注解2 在式(10)中事件触发条件是起到判断触发时刻的作用,如果其成立,则表示事件被触发。而式(15)指触发时刻(包括该触发时刻)与下一个触发时刻之间的时间段处于不触发状态,即 $k \in [k_s^i, k_{s+1}^i)$ 仍处于不触发状态。

定义:对于给定的干扰抑制水平 $\gamma > 0$,如果以下不等式成立,那么增广系统(14)在零初始条件下满足 H_∞ 一致性控制。

$$\sum_{k=0}^{\infty} \|\bar{\mathbf{z}}(k) - \ell\bar{\mathbf{z}}(k)\|^2 < \gamma^2 \sum_{k=0}^{\infty} \|\boldsymbol{\omega}(k)\|^2 \quad (16)$$

式中: $\ell \triangleq (\frac{1}{N}\mathbf{1}_{N \times N}) \otimes \mathbf{I}_{bn_z}$ 。

本文旨在设计非脆弱控制器(11)使得:

(a) $\boldsymbol{\omega}(k) = \mathbf{0}$ 时,增广系统(14)是渐近稳定的;

(b) 零初始条件下,增广系统(14)满足给定 H_∞ 一致性控制约束(16)。

3 主要结果

3.1 一致性控制分析

定理1将给出使增广系统(14)渐近稳定并满足 H_∞ 一致性控制约束的充分条件。

定理1 给定干扰抑制水平 γ ,观测器增益 $\mathbf{H}$,控制器增益 $\mathbf{K}$ 以及增益扰动项 $\Delta\mathbf{K}$ 。如果存在正定对称矩阵 $\mathbf{P}$ 和正标量 ρ 满足不等式

$$\bar{\boldsymbol{\Omega}} \triangleq \begin{bmatrix} \bar{\boldsymbol{\Omega}}_{11} & * & * \\ \bar{\boldsymbol{\Omega}}_{21} & \bar{\boldsymbol{\Omega}}_{22} & * \\ \bar{\boldsymbol{\Omega}}_{31} & \bar{\boldsymbol{\Omega}}_{32} & \bar{\boldsymbol{\Omega}}_{33} \end{bmatrix} < 0 \quad (17)$$

则增广系统(14)在 $\boldsymbol{\omega}(k) = \mathbf{0}$ 时渐近稳定,且在 $\boldsymbol{\omega}(k) \neq \mathbf{0}$ 和零初始条件下,满足 H_∞ 一致性控制约束(16),其中相关矩阵为

$$\bar{\boldsymbol{\Omega}}_{11} \triangleq \mathbf{A}_1^T \mathbf{P} \mathbf{A}_1 + \bar{\mathbf{D}}_1 - \mathbf{P} + \rho \mathbf{M}, \bar{\boldsymbol{\Omega}}_{21} \triangleq \mathbf{B}_1^T \mathbf{P} \mathbf{A}_1$$

$$\bar{\boldsymbol{\Omega}}_{22} \triangleq \mathbf{B}_1^T \mathbf{P} \mathbf{B}_1 - \rho \mathbf{I}_{bNn_x}, \bar{\boldsymbol{\Omega}}_{31} \triangleq \mathbf{E}_1^T \mathbf{P} \mathbf{A}_1$$

$$\bar{\boldsymbol{\Omega}}_{32} \triangleq \mathbf{E}_1^T \mathbf{P} \mathbf{B}_1, \bar{\boldsymbol{\Omega}}_{33} \triangleq \mathbf{E}_1^T \mathbf{P} \mathbf{E}_1 - \gamma^2 \mathbf{I}_{bNn_x}$$

$$\bar{\mathbf{D}}_1 \triangleq (\mathbf{D}_1 - \ell \mathbf{D}_1)^T (\mathbf{D}_1 - \ell \mathbf{D}_1)$$

式(17)中*表示对称矩阵中的对称块,下同。

证明 首先,构造如下Lyapunov函数

$$V(k) = \boldsymbol{\eta}^T(k) \mathbf{P} \boldsymbol{\eta}(k) \quad (18)$$

然后,计算 $V(k)$ 沿系统(14)的差分,可以得到

$$\Delta V(k) = \boldsymbol{\eta}^T(k+1) \mathbf{P} \boldsymbol{\eta}(k+1) - \boldsymbol{\eta}^T(k) \mathbf{P} \boldsymbol{\eta}(k) = [\mathbf{A}_1 \boldsymbol{\eta}(k) + \mathbf{B}_1 \mathbf{e}(k) + \mathbf{E}_1 \boldsymbol{\omega}(k)]^T \mathbf{P} \times [\mathbf{A}_1 \boldsymbol{\eta}(k) + \mathbf{B}_1 \mathbf{e}(k) + \mathbf{E}_1 \boldsymbol{\omega}(k)] - \boldsymbol{\eta}^T(k) \mathbf{P} \boldsymbol{\eta}(k) = \boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{A}_1 \boldsymbol{\eta}(k) + \mathbf{e}^T(k) \mathbf{B}_1^T \mathbf{P} \mathbf{B}_1 \mathbf{e}(k) + \boldsymbol{\omega}^T(k) \mathbf{E}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) - \boldsymbol{\eta}^T(k) \mathbf{P} \boldsymbol{\eta}(k) + 2\boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{B}_1 \mathbf{e}(k) + 2\boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) + 2\mathbf{e}^T(k) \mathbf{B}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) \quad (19)$$

当 $\boldsymbol{\omega}(k) = \mathbf{0}$ 时,引入正标量 ρ ,由式(15)可知

$$\rho [\boldsymbol{\eta}^T(k) \mathbf{M} \boldsymbol{\eta}(k) - \mathbf{e}^T(k) \mathbf{e}(k)] > 0 \quad (20)$$

由式(19)可知

$$\Delta V_\omega(k) < \boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{A}_1 \boldsymbol{\eta}(k) + \mathbf{e}^T(k) \mathbf{B}_1^T \mathbf{P} \mathbf{B}_1 \mathbf{e}(k) - \boldsymbol{\eta}^T(k) \mathbf{P} \boldsymbol{\eta}(k) + 2\boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{B}_1 \mathbf{e}(k) + \rho [\boldsymbol{\eta}^T(k) \mathbf{M} \boldsymbol{\eta}(k) - \mathbf{e}^T(k) \mathbf{e}(k)] = \tilde{\boldsymbol{\eta}}^T(k) \boldsymbol{\Omega} \tilde{\boldsymbol{\eta}}(k) \quad (21)$$

式中:

$$\boldsymbol{\Omega} \triangleq \begin{bmatrix} \boldsymbol{\Omega}_{11} & * \\ \bar{\boldsymbol{\Omega}}_{21} & \bar{\boldsymbol{\Omega}}_{22} \end{bmatrix}, \quad \tilde{\boldsymbol{\eta}}(k) \triangleq \begin{bmatrix} \boldsymbol{\eta}(k) \\ \mathbf{e}(k) \end{bmatrix},$$

$$\boldsymbol{\Omega}_{11} \triangleq \mathbf{A}_1^T \mathbf{P} \mathbf{A}_1 - \mathbf{P} + \rho \mathbf{M}$$

根据式(17)可知 $\boldsymbol{\Omega} < 0$,显然,当 $\boldsymbol{\omega}(k) = \mathbf{0}$ 时增广系统(14)是渐近稳定的。

在零初始条件下且 $\boldsymbol{\omega}(k) \neq \mathbf{0}$ 时,结合式(19)及(20),进一步可得

$$\Delta V(k) < \boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{A}_1 \boldsymbol{\eta}(k) + \mathbf{e}^T(k) \mathbf{B}_1^T \mathbf{P} \mathbf{B}_1 \mathbf{e}(k) + \boldsymbol{\omega}^T(k) \times \mathbf{E}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) - \boldsymbol{\eta}^T(k) \mathbf{P} \boldsymbol{\eta}(k) + 2\boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{B}_1 \mathbf{e}(k) + 2\boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) + 2\mathbf{e}^T(k) \mathbf{B}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) + \rho [\boldsymbol{\eta}^T(k) \mathbf{M} \boldsymbol{\eta}(k) - \mathbf{e}^T(k) \mathbf{e}(k)] \quad (22)$$

将 $(\bar{\mathbf{z}}(k) - \ell\bar{\mathbf{z}}(k))^T (\bar{\mathbf{z}}(k) - \ell\bar{\mathbf{z}}(k)) - \gamma^2 \boldsymbol{\omega}^T(k) \boldsymbol{\omega}(k)$ 加入到式(22)两端,可以得到

$$\Delta V(k) + \boldsymbol{\eta}^T(k) \bar{\mathbf{D}}_1 \boldsymbol{\eta}(k) - \gamma^2 \boldsymbol{\omega}^T(k) \boldsymbol{\omega}(k) < \boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{A}_1 \boldsymbol{\eta}(k) + \mathbf{e}^T(k) \mathbf{B}_1^T \mathbf{P} \mathbf{B}_1 \mathbf{e}(k) + \boldsymbol{\omega}^T(k) \mathbf{E}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) - \boldsymbol{\eta}^T(k) \mathbf{P} \boldsymbol{\eta}(k) + 2\boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{B}_1 \mathbf{e}(k) + 2\boldsymbol{\eta}^T(k) \mathbf{A}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) + 2\mathbf{e}^T(k) \mathbf{B}_1^T \mathbf{P} \mathbf{E}_1 \boldsymbol{\omega}(k) + \rho [\boldsymbol{\eta}^T(k) \mathbf{M} \boldsymbol{\eta}(k) - \mathbf{e}^T(k) \mathbf{e}(k)] + \boldsymbol{\eta}^T(k) \bar{\mathbf{D}}_1 \boldsymbol{\eta}(k) - \gamma^2 \boldsymbol{\omega}^T(k) \boldsymbol{\omega}(k) = \tilde{\boldsymbol{\eta}}^T(k) \bar{\boldsymbol{\Omega}} \tilde{\boldsymbol{\eta}}(k) \quad (23)$$

式中: $\tilde{\boldsymbol{\eta}}(k) \triangleq [\boldsymbol{\eta}^T(k) \quad \mathbf{e}^T(k) \quad \boldsymbol{\omega}^T(k)]^T$ 。

根据式(17)中 $\bar{\boldsymbol{\Omega}} < 0$ 可得

$$\Delta V(k) < -(\bar{\mathbf{z}}(k) - \ell\bar{\mathbf{z}}(k))^T (\bar{\mathbf{z}}(k) - \ell\bar{\mathbf{z}}(k)) + \gamma^2 \boldsymbol{\omega}^T(k) \boldsymbol{\omega}(k) \quad (24)$$

进一步可知

$$\sum_{k=0}^{\infty} \Delta V(k) = \eta^T(\infty) P \eta(\infty) - \eta^T(0) P \eta(0) < - \sum_{k=0}^{\infty} [\bar{z}(k) - \ell \bar{z}(k)]^T [\bar{z}(k) - \ell \bar{z}(k)] + \sum_{k=0}^{\infty} \gamma^2 \omega^T(k) \omega(k) \quad (25)$$

由于 $P > 0$ 且初始条件为零,很容易得出

$$\eta^T(\infty) P \eta(\infty) > 0, \quad \eta^T(0) P \eta(0) = 0 \quad (26)$$

进而可以得到

$$\sum_{k=0}^{\infty} \|\bar{z}(k) - \ell \bar{z}(k)\|^2 < \gamma^2 \sum_{k=0}^{\infty} \|\omega(k)\|^2 \quad (27)$$

证明结束。

3.2 增益求解

本部分将求解观测器增益和控制器增益。

定理2 对于给定的干扰抑制水平 γ , 常数 ε , 正标量 ρ , 增广系统(14)是渐近稳定的且满足 H_{∞} 一致性控制约束(16), 如果存在矩阵 $\tilde{H}$ 和 $\tilde{K}$, 正定对称矩阵 $\bar{P} > 0$ 使得以下不等式成立。

$$\begin{bmatrix} \hat{\tilde{E}} & * & * \\ \hat{\tilde{R}}_1^T & -\varepsilon P & * \\ \bar{R}_2 & 0 & -\varepsilon^{-1} I_{bNn_x} \end{bmatrix} < 0 \quad (28)$$

式中:

$$\begin{aligned} \hat{\tilde{E}} &\triangleq \begin{bmatrix} A_{11} & * & * & * \\ 0 & -\rho I_{bNn_x} & * & * \\ 0 & 0 & -\gamma^2 I_{bNn_x} & * \\ A_{51} & A_{52} & A_{53} & -P \end{bmatrix} \\ A_{11} &\triangleq \bar{D}_1 - P + \rho M, P \triangleq \text{diag}\{I_N \otimes \bar{P}, I_N \otimes \bar{P}\} \\ A_{51} &\triangleq \begin{bmatrix} I_N \otimes (\bar{P}\hat{A}) - L \otimes (\hat{B}\tilde{K}) & -L \otimes (\hat{B}\tilde{K}) \\ 0 & I_N \otimes (\bar{P}\hat{A}) - I_N \otimes (\tilde{H}\bar{C}) \end{bmatrix} \\ A_{52} &\triangleq \begin{bmatrix} -L \otimes (\hat{B}\tilde{K}) \\ 0 \\ 0 \end{bmatrix}, A_{53} \triangleq \begin{bmatrix} I_N \otimes (\bar{P}\hat{E}) & 0 \\ -I_N \otimes (\bar{P}\hat{E}) & I_N \otimes (\tilde{H}\bar{F}) \\ 0 & 0 \end{bmatrix} \\ \hat{\tilde{R}}_1 &\triangleq \begin{bmatrix} 0 & 0 & 0 \\ -L \otimes (\hat{B}\tilde{K}H_1) & -L \otimes (\hat{B}\tilde{K}H_1) & -L \otimes (\hat{B}\tilde{K}H_1) \end{bmatrix} \\ \bar{R}_2 &\triangleq \begin{bmatrix} R_2 & 0 \end{bmatrix}, R_2 \triangleq \text{diag}\{I_N \otimes G_1, I_N \otimes G_1, I_N \otimes G_1\} \end{aligned}$$

如果(28)是可行的, 观测器增益 H 及控制器增益 K 可以通过式(29)计算获得。

$$H = \bar{P}^{-1} \tilde{H}, \quad K = \tilde{P}^{-1} \tilde{K} = V \theta^{-1} \bar{P}_1^{-1} \theta V^T \tilde{K} \quad (29)$$

式中: $\bar{P}_1$ 根据式(3)计算。

证明 根据引理1及式(17)可得

$$\bar{\Xi} + \Delta \Xi < 0 \quad (30)$$

式中:

$$\begin{aligned} \bar{\Xi} &\triangleq \begin{bmatrix} A_{11} & * & * & * \\ 0 & -\rho I_{bNn_x} & * & * \\ 0 & 0 & -\gamma^2 I_{bNn_x} & * \\ \bar{A}_1 & \bar{B}_1 & E_1 & -P^{-1} \end{bmatrix} \\ R_1 &\triangleq \begin{bmatrix} -L \otimes (\hat{B}KH_1) & -L \otimes (\hat{B}KH_1) & -L \otimes (\hat{B}KH_1) \\ 0 & 0 & 0 \end{bmatrix} \\ \bar{F}_1 &\triangleq \text{diag}\{I_N \otimes F_1, I_N \otimes F_1, I_N \otimes F_1\} \\ \Delta \Xi &\triangleq \begin{bmatrix} 0 & * \\ R_1 \bar{F}_1 R_2 & 0 \end{bmatrix} \end{aligned}$$

定义 $\bar{R}_1 \triangleq \begin{bmatrix} 0 & R_1^T \end{bmatrix}^T$, 可以得到

$$\bar{\Xi} + \bar{R}_1 \bar{F}_1 \bar{R}_2 + \bar{R}_2^T \bar{F}_1^T \bar{R}_1^T < 0 \quad (31)$$

根据引理3可得

$$\bar{\Xi} + \varepsilon^{-1} \bar{R}_1 \bar{R}_1^T + \varepsilon \bar{R}_2^T \bar{R}_2 < 0 \quad (32)$$

由此可知不等式(33)成立

$$\begin{bmatrix} \bar{\Xi} & * & * \\ \bar{R}_1^T & -\varepsilon I_{bNn_x} & * \\ \bar{R}_2 & 0 & -\varepsilon^{-1} I_{bNn_x} \end{bmatrix} < 0 \quad (33)$$

利用 $\text{diag}\{I, I, I, P, I\}$ 对式(33)执行全等变换, 可以得到定理2。此外, 由 $P = \text{diag}\{I_N \otimes \bar{P}, I_N \otimes \bar{P}\}$ 及引理2可知 $\bar{P}\hat{B} = \hat{B}\tilde{P}$ 。通过定义 $\tilde{K} \triangleq \tilde{P}K$ 和 $\tilde{H} \triangleq \bar{P}H$, 则增益矩阵可以通过式(29)计算。证明结束。

注解3 本文建立了一个统一的框架来处理多速率多智能体系统在事件触发机制下的非脆弱一致性控制问题。多速率采样、事件触发机制以及控制器执行过程中的扰动大大增加了系统分析与控制器设计的困难, 这些因素所带来的影响最终都反映在了确保控制器存在的充分条件中。

4 仿真结果

本节将提供一个数值仿真例子来验证所提出控制方法的有效性。

考虑由3个智能体组成的多智能体系统, 其邻接矩阵 Q_Q 及拓扑结构(见图1)预设如下:

$$Q_Q = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

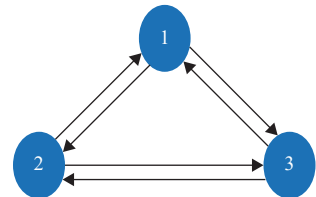


图1 拓朴结构

Fig.1 Topology

多智能体系统参数如下

$$\begin{aligned} A &= \begin{bmatrix} 0.9472 & -0.0598 \\ 0.1260 & 0.9525 \end{bmatrix}, \quad B = \begin{bmatrix} 0.4320 \\ 0.1845 \end{bmatrix} \\ E &= \begin{bmatrix} 0.0991 \\ 0.1023 \end{bmatrix}, \quad C = \begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix} \\ F &= \begin{bmatrix} 0.1 \\ 0.1 \end{bmatrix}, \quad D = \begin{bmatrix} 0.5 & 0.1 \end{bmatrix} \end{aligned}$$

设置 $T_m = m$ 和 $t_m = 2m$,所有智能体的初始值选择为 $\mathbf{x}_1(0) = [2.4 \ 1]^T, \mathbf{x}_2(0) = [-2 \ 0.5]^T, \mathbf{x}_3(0) = [-3.5 \ 1]^T$ 。观测器初始值设为 $\xi_1(0) = [0 \ 0]^T, \xi_2(0) = [0 \ 0]^T, \xi_3(0) = [0 \ 0]^T$ 。此外,其余相关参数设置为 $\gamma = 0.8, \rho = 0.4, \varepsilon = 1, \sigma_1 = 0.2, \sigma_2 = 0.3, \sigma_3 = 0.4$ 。过程噪声及测量噪声为 $\omega_1(k) = e^{-k}\sin(k), \omega_2(k) = e^{-0.1k}, \omega_3(k) = e^{-k}, v(k) = e^{-0.1k}$ 。

$$K = \begin{bmatrix} 0.0032 & 0.0099 & -0.0065 & -0.0066 \\ -1.5085 \times 10^{-7} & -3.1717 \times 10^{-7} & 2.6785 \times 10^{-7} & 2.0017 \times 10^{-7} \end{bmatrix}$$

仿真结果见图2~10。图2~3绘制了在非脆弱控制器控制下3个智能体的状态轨迹,其中 $x_{i\varsigma}(T_m)$ 表示第 i 智能体的第 ς 个状态($\varsigma = 1, 2$),从图中可以看出,随着时间的推移,状态最终趋于一致。图4~5绘制了在具有一般形式的控制器下3个智能体的状态轨迹。很明显,本文所提出的控制方法更加有效,体现了所提出控制方法的优越性。图6~7绘制了智能体 i 的测量输出,从图中可以看出采样时刻为 $0, 2, 4, \dots, 60$,测量输出的采样数只有状态的一半,降低了采样成本,体现了多速率策略的优势。图8~9展示了一致性误差 $\bar{z}(k) - \ell\bar{z}(k)$,随着时间推移,误差趋于0。此外,图10描绘了3个智能体的触发时刻,显然信息传输的次数和控制协议的更新次数明显减少,有效缓解了通信负担。

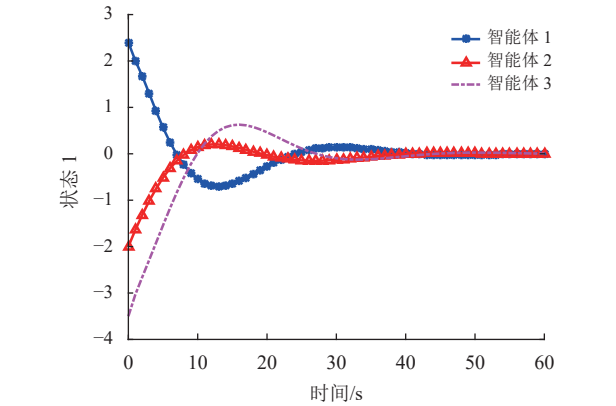


图 2 非脆弱控制器下3个智能体的状态轨迹 $x_{i1}(T_m)$

Fig.2 The state trajectories $x_{i1}(T_m)$ of the three agents under the non-fragile controller

控制器增益扰动的相关参数为

$$\begin{aligned} H_1 &= \begin{bmatrix} 1.0 & 1.0 & 1.0 & 1.0 \\ 0.6 & 0.6 & 0.6 & 0.6 \\ 0.9 & 0.9 & 0.9 & 0.9 \\ 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix} \\ G_1 &= \begin{bmatrix} 0.4 & 0.4 & 0.4 & 0.4 \\ 0.3 & 0.3 & 0.3 & 0.3 \\ 0.5 & 0.5 & 0.5 & 0.5 \\ 0.6 & 0.6 & 0.6 & 0.6 \end{bmatrix} \end{aligned}$$

根据定理2并利用MATLAB工具箱,观测器增益 H 及控制器增益 K 计算为

$$H = \begin{bmatrix} 1.1687 & -0.4195 & 1.1944 & -0.6001 \\ -0.2267 & 1.8153 & -0.1052 & 1.9323 \end{bmatrix}^T$$

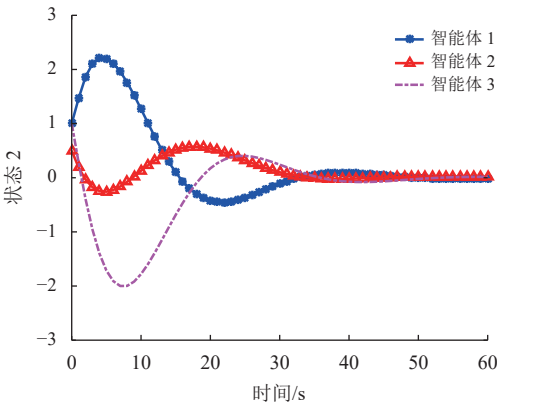


图 3 非脆弱控制器下3个智能体的状态轨迹 $x_{i2}(T_m)$

Fig.3 The state trajectories $x_{i2}(T_m)$ of the three agents under the non-fragile controller

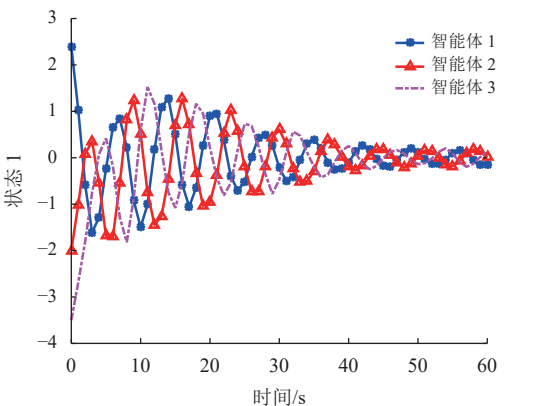


图 4 一般控制器下3个智能体的状态轨迹 $x_{i1}(T_m)$

Fig.4 The state trajectories $x_{i1}(T_m)$ of the three agents under the general controller

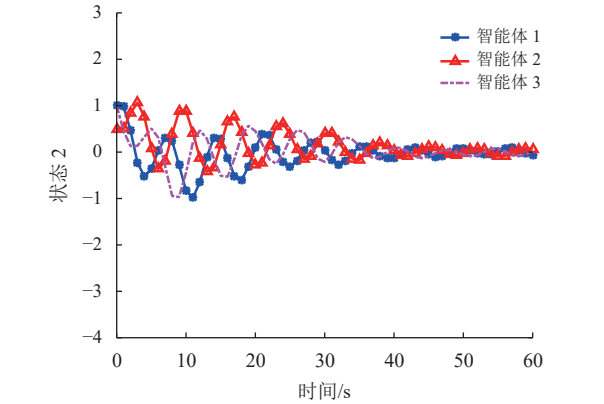


图5 一般控制器下3个智能体的状态轨迹 $x_{i2}(T_m)$

Fig.5 The state trajectories $x_{i2}(T_m)$ of the three agents under the general controller

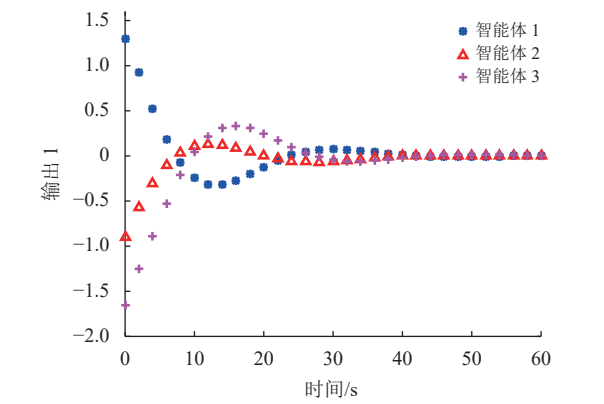


图6 3个智能体的测量输出 $y_{i1}(t_m)$

Fig.6 Measurement outputs $y_{i1}(t_m)$ of the three agents

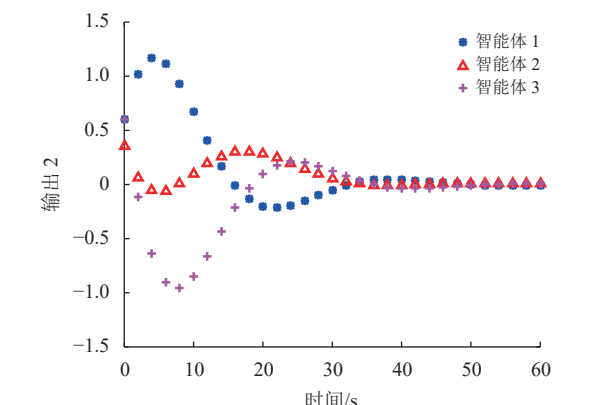


图7 3个智能体的测量输出 $y_{i2}(t_m)$

Fig.7 Measurement outputs $y_{i2}(t_m)$ of the three agents

5 结论

本文针对一类多速率多智能体系统,研究了在事件触发机制下的非脆弱 H_∞ 一致性控制问题。首先,利用提升技术将多速率多智能体系统统一为单速率多智能体系统。接下来,对比时间触发机制,提出了一种基于相对事件触发机制的分布式一致性控制方

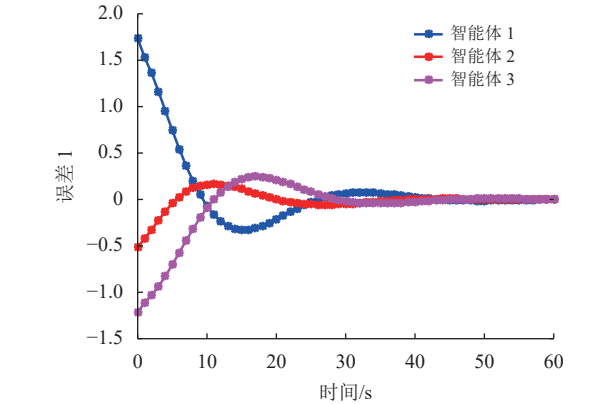


图8 一致性误差1

Fig.8 Consensus error 1

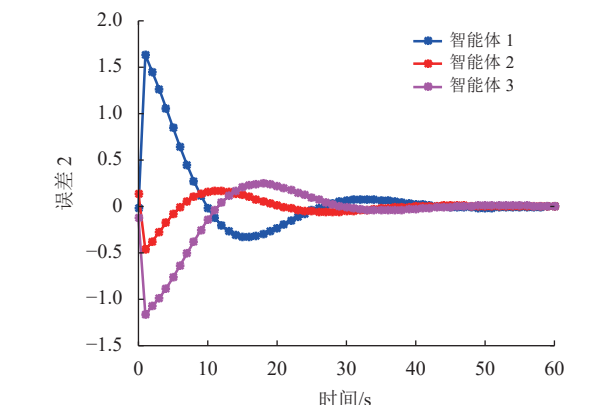


图9 一致性误差2

Fig.9 Consensus error 2

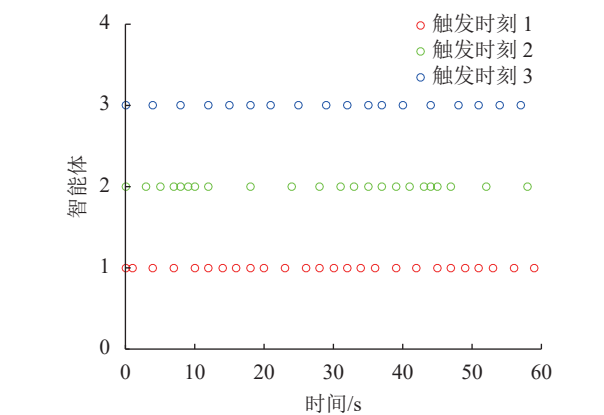


图10 3个智能体的触发时刻

Fig.10 Triggering instants of three agents

案,并且所设计的控制器具有非脆弱性。然后,利用Lyapunov稳定性理论,获得了增广系统渐近稳定且满足给定 H_∞ 一致性控制约束的充分条件。最后,通过数值例子验证了所提出控制方案的有效性。论文未来潜在的研究方向总结如下:(1) 提升技术的使用造成了大量计算负担,寻找更有效的方法来处理多速率系统;(2) 将研究结果扩展到更复杂的系统,如时

滞系统、马尔可夫跳变系统、T-S模糊系统和传感器网络;(3) 研究信道衰落、编码解码机制等对多智能体系统一致性控制问题的影响。

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