DOI:10.13878/j.cnki.jnuist.2019.04.003

王誉达[1]　查利娟[1,2]　刘金良[1]　费树岷[3]

基于事件触发和欺骗攻击的多智能体一致性控制

摘要

本文研究了基于事件触发和欺骗攻击的多智能体一致性问题.为了降低智能体间无线通信网络负载,本文引入事件触发机制来减少智能体之间通信的冗余数据传输量.由于智能体间无线通信网络易遭受网络攻击,因此考虑无线通信网络环境下欺骗攻击的影响,建立了一类基于事件触发和欺骗攻击的多智能体系统数学模型.基于此模型,通过利用Lyapunov稳定性理论、多智能体一致性理论和线性矩阵不等式技术分别给出多智能体一致性控制的稳定性条件和控制器设计算法.最后,通过仿真算例验证了所提出设计方法的有效性.

关键词

多智能体系统;一致性;事件触发;欺骗攻击

中图分类号 TP13;TP18

文献标志码 A

0　引言

在过去20年里,随着计算机技术、传感器技术、多智能体网络的发展,多智能体系统被逐渐应用到空气质量监测[1]、农业生产[2]、灾害监测与评估[3]等领域.值得注意的是,多智能体的协同控制是多智能体研究的基础,它具有较低的运作成本、较好的容错性、较高的鲁棒性、较强的机动性以及自适应性等不可比拟的优势.然而目前基于多智能体协同控制的研究面临着许多问题,例如同步问题、剧集蜂拥问题、编队控制问题等,这些问题归根结底都是一致性问题,而一致性问题又是多智能体协同控制中最具挑战性的问题之一.所谓的多智能体一致性研究是指智能体个体通过有限的局部信息来达到所有智能体状态一致的问题,其中一致性问题可以分为两类:领导-跟随型和无领导型.领导-跟随型是指在编队中选择一个或几个领导者,其余成员作为跟随者跟随领导者来保持状态一致;而无领导型则是针对智能体编队选择一个点作为所有智能体的参照点,以此来保持与所有智能体的状态一致.近年来,多智能体的一致性问题引起越来越多学者的关注[4-8].

在实际应用中,多个智能体之间通过无线通信网络交换彼此信息.由于多智能体自身能源和无线通信网络的带宽是有限的,因此,需要选择合适的信息传输机制来进行智能体之间通信.传统的时间触发机制是周期性地进行状态采样和信息传输,该机制简单且易于实现.但是当系统的运行性能处于良好的状态时,周期性地触发控制任务会使大量的冗余信息释放到有限带宽的通信网络中,这不仅会导致网络资源的浪费,更会减少智能体的续航时间.为了克服时间触发机制的不足,许多学者相继采用事件触发机制来节约网络资源[8-10].所谓的事件触发机制通过事先设定的触发条件来判别当前的数据是否被传输.现有的事件触发机制可以分为4种,自触发机制[9]、自适应事件触发机制[10]、动态事件触发机制[11]和离散事件触发机制[12].其中Yue等[12]提出的基于采样数据的离散事件触发机制考虑传输时延,它只检测离散时刻的系统状态,当采集的信号和上一个传输时刻的信号满足一定的触发条件才会传输数据.基于文献[12]提出的事件触发机制,诸多学者对事件触发问题进行深入的研究与应用[13-17].例如:文献[14]研究了不完全前提匹配的网络化非线性系统的事件触发预测控制问题;文献[15]研究了基于事件触发的分布式传感网络滤波

收稿日期 2019-05-28

资助项目 国家自然科学基金(61903182);中国博士后科学基金(2019M651651);江苏省省属高校自然科学研究面上项目(18KJB120002)

作者简介

王誉达,男,硕士生,研究方向为网络化控制系统.wangyd1996@163.com

查利娟(通信作者),女,博士,讲师,研究方向为网络化控制系统、非线性系统及复杂网络.zhalijuan@vip.163.com

1　南京财经大学　信息工程学院,南京,210023

2　东南大学　数学学院,南京,210096

3　东南大学　自动化学院,南京,210096

问题;文献[16]则整合该事件触发机制和时间触发机制,提出一类混合触发机制,并研究了混合触发机制下 T-S 模糊系统的量化镇定问题.在考虑有限通信资源的前提下,文献[17]研究了事件触发下时滞神经网络的状态估计问题.

网络使得智能体之间的通信方便快捷,但同时由于其开放性给多智能体的控制带来时延、丢包等诸多挑战.而作为影响网络安全最重要的因素之一,网络攻击将会使智能体的通信信息被窃取篡改,进而导致智能体性能下降,甚至完不成预期任务.网络攻击的主要形式有拒绝服务(DoS)攻击[18]、重放攻击[19]、欺骗攻击[20]等.其中,DoS 攻击对系统造成的危害主要在于阻止信息及时传输,即造成系统传输信息的丢失.重放攻击中,攻击者会在一定时间内恶意地重复传输系统已接受过的数据,造成系统多次执行不必要的操作,从而达到破坏系统性能的目的.相比以上两种攻击形式,欺骗攻击是较难发现和预防的,此类攻击通过影响数据的完整性来达到其预期目的,其攻击者将伪造数据注入到正常的数据传输中,往往这些数据会导致系统的信息被窃取或者替换,最终破坏系统的稳定性或使系统完成攻击者的指令.近年来,欺骗攻击成为网络安全的热点问题,受到许多学者的广泛关注.例如:文献[20]分析了欺骗攻击对基于分散事件触发 H_∞ 控制的神经网络的影响;文献[21]研究了在欺骗攻击下基于离散时间随机非线性系统的安全控制问题;文献[22]考虑了欺骗攻击的影响,研究了一类离散时滞的分布式递归滤波问题.

基于上述分析,本文针对有领导者的多智能体,考虑欺骗攻击对多智能体之间通信网络的影响,利用多智能体一致性理论进一步研究基于事件触发的多智能体一致性问题.最后,通过数值算例对本文所提的设计方法的有效性进行验证.

注 1 在本文中,$\mathbf{R}^m$ 代表 m 维的欧式空间,$\|\cdot\|$ 代表向量的欧式范数,$\boldsymbol{I}_m$ 为 m 维单位矩阵,符号 $\boldsymbol{S}=\mathrm{diag}\{\cdot\}$ 代表 $\boldsymbol{S}$ 为分块对角矩阵,$\otimes$ 表示 Kronecker 乘积,$\boldsymbol{A}>0$ 表示矩阵 $\boldsymbol{A}$ 为实正定矩阵.对于矩阵 $\boldsymbol{B}$ 与两个对称矩阵 $\boldsymbol{A},\boldsymbol{C}$,$\begin{pmatrix}\boldsymbol{A} & * \\ \boldsymbol{B} & \boldsymbol{C}\end{pmatrix}$ 表示一个对称矩阵,其中 $*$ 表示 $\boldsymbol{B}$ 的转置矩阵.

1 系统模型

1.1 图理论

有向图 $F(\boldsymbol{W})=(V,E,\boldsymbol{W})$ 由 V 个顶点、一系列有向边 $E=\{e_{ij}=(v_i,v_j)\}\subset V\times V$ 和一个具有非负项的加权邻接矩阵 $\boldsymbol{W}=[a_{ij}]$ 组成.边 $e_{ij}=(v_i,v_j)$ 表示智能体 j 收到智能体 i 的信息,但是反之则不一定.如果 $e_{ij}\in E$,则可以说智能体 i 是智能体 j 的邻居.$N_i=\{v_j\mid e_{ji}=(v_j,v_i)\}$ 表示节点 v_i 的邻居集合.从 v_i 到 v_j 的有向路径是边的序列 $(v_i,v_{i1}),(v_{i1},v_{i2}),\cdots,(v_{il},v_j)$,这些边具有不同的顶点 $v_{ik},k=1,2,\cdots,l$.有向图如果有一个根节点存在一条从该根节点到其他节点的有向路径,则该有向图包含一棵有向生成树.N 个智能体的通信网络的邻接矩阵是 $\boldsymbol{W}=[a_{ij}]\in\mathbf{R}^{N\times N}$,其中 $a_{ij}>0$ 表示 $(v_j,v_i)\in E$,否则 $a_{ij}=0$.这里假设对于所有的 $i\in V$ 有 $a_{ii}=0$.此外,定义该有向图的 Laplacian 矩阵 $\boldsymbol{L}=[l_{ij}]$,其中 $l_{ij}=-\sum_{j=1,j\neq i}^{N}l_{ij}$,$l_{ij}=-a_{ij},i\neq j$.

为了更清晰地解释邻接矩阵,这里给出如下 4 阶邻接矩阵:

$$\boldsymbol{W}=\begin{bmatrix}0&1&0&0\\1&0&1&0\\0&0&0&1\\1&0&1&0\end{bmatrix}.$$

如图 1 所示,智能体 2、智能体 4 能够接收到智能体 1 的信息,即智能体 1 的信息通过事件发生器后,经过无线网络成功传输到智能体 2 和智能体 4.智能体 2 的信息能够被智能体 1 成功接收;智能体 3 的信息能够被智能体 2 和智能体 4 成功接收;智能体 4 的信息能够被智能体 3 成功接收.

1.2 系统模型描述

该多智能体系统由 N 个如下的智能体组成,每个智能体标号为 $1,2,\cdots,N$,虚拟智能体领导者标号为 0.单个智能体建模[23]如下:

$$\begin{cases}\dot{\boldsymbol{x}}_i(t)=\boldsymbol{A}\boldsymbol{x}_i(t)+\boldsymbol{C}\boldsymbol{g}(\boldsymbol{x}_i(t),t)+\boldsymbol{B}\boldsymbol{u}_i(t),\\ \dot{\boldsymbol{x}}_0(t)=\boldsymbol{A}\boldsymbol{x}_0(t)+\boldsymbol{C}\boldsymbol{g}(\boldsymbol{x}_0(t),t),\end{cases}\tag{1}$$

其中,$\boldsymbol{x}_i(t)\in\mathbf{R}^m$ 是智能体 i 的状态,$\boldsymbol{g}(\boldsymbol{x}_i(t),t)\in\mathbf{R}^n$ 代表其非线性动态函数,$\boldsymbol{u}_i(t)\in\mathbf{R}^m$ 是智能体 i 的控制输入.$\boldsymbol{A},\boldsymbol{B},\boldsymbol{C}$ 都是具有合适维度的常数矩阵.为方便后续研究,假设存在领导者 $\boldsymbol{x}_0(t)$,初始条件为 $\boldsymbol{x}_{i0}=\boldsymbol{x}_i(0),i\in S_N$.

假设 1 智能体的非线性动态函数 $\boldsymbol{g}(\boldsymbol{x})$ 满足 Lipschitz 条件,即存在一个非负实数 l,有

$$\|\boldsymbol{g}(\boldsymbol{x})-\boldsymbol{g}(\boldsymbol{y})\|\leqslant l\|\boldsymbol{x}-\boldsymbol{y}\|.\tag{2}$$

如图 1 所示,本文的目的是针对多智能体一致性问题进行研究,给出基于事件触发和欺骗攻击下

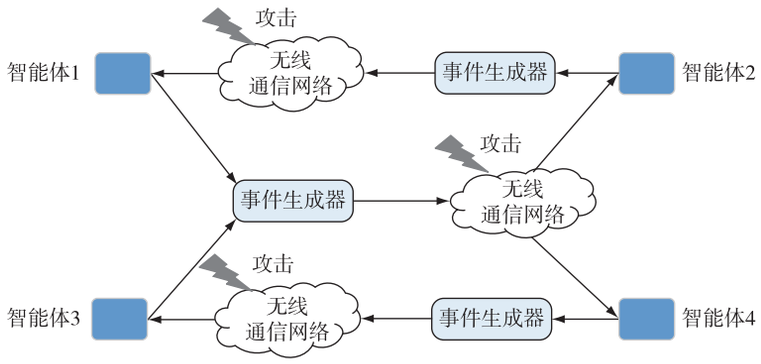


图 1　基于事件触发和欺骗攻击的多智能体通信流程

Fig. 1　Communication flow chart of agents with event triggering and deception attack

的控制器设计方案.设计如下的控制器:

$$\boldsymbol{u}_i(t) = -\boldsymbol{K}\{\sum_{j\in N_i} a_{ij}[\boldsymbol{x}_i(t) - \hat{\boldsymbol{x}}_j(t)] + b_i(\boldsymbol{x}_i(t) - \boldsymbol{x}_0(t))\}, \tag{3}$$

其中,$\boldsymbol{K}$ 是控制器增益,a_{ij} 是邻接矩阵 $\boldsymbol{W}$ 的第(i,j)条记录,$b_i \geqslant 0$ 是智能体 i 与领导者 $\boldsymbol{x}_0$ 之间的耦合权重,即 b_i 的定义为:$b_i\begin{cases} >0, i\in\mathcal{A}, \\ =0, \text{其他}. \end{cases}$其中 $\mathcal{A}=\{i \mid$ 智能体 i 能接收到来自领导者 $\boldsymbol{x}_0$ 的信息$\}$.

1.3　事件触发

本文假设智能体的数据信息由采样器采样后传输,假定采样器是时间驱动的,采样周期为 h,采样时刻可以表示为 $kh(k=0,1,2,\cdots)$.周期性采样会导致传输大量冗余数据,造成智能体间无线通信网络拥塞和通信资源浪费.为解决这些问题,引入事件触发机制决定当前本地数据是否应该被传输.具体来说,当本地数据违背预先给定的事件触发条件时,则该数据便被传输;当本地数据满足预设的事件触发条件反而会被丢弃不传.本文考虑如下的事件触发条件[12]:

$$\boldsymbol{e}_i^{\mathrm{T}}(t)\boldsymbol{\Omega}_i\boldsymbol{e}_i(t) \geqslant \lambda_i \boldsymbol{x}_i^{\mathrm{T}}(t_kh+\nu h)\boldsymbol{\Omega}_i\boldsymbol{x}_i(t_kh+\nu h), \tag{4}$$

其中,$\lambda_i \in [0,1)$,$\boldsymbol{\Omega}_i$ 是具有合适维度的矩阵,t_kh 表示当前数据采样的前一时刻,$t_kh+\nu h$ 表示当前的采样时刻,故而最近被传输的数据和当前采样的数据被分别表示为 $\boldsymbol{x}_i(t_kh)$ 和 $\boldsymbol{x}_i(t_kh+\nu h)$.

由于智能体间无线通信网络的存在,网络诱导时滞不可避免.本文采用文献[16]中的方法,定义第 t_kh 传输时刻产生的网络诱导时滞为 τ_k,下面将分为两种情况讨论:

情况 1.当 $\tau_kh+h+\tau_m \geqslant \tau_{k+1}h+\tau_{k+1}$ 时,其中 $\tau_m=\max\{\tau_k\}$,定义如下实变函数:

$$\tau(t) = t - t_kh, \quad t\in[\tau_kh+\tau_k, \tau_{k+1}h+\tau_{k+1}), \tag{5}$$

则 $\tau(t)$ 满足 $0\leqslant\tau_k\leqslant\tau(t)\leqslant(\tau_{k+1}-\tau_k)h+\tau_{k+1}\leqslant h+\tau_m$.

情况 2.当 $\tau_kh+h+\tau_m < \tau_{k+1}h+\tau_{k+1}$ 时,相邻两个智能体的通信时间间隔可分为 3 类区间进行讨论,即$[\tau_kh+\tau_k, \tau_{k+1}h+\tau_{k+1}) = [\tau_kh+\tau_k, \tau_kh+h+\tau_m) \cup [\tau_kh+\nu h+\tau_m, \tau_kh+\nu h+h+\tau_m) \cup [\tau_kh+\theta_Mh+\tau_m, \tau_{k+1}h+\tau_{k+1})$,其中 $\nu=1,2,\cdots,\theta_M-1,\theta_M$ 是整数.定义函数:

$$\tau(t)=\begin{cases} t-t_kh, & t\in[\tau_kh+\tau_k, \tau_kh+h+\tau_m), \\ t-t_kh-\nu h, & t\in[\tau_kh+\nu h+\tau_m, \tau_kh+\nu h+h+\tau_m), \nu=1,2,\cdots,\theta_M-1, \\ t-t_kh-\theta_Mh, & t\in[\tau_kh+\theta_Mh+\tau_m, \tau_{k+1}h+\tau_{k+1}), \end{cases} \tag{6}$$

则由上述 $\tau(t)$ 的定义可知 $0\leqslant\tau_k\leqslant\tau(t)\leqslant h+\tau_m \triangleq \tau_M$,$t\in[i_k^{\nu}h+\tau_{i_k^{\nu}}, i_k^{\nu}h+h+\tau_{i_k^{\nu}+1})$,$\tau_M$ 是一个常数,表示采样数据传输的时滞上界.

结合上述两种情况,定义误差向量为 $\boldsymbol{e}_i(t)=\boldsymbol{x}_i(t_kh)-\boldsymbol{x}_i(t_kh+\nu h)$.具体来说,在情况 1 下,$\boldsymbol{e}_i(t)=0$.在情况 2 中,定义:

$$\boldsymbol{e}_i(t)=\begin{cases} 0, & t\in[\tau_kh+\tau_k, \tau_kh+h+\tau_m), \\ \boldsymbol{x}_i(t_kh)-\boldsymbol{x}_i(t_kh+\nu h), & t\in[\tau_kh+\nu h+\tau_m, \tau_kh+\nu h+h+\tau_m), \nu=1,2,\cdots,\theta_M-1, \\ \boldsymbol{x}_i(t_kh)-\boldsymbol{x}_i(t_kh+\theta_Mh), & t\in[\tau_kh+\theta_Mh+\tau_m, \tau_{k+1}h+\tau_{k+1}). \end{cases} \tag{7}$$

因此,当前时刻被传输的数据信息为

$$\bar{\boldsymbol{x}}_i(t)=\boldsymbol{x}_i(t-\tau(t))+\boldsymbol{e}_i(t). \tag{8}$$

注 2　在式(4)中,$\lambda_i\in[0,1)$ 是事件发生器 i 对采集到的智能体 i 的信息进行判断是否应该被传输的参数,它决定事件触发的频率.当 $\lambda_i=0$ 时,所有

的采样数据都被释放传输,传输数据为 $\bar{\boldsymbol{x}}_i(t)=\boldsymbol{x}_i(t)$;当 $\lambda_i\in[0,1)$ 时,有违背不等式(4)的数据才被传输,传输数据为 $\bar{\boldsymbol{x}}_i(t)=\boldsymbol{x}_i(t-\tau(t))+\boldsymbol{e}_i(t)$.

1.4 欺骗攻击

由于智能体间无线通信网络的开放性,网络易遭受网络攻击.通常,网络攻击目的是更改或阻断智能体无线通信网络中传输的数据,降低无线网络传输的可靠性[15].本文考虑的欺骗攻击是一种更改智能体无线通信网络中传输数据的网络攻击,以达到其降低智能体间无线通信信息传输可靠性的目的.本文假设欺骗攻击能够获取从智能体 j_i 到智能体 i 即将通过网络传输的信号,并通过非线性函数 $\boldsymbol{f}(\boldsymbol{x}_i(t))$ 对该传输信号进行更改.

鉴于欺骗攻击随机发生,于是文中采用随机变量 $\sigma(t)\in\{0,1\}$ 描述欺骗攻击是否发生,且 $\sigma(t)$ 满足 Bernoulli 分布.为了讨论方便,假定随机变量满足以下统计特性:期望 $\mathbb{E}\{\sigma(t)\}=\bar{\sigma}$,方差 $\mathbb{E}\{(\sigma(t)-\bar{\sigma})^2\}=\varepsilon^2$.本文讨论的是在给定欺骗攻击发生概率的前提下,欺骗攻击对智能体间通信信息传输的影响.于是,智能体 i 接收到来自智能体 j_i 的信号为

$$\hat{\boldsymbol{x}}_j(t)=\sigma(t)\boldsymbol{f}(\boldsymbol{x}_j(t-\eta(t)))+(1-\sigma(t))\bar{\boldsymbol{x}}_j(t),\tag{9}$$

其中,$\eta(t)$ 表示攻击发生时攻击信号被智能体间无线通信网络传输产生的时滞,$\sigma(t)$ 表示欺骗攻击是否发生,是一个随机变量.当 $\sigma(t)=1$ 时,攻击发生;当 $\sigma(t)=0$ 时,攻击未发生.

注 3 近年来,由于无线通信网络的广泛应用及科学技术的迅猛发展,无线通信网络的网络安全问题引起学者们的广泛关注.在现有文献中,研究者们针对网络攻击下若干系统的控制综合问题进行研究[18,22,24].然而,对多智能体间通信的安全问题研究目前还不够充分.基于此,本文对无线通信网络遭受欺骗攻击下的多智能体一致性进行研究.

注 4 在式(8)和式(9)中,$\tau(t)\in[0,\tau_M]$ 是数据在智能体间无线通信网络中传输的时滞,$\eta(t)$ 是攻击发生时攻击信号被智能体之间无线通信网络传输产生的时滞,同样本文假定 $\eta(t)$ 满足 $0\leqslant\eta(t)\leqslant\eta_M$,$\eta_M$ 是常数,代表智能体间无线通信网络攻击信号的时滞上界.

1.5 多智能体一致性模型

令 $\boldsymbol{\delta}_i(t)=\boldsymbol{x}_i(t)-\boldsymbol{x}_0(t)$,根据式(1)、(3)、(8)和(9),有误差系统:

$$\begin{aligned}\dot{\boldsymbol{\delta}}_i(t)=&\boldsymbol{A}\boldsymbol{x}_i(t)-\boldsymbol{A}\boldsymbol{x}_0(t)+\boldsymbol{C}\boldsymbol{g}(\boldsymbol{x}_i(t),t)-\\&\boldsymbol{C}\boldsymbol{g}(\boldsymbol{x}_0(t),t)-\boldsymbol{B}\boldsymbol{K}\{\sum_{j\in N_i}a_{ij}[\bar{\boldsymbol{x}}_i(t)-\hat{\boldsymbol{x}}_j(t)]+\\&b_i(\bar{\boldsymbol{x}}_i(t)-\boldsymbol{x}_0(t))\}.\end{aligned}\tag{10}$$

定义如下增广矩阵:

$$\begin{cases}\boldsymbol{\delta}(t)=[\boldsymbol{\delta}_1^{\mathrm{T}}(t),\boldsymbol{\delta}_2^{\mathrm{T}}(t),\cdots,\boldsymbol{\delta}_N^{\mathrm{T}}(t)]^{\mathrm{T}},\\ \boldsymbol{e}(t)=[\boldsymbol{e}_1^{\mathrm{T}}(t),\boldsymbol{e}_2^{\mathrm{T}}(t),\cdots,\boldsymbol{e}_N^{\mathrm{T}}(t)]^{\mathrm{T}},\\ \boldsymbol{g}(\boldsymbol{x}(t),t)=[\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_1(t),t)-\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_0(t),t),\cdots,\\ \quad\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_N(t),t)-\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_0(t),t)]^{\mathrm{T}},\\ \boldsymbol{F}(\boldsymbol{x}(t-\eta(t)))=[\boldsymbol{f}^{\mathrm{T}}(\boldsymbol{x}_1(t-\eta(t))),\\ \quad\boldsymbol{f}^{\mathrm{T}}(\boldsymbol{x}_2(t-\eta(t))),\cdots,\boldsymbol{f}^{\mathrm{T}}(\boldsymbol{x}_N(t-\eta(t)))]^{\mathrm{T}},\\ \boldsymbol{x}(t)=[\boldsymbol{x}_1^{\mathrm{T}}(t),\boldsymbol{x}_2^{\mathrm{T}}(t),\cdots,\boldsymbol{x}_N^{\mathrm{T}}(t)]^{\mathrm{T}},\\ \hat{\boldsymbol{B}}=\mathrm{diag}\{b_1,b_2,\cdots,b_N\}.\end{cases}$$

则根据式(10),有

$$\begin{aligned}\dot{\boldsymbol{\delta}}(t)=&(\boldsymbol{I}_N\otimes\boldsymbol{A})\boldsymbol{\delta}(t)+(\boldsymbol{I}_N\otimes\boldsymbol{C})\boldsymbol{g}(\boldsymbol{x}(t),t)-\\&\boldsymbol{I}_N\otimes\boldsymbol{B}\{(\boldsymbol{L}\otimes\boldsymbol{K})\boldsymbol{x}(t-\tau(t))+(\boldsymbol{D}\otimes\boldsymbol{K})\boldsymbol{e}(t)-\\&\alpha(t)(\boldsymbol{W}\otimes\boldsymbol{K})\boldsymbol{F}(t-\eta(t))+\alpha(t)(\boldsymbol{W}\otimes\boldsymbol{K})\boldsymbol{x}(t-\\&\tau(t))-(1-\alpha(t))(\boldsymbol{W}\otimes\boldsymbol{K})\boldsymbol{e}(t)+\\&(\hat{\boldsymbol{B}}\otimes\boldsymbol{K})\boldsymbol{\delta}(t-\tau(t))-(\hat{\boldsymbol{B}}\otimes\boldsymbol{K})\boldsymbol{e}(t)\}.\end{aligned}\tag{11}$$

定义

$$\begin{cases}\boldsymbol{\xi}(t)=\begin{bmatrix}\boldsymbol{x}(t)\\ \boldsymbol{\delta}(t)\end{bmatrix},\ \bar{\boldsymbol{A}}=\begin{bmatrix}\boldsymbol{I}_N\otimes\boldsymbol{A}&0\\0&\boldsymbol{I}_N\otimes\boldsymbol{A}\end{bmatrix},\\ \bar{\boldsymbol{B}}=\begin{bmatrix}\boldsymbol{I}_N\otimes\boldsymbol{B}&0\\0&\boldsymbol{I}_N\otimes\boldsymbol{B}\end{bmatrix},\ \bar{\boldsymbol{C}}=\begin{bmatrix}\boldsymbol{I}_N\otimes\boldsymbol{C}&0\\\boldsymbol{I}_N\otimes\boldsymbol{C}&-\boldsymbol{I}_N\otimes\boldsymbol{C}\end{bmatrix},\\ \bar{\boldsymbol{L}}_1=\begin{bmatrix}\boldsymbol{L}&\hat{\boldsymbol{B}}\\0&\bar{\boldsymbol{L}}\end{bmatrix},\ \bar{\boldsymbol{L}}_2=\begin{bmatrix}\bar{\boldsymbol{L}}\\\bar{\boldsymbol{L}}\end{bmatrix},\ \bar{\boldsymbol{W}}_1=\begin{bmatrix}\boldsymbol{W}\\\boldsymbol{W}\end{bmatrix},\\ \bar{\boldsymbol{W}}_2=\begin{bmatrix}\boldsymbol{W}&0\\\boldsymbol{W}&0\end{bmatrix},\ \bar{\boldsymbol{g}}(\boldsymbol{x}(t),t)=\begin{bmatrix}\boldsymbol{G}(\boldsymbol{x}(t),t)\\\boldsymbol{G}(\boldsymbol{x}_0(t),t)\end{bmatrix},\\ \boldsymbol{G}(\boldsymbol{x}(t),t)=[\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_1(t),t),\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_2(t),t),\cdots,\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_N(t),t)]^{\mathrm{T}},\\ \boldsymbol{G}(\boldsymbol{x}_0(t),t)=[\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_0(t),t),\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_0(t),t),\cdots,\boldsymbol{g}^{\mathrm{T}}(\boldsymbol{x}_0(t),t)]^{\mathrm{T}},\\ \boldsymbol{K}_1=\boldsymbol{I}_{2N}\otimes\boldsymbol{K},\ \boldsymbol{K}_2=\boldsymbol{I}_N\otimes\boldsymbol{K}.\end{cases}$$

进而由式(11)可得:

$$\begin{aligned}\dot{\bar{\boldsymbol{\xi}}}(t)=&\bar{\boldsymbol{A}}\bar{\boldsymbol{\xi}}(t)+\bar{\boldsymbol{C}}\bar{\boldsymbol{g}}(\boldsymbol{x}(t),t)-[\bar{\boldsymbol{B}}\bar{\boldsymbol{L}}_1\boldsymbol{K}_1+\\&\sigma(t)\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_2\boldsymbol{K}_1]\bar{\boldsymbol{\xi}}(t-\tau(t))-[\bar{\boldsymbol{B}}\bar{\boldsymbol{L}}_2\boldsymbol{K}_2+\\&\sigma(t)\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2]\boldsymbol{e}(t)+\sigma(t)\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2\boldsymbol{F}(t-\eta(t)).\end{aligned}\tag{12}$$

注 5 在系统(12)中,本文对基于事件触发和欺骗攻击的多智能体一致性问题进行一体化联合设计.不同于现有对多智能体的研究,本文考虑欺骗攻击对多智能体间无线通信的影响,引入事件触发机制减少通信数据传输量,研究基于事件触发机制和欺骗攻击的多智能体一致性问题.

接下来,给出一个假设和两个引理来帮助后面的理论分析.

假设 2[24] 欺骗攻击函数 $\boldsymbol{f}(\boldsymbol{x})$ 满足如下条件:

$$\|\boldsymbol{f}(\boldsymbol{x}(t))\|_2 \leqslant \|\boldsymbol{F}\boldsymbol{x}(t)\|_2, \tag{13}$$

其中 $\boldsymbol{F}$ 为实数常量矩阵.

引理 1[16] 假设 $\tau(t) \in [0,\tau_M]$,对于任意常数矩阵 $\boldsymbol{R} \in \mathbf{R}^{m\times m}$ 和 $\boldsymbol{M} \in \mathbf{R}^{m\times m}$ 满足 $\begin{bmatrix} \boldsymbol{R} & * \\ \boldsymbol{M} & \boldsymbol{R} \end{bmatrix} \geqslant 0$,有如下等式成立:

$$-\tau_M\int_{t-\tau_M}^{t} \dot{\boldsymbol{x}}^{\mathrm{T}}(s)\boldsymbol{R}\dot{\boldsymbol{x}}(s)\mathrm{d}s \leqslant \boldsymbol{\psi}^{\mathrm{T}}(t)\begin{bmatrix} -\boldsymbol{R} & * & * \\ \boldsymbol{R}+\boldsymbol{M} & -2\boldsymbol{R}-\boldsymbol{M}-\boldsymbol{M}^{\mathrm{T}} & * \\ -\boldsymbol{M} & \boldsymbol{R}+\boldsymbol{M} & -\boldsymbol{R} \end{bmatrix}\boldsymbol{\psi}(t), \tag{14}$$

其中 $\boldsymbol{\psi}(t) = [\boldsymbol{x}^{\mathrm{T}}(t), \boldsymbol{x}^{\mathrm{T}}(t-\tau(t)), \boldsymbol{x}^{\mathrm{T}}(t-\tau_M)]^{\mathrm{T}}$.

引理 2[25] 对于任意正定矩阵 $\boldsymbol{R},\boldsymbol{P}$ 和标量 γ,有如下不等式成立:

$$-\boldsymbol{P}\boldsymbol{R}^{-1}\boldsymbol{P} \leqslant -2\gamma\boldsymbol{P} + \gamma^2\boldsymbol{R}. \tag{15}$$

2 定理

定理 1 对于给定的事件触发参数 $\lambda_i (i = 1,2,\cdots,N)$,时滞上界 τ_M,η_M,标量 μ,欺骗攻击的概率期望 $\bar{\sigma}$,以及增益矩阵 $\boldsymbol{K}$ 和攻击上界矩阵 $\boldsymbol{F}$,如果存在正定矩阵 $\boldsymbol{P} > 0, \boldsymbol{Q}_1 > 0, \boldsymbol{Q}_2 > 0, \boldsymbol{R}_1 > 0, \boldsymbol{R}_2 > 0, \boldsymbol{\Omega}_i > 0 (i = 1,2,\cdots,N)$,合适维度的矩阵 $\boldsymbol{M},\boldsymbol{N}$,使得下面矩阵不等式成立:

$$\boldsymbol{\jmath} = \begin{bmatrix} \boldsymbol{\Gamma}_1 & * & * \\ \boldsymbol{\Gamma}_2 & \boldsymbol{\Gamma}_3 & * \\ \boldsymbol{\Gamma}_4 & 0 & \boldsymbol{\Gamma}_5 \end{bmatrix} < 0, \tag{16}$$

其中,

$$\boldsymbol{\Gamma}_1 = \begin{pmatrix} \boldsymbol{\Psi}_1 & * & * \\ \boldsymbol{\Psi}_2 & \boldsymbol{\Psi}_3 & * \\ \boldsymbol{\Psi}_4 & 0 & \boldsymbol{\Psi}_5 \end{pmatrix},$$

$$\boldsymbol{\Psi}_1 = \begin{pmatrix} \boldsymbol{\Gamma}_6 & * & * \\ \boldsymbol{\Gamma}_7 & \boldsymbol{\Gamma}_8 & * \\ -\boldsymbol{M} & \boldsymbol{R}_1+\boldsymbol{M} & -\boldsymbol{Q}_1-\boldsymbol{R}_1 \end{pmatrix},$$

$$\boldsymbol{\Psi}_2 = \begin{bmatrix} \boldsymbol{R}_2+\boldsymbol{N} & 0 & 0 \\ -\boldsymbol{N} & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{\Psi}_3 = \begin{pmatrix} -\boldsymbol{R}_2-\boldsymbol{N}-\boldsymbol{N}^{\mathrm{T}} & * \\ \boldsymbol{R}_2+\boldsymbol{N} & -\boldsymbol{Q}_2-\boldsymbol{R}_2 \end{pmatrix},$$

$$\boldsymbol{\Psi}_4 = \begin{pmatrix} \bar{\boldsymbol{C}}^{\mathrm{T}}(\boldsymbol{I}_{2N}\otimes\boldsymbol{P}) & 0 & 0 \\ \boldsymbol{\Gamma}_9 & 0 & 0 \\ \boldsymbol{\Gamma}_{10} & 0 & 0 \end{pmatrix},$$

$$\boldsymbol{\Psi}_5 = \mathrm{diag}\{-\boldsymbol{I}, -\boldsymbol{H}_1^{\mathrm{T}}\boldsymbol{\Omega}\boldsymbol{H}_1, -\boldsymbol{I}\},$$

$$\boldsymbol{\Gamma}_2 = [\boldsymbol{\Psi}_6, \boldsymbol{\Psi}_7],$$

$$\boldsymbol{\Psi}_6 = \begin{bmatrix} 0 & 0 & 0 & \boldsymbol{F}\boldsymbol{H}_1 \\ \mu\boldsymbol{H}_2 & 0 & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{\Psi}_7 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{\Gamma}_4 = [\boldsymbol{\Gamma}_{11}, 0, 0, 0, 0, \boldsymbol{\Gamma}_{12}],$$

$$\boldsymbol{\Gamma}_6 = \boldsymbol{I}_{2N}\otimes(\boldsymbol{P}\boldsymbol{A} + \boldsymbol{A}^{\mathrm{T}}\boldsymbol{P}) + \boldsymbol{Q}_1 + \boldsymbol{Q}_2 - \boldsymbol{R}_1 - \boldsymbol{R}_2,$$

$$\boldsymbol{\Gamma}_7 = -\bar{\boldsymbol{K}}_1^{\mathrm{T}}\bar{\boldsymbol{L}}_1^{\mathrm{T}}\bar{\boldsymbol{B}}^{\mathrm{T}}(\boldsymbol{I}_{2N}\otimes\boldsymbol{P}) - \bar{\sigma}\bar{\boldsymbol{K}}_1^{\mathrm{T}}\bar{\boldsymbol{W}}_2^{\mathrm{T}}\bar{\boldsymbol{B}}^{\mathrm{T}}(\boldsymbol{I}_{2N}\otimes\boldsymbol{P}) + \boldsymbol{R}_1 + \boldsymbol{M},$$

$$\boldsymbol{\Gamma}_8 = \lambda\boldsymbol{H}_1^{\mathrm{T}}\boldsymbol{\Omega}\boldsymbol{H}_1 - 2\boldsymbol{R}_1 - \boldsymbol{M} - \boldsymbol{M}^{\mathrm{T}},$$

$$\boldsymbol{\Gamma}_9 = -\bar{\boldsymbol{K}}_2^{\mathrm{T}}\bar{\boldsymbol{L}}_2^{\mathrm{T}}\bar{\boldsymbol{B}}^{\mathrm{T}}(\boldsymbol{I}_{2N}\otimes\boldsymbol{P}) - \bar{\sigma}\bar{\boldsymbol{K}}_2^{\mathrm{T}}\bar{\boldsymbol{W}}_1^{\mathrm{T}}\bar{\boldsymbol{B}}^{\mathrm{T}}(\boldsymbol{I}_{2N}\otimes\boldsymbol{P}),$$

$$\boldsymbol{\Gamma}_{10} = \bar{\sigma}\bar{\boldsymbol{K}}_2^{\mathrm{T}}\bar{\boldsymbol{W}}_1^{\mathrm{T}}\bar{\boldsymbol{B}}^{\mathrm{T}}(\boldsymbol{I}_{2N}\otimes\boldsymbol{P}),$$

$$\boldsymbol{H}_1 = [\boldsymbol{I}_{N\times n}, 0_{N\times n}], \quad \boldsymbol{H}_2 = [0_{N\times n}, \boldsymbol{I}_{N\times n}],$$

$$\boldsymbol{\Gamma}_3 = \mathrm{diag}\{-\boldsymbol{I}, -\boldsymbol{I}\},$$

$$\boldsymbol{\Gamma}_{12} = \begin{bmatrix} -\tau_M[\bar{\boldsymbol{B}}\bar{\boldsymbol{L}}_2\boldsymbol{K}_2 + \bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2] & \tau_M\bar{\boldsymbol{C}} & \tau_M\bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2 \\ -\eta_M[\bar{\boldsymbol{B}}\bar{\boldsymbol{L}}_2\boldsymbol{K}_2 + \bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2] & \eta_M\bar{\boldsymbol{C}} & \eta_M\bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2 \\ -\varepsilon\tau_M\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2 & 0 & \varepsilon\tau_M\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2 \\ -\varepsilon\eta_M\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2 & 0 & \varepsilon\eta_M\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2 \end{bmatrix},$$

$$\varepsilon = \sqrt{\bar{\sigma}(1-\bar{\sigma})},$$

$$\boldsymbol{\Gamma}_{11} = \begin{bmatrix} \tau_M\bar{\boldsymbol{A}} & -\tau_M(\bar{\boldsymbol{B}}\bar{\boldsymbol{L}}_1\boldsymbol{K}_1 + \bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_2\boldsymbol{K}_1) & 0 \\ \eta_M\bar{\boldsymbol{A}} & -\eta_M(\bar{\boldsymbol{B}}\bar{\boldsymbol{L}}_1\boldsymbol{K}_1 + \bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_2\boldsymbol{K}_1) & 0 \\ 0 & -\varepsilon\tau_M\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_2\boldsymbol{K}_1 & 0 \\ 0 & -\varepsilon\eta_M\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_2\boldsymbol{K}_1 & 0 \end{bmatrix},$$

$$\boldsymbol{\Gamma}_5 = \mathrm{diag}\{-\boldsymbol{R}_1^{-1}, -\boldsymbol{R}_2^{-1}, -\boldsymbol{R}_1^{-1}, -\boldsymbol{R}_2^{-1}\},$$

则系统(12)达成局部领导跟随一致.

证明 为系统(12)选取如下 Lyapunov 泛函:

$$\begin{aligned} V(t) = {} & \boldsymbol{\xi}^{\mathrm{T}}(t)(\boldsymbol{I}_{2N}\otimes\boldsymbol{P})\boldsymbol{\xi}(t) + \\ & \int_{t-\tau_M}^{t}\boldsymbol{\xi}^{\mathrm{T}}(s)\boldsymbol{Q}_1\boldsymbol{\xi}(s)\mathrm{d}s + \int_{t-\eta_M}^{t}\boldsymbol{\xi}^{\mathrm{T}}(s)\boldsymbol{Q}_2\boldsymbol{\xi}(s)\mathrm{d}s + \\ & \tau_M\int_{t-\tau_M}^{t}\int_{s}^{t}\boldsymbol{\xi}^{\mathrm{T}}(v)\boldsymbol{R}_1\boldsymbol{\xi}(v)\mathrm{d}v\mathrm{d}s + \\ & \eta_M\int_{t-\eta_M}^{t}\int_{s}^{t}\boldsymbol{\xi}^{\mathrm{T}}(v)\boldsymbol{R}_2\boldsymbol{\xi}(v)\mathrm{d}v\mathrm{d}s. \end{aligned} \tag{17}$$

对 $V(t)$ 沿系统(12)求导并取其数学期望得

$$\begin{aligned} \mathbb{E}\{\dot{V}(t)\} = {} & 2\boldsymbol{\xi}^{\mathrm{T}}(t)(\boldsymbol{I}_{2N}\otimes\boldsymbol{P})\dot{\boldsymbol{\xi}}(t) + \\ & \boldsymbol{\xi}^{\mathrm{T}}(t)(\boldsymbol{Q}_1+\boldsymbol{Q}_2)\boldsymbol{\xi}(t) - \boldsymbol{\xi}^{\mathrm{T}}(t-\tau_M)\boldsymbol{Q}_2\boldsymbol{\xi}(t-\tau_M) - \\ & \boldsymbol{\xi}^{\mathrm{T}}(t-\eta_M)\boldsymbol{Q}_2\boldsymbol{\xi}(t-\eta_M) + \mathbb{E}\{\dot{\boldsymbol{\xi}}^{\mathrm{T}}(t)(\tau_M^2\boldsymbol{R}_1 + \eta_M^2\boldsymbol{R}_2)\dot{\boldsymbol{\xi}}(t)\} - \end{aligned}$$

$$\tau_M\int_{t-\tau_M}^{t}\dot{\boldsymbol{\xi}}^{\mathrm{T}}(s)\boldsymbol{R}_1\dot{\boldsymbol{\xi}}(s)\mathrm{d}s-\eta_M\int_{t-\eta_M}^{t}\dot{\boldsymbol{\xi}}^{\mathrm{T}}(s)\boldsymbol{R}_2\dot{\boldsymbol{\xi}}(s)\mathrm{d}s.\tag{18}$$

注意到 $\dot{\boldsymbol{\xi}}(t)=\mathscr{A}+(\sigma(t)-\bar{\sigma})\mathscr{B}$,其中,

$$\mathscr{A}=\bar{\boldsymbol{A}}\boldsymbol{\xi}(t)+\bar{\boldsymbol{C}}\bar{\boldsymbol{g}}(\boldsymbol{x}(t),t)-[\bar{\boldsymbol{B}}\bar{\boldsymbol{L}}_1\boldsymbol{K}_1+\bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_2\boldsymbol{K}_1]\boldsymbol{\xi}(t-\tau(t))-[\bar{\boldsymbol{B}}\bar{\boldsymbol{L}}_2\boldsymbol{K}_2+\bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2]\boldsymbol{e}(t)+\bar{\sigma}\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2\boldsymbol{F}(t-\eta(t)),$$

$$\mathscr{B}=\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_2\boldsymbol{K}_1\boldsymbol{\xi}(t-\tau(t))+\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2\boldsymbol{e}(t)-\bar{\boldsymbol{B}}\bar{\boldsymbol{W}}_1\boldsymbol{K}_2\boldsymbol{F}(t-\eta(t)).$$

又有 $\mathbb{E}\{\sigma(t)\}=\bar{\sigma}$, $\mathbb{E}\{\sigma(t)-\bar{\sigma}\}=0$, $\mathbb{E}\{(\sigma(t)-\bar{\sigma})^2\}=\varepsilon^2$,记 $\boldsymbol{R}=\tau_M^2\boldsymbol{R}_1+\eta_M^2\boldsymbol{R}_2$,则有

$$\mathbb{E}\{\dot{\boldsymbol{\xi}}^{\mathrm{T}}(t)(\tau_M^2\boldsymbol{R}_1+\eta_M^2\boldsymbol{R}_2)\dot{\boldsymbol{\xi}}(t)\}=\mathscr{A}^{\mathrm{T}}\boldsymbol{R}\mathscr{A}+\varepsilon^2\mathscr{B}^{\mathrm{T}}\boldsymbol{R}\mathscr{B}.\tag{19}$$

由引理 1 可得:

$$-\tau_M\int_{t-\tau_M}^{t}\dot{\boldsymbol{\xi}}^{\mathrm{T}}(s)\boldsymbol{R}_1\dot{\boldsymbol{\xi}}(s)\mathrm{d}s\leqslant\boldsymbol{\psi}_1^{\mathrm{T}}(t)\begin{bmatrix}-\boldsymbol{R}_1 & * & *\\ \boldsymbol{R}_1+\boldsymbol{M} & -2\boldsymbol{R}_1-\boldsymbol{M}-\boldsymbol{M}^{\mathrm{T}} & *\\ -\boldsymbol{M} & \boldsymbol{R}_1+\boldsymbol{M} & -\boldsymbol{R}_1\end{bmatrix}\boldsymbol{\psi}_1(t),$$

$$-\eta_M\int_{t-\eta_M}^{t}\dot{\boldsymbol{\xi}}^{\mathrm{T}}(s)\boldsymbol{R}_2\dot{\boldsymbol{\xi}}(s)\mathrm{d}s\leqslant\boldsymbol{\psi}_2{}^{\mathrm{T}}(t)\begin{bmatrix}-\boldsymbol{R}_2 & * & *\\ \boldsymbol{R}_2+\boldsymbol{N} & -2\boldsymbol{R}_2-\boldsymbol{N}-\boldsymbol{N}^{\mathrm{T}} & *\\ -\boldsymbol{N} & \boldsymbol{R}_2+\boldsymbol{N} & -\boldsymbol{R}_2\end{bmatrix}\boldsymbol{\psi}_2(t),$$

其中,

$$\boldsymbol{\psi}_1(t)=[\boldsymbol{\xi}^{\mathrm{T}}(t),\boldsymbol{\xi}^{\mathrm{T}}(t-\tau(t)),\boldsymbol{\xi}^{\mathrm{T}}(t-\tau_M)]^{\mathrm{T}},$$

$$\boldsymbol{\psi}_2(t)=[\boldsymbol{\xi}^{\mathrm{T}}(t),\boldsymbol{\xi}^{\mathrm{T}}(t-\eta(t)),\boldsymbol{\xi}^{\mathrm{T}}(t-\eta_M)]^{\mathrm{T}},$$

$\boldsymbol{R}_1,\boldsymbol{R}_2,\boldsymbol{M},\boldsymbol{N}$ 满足 $\begin{bmatrix}\boldsymbol{R}_1 & *\\ \boldsymbol{M} & \boldsymbol{R}_1\end{bmatrix}\geqslant 0,\begin{bmatrix}\boldsymbol{R}_2 & *\\ \boldsymbol{N} & \boldsymbol{R}_2\end{bmatrix}\geqslant 0.$

考虑到事件触发的条件约束式(4),可得:

$$\lambda\boldsymbol{x}^{\mathrm{T}}(t-\tau(t))\boldsymbol{\Omega}\boldsymbol{x}(t-\tau(t))-\boldsymbol{e}^{\mathrm{T}}(t)\boldsymbol{\Omega}\boldsymbol{e}(t)>0.\tag{20}$$

根据假设条件式(13),可得欺骗攻击的约束条件如下:

$$\boldsymbol{x}^{\mathrm{T}}(t-\eta(t))\boldsymbol{F}^{\mathrm{T}}\boldsymbol{F}\boldsymbol{x}(t-\eta(t))-\boldsymbol{F}^{\mathrm{T}}(\boldsymbol{x}(t-\eta(t)))\boldsymbol{F}(\boldsymbol{x}(t-\eta(t)))>0.\tag{21}$$

又因智能体的非线性动态函数满足假设条件式(2),有

$$\mu^2\boldsymbol{\delta}^{\mathrm{T}}(t)\boldsymbol{\delta}(t)-[\boldsymbol{G}(\boldsymbol{x}(t),t)-\boldsymbol{G}(\boldsymbol{x}_0(t),t)]^{\mathrm{T}}\cdot[\boldsymbol{G}(\boldsymbol{x}(t),t)-\boldsymbol{G}(\boldsymbol{x}_0(t),t)]>0.\tag{22}$$

结合以上式(18)—(22),可得:

$$\begin{aligned}\mathbb{E}\{\dot{V}(t)\}\leqslant{}&2\boldsymbol{\xi}^{\mathrm{T}}(t)(\boldsymbol{I}_{2N}\otimes\boldsymbol{P})\dot{\boldsymbol{\xi}}(t)+\boldsymbol{\xi}^{\mathrm{T}}(t)(\boldsymbol{Q}_1+\boldsymbol{Q}_2)\boldsymbol{\xi}(t)-\boldsymbol{\xi}^{\mathrm{T}}(t-\tau_M)\boldsymbol{Q}_2\boldsymbol{\xi}(t-\tau_M)-\\&\boldsymbol{\xi}^{\mathrm{T}}(t-\eta_M)\boldsymbol{Q}_2\boldsymbol{\xi}(t-\eta_M)+\mathscr{A}^{\mathrm{T}}\boldsymbol{R}\mathscr{A}+\varepsilon^2\mathscr{B}^{\mathrm{T}}\boldsymbol{R}\mathscr{B}+\\&\boldsymbol{\psi}_1^{\mathrm{T}}(t)\begin{bmatrix}-\boldsymbol{R}_1 & * & *\\ \boldsymbol{R}_1+\boldsymbol{M} & -2\boldsymbol{R}_1-\boldsymbol{M}-\boldsymbol{M}^{\mathrm{T}} & *\\ -\boldsymbol{M} & \boldsymbol{R}_1+\boldsymbol{M} & -\boldsymbol{R}_1\end{bmatrix}\boldsymbol{\psi}_1(t)+\\&\boldsymbol{\psi}_2^{\mathrm{T}}(t)\begin{bmatrix}-\boldsymbol{R}_2 & * & *\\ \boldsymbol{R}_2+\boldsymbol{N} & -2\boldsymbol{R}_2-\boldsymbol{N}-\boldsymbol{N}^{\mathrm{T}} & *\\ -\boldsymbol{N} & \boldsymbol{R}_2+\boldsymbol{N} & -\boldsymbol{R}_2\end{bmatrix}\boldsymbol{\psi}_2(t)+\\&\lambda\boldsymbol{x}^{\mathrm{T}}(t-\tau(t))\boldsymbol{\Omega}\boldsymbol{x}(t-\tau(t))-\boldsymbol{e}^{\mathrm{T}}(t)\boldsymbol{\Omega}\boldsymbol{e}(t)+\boldsymbol{x}^{\mathrm{T}}(t-\eta(t))\boldsymbol{F}^{\mathrm{T}}\boldsymbol{F}\boldsymbol{x}(t-\eta(t))-\boldsymbol{F}^{\mathrm{T}}(\boldsymbol{x}(t-\eta(t)))\boldsymbol{F}(\boldsymbol{x}(t-\eta(t)))+\\&\mu^2\boldsymbol{\delta}^{\mathrm{T}}(t)\boldsymbol{\delta}(t)-[\boldsymbol{G}(\boldsymbol{x}(t),t)-\boldsymbol{G}(\boldsymbol{x}_0(t),t)]^{\mathrm{T}}[\boldsymbol{G}(\boldsymbol{x}(t),t)-\boldsymbol{G}(\boldsymbol{x}_0(t),t)].\end{aligned}\tag{23}$$

由式(23),利用 Schur 补可得:

$$\mathbb{E}\{\dot{V}(t)\}\leqslant\boldsymbol{\zeta}^{\mathrm{T}}(t)\boldsymbol{\jmath}\boldsymbol{\zeta}(t),\tag{24}$$

其中 $\boldsymbol{\zeta}^{\mathrm{T}}(t)=[\boldsymbol{\psi}_1^{\mathrm{T}}(t),\boldsymbol{\xi}^{\mathrm{T}}(t-\eta(t)),\boldsymbol{\xi}^{\mathrm{T}}(t-\eta_M),\bar{\boldsymbol{g}}^{\mathrm{T}}(\boldsymbol{x}(t),t),\boldsymbol{e}^{\mathrm{T}}(t),\boldsymbol{F}^{\mathrm{T}}(\boldsymbol{x}(t-\eta(t))),\underbrace{\boldsymbol{I},\cdots,\boldsymbol{I}}_{6\text{个}}]$.

则若要 $\mathbb{E}\{\dot{V}(t)\}<0$,只要 $\boldsymbol{\jmath}<0$.故由式(24)和式(16)可得,多智能体达到领导跟随一致.综上所述,定理 1 得证.

定理 1 得到多智能体系统达到领导跟随一致的充分条件,基于此,考虑欺骗攻击和网络资源受限的影响,在下面的定理中将给出控制增益 $\boldsymbol{K}$ 的设计方法.

定理 2 对于给定的事件触发参数 $\lambda_i(i=1,2,\cdots,N)$,时滞上界 τ_M,η_M,标量 $\mu,\gamma_1,\gamma_2,\gamma_3$,欺骗攻击的概率期望 $\bar{\sigma}$,以及矩阵 $\boldsymbol{F}$,如果存在正定矩阵 $\hat{\boldsymbol{P}}>0,\hat{\boldsymbol{Q}}_1>0,\hat{\boldsymbol{Q}}_2>0,\hat{\boldsymbol{R}}_1>0,\hat{\boldsymbol{R}}_2>0,\boldsymbol{\Omega}_i>0(i=1,2,\cdots,N)$,$\boldsymbol{X}>0,\boldsymbol{Y}>0$,合适维度的矩阵 $\hat{\boldsymbol{M}},\hat{\boldsymbol{N}}$ 使得下面线性矩阵不等式成立:

$$\hat{\boldsymbol{\jmath}}=\begin{bmatrix}\hat{\boldsymbol{\Gamma}}_1 & * & *\\ \hat{\boldsymbol{\Gamma}}_2 & \hat{\boldsymbol{\Gamma}}_3 & *\\ \hat{\boldsymbol{\Gamma}}_4 & 0 & \hat{\boldsymbol{\Gamma}}_5\end{bmatrix}<0,\tag{25}$$

其中,

$$\hat{\boldsymbol{\Gamma}}_1=\begin{pmatrix}\hat{\boldsymbol{\Psi}}_1 & * & *\\ \hat{\boldsymbol{\Psi}}_2 & \hat{\boldsymbol{\Psi}}_3 & *\\ \hat{\boldsymbol{\Psi}}_4 & 0 & \hat{\boldsymbol{\Psi}}_5\end{pmatrix},$$

$$\hat{\boldsymbol{\Psi}}_1=\begin{pmatrix}\hat{\boldsymbol{\Gamma}}_6 & * & *\\ \hat{\boldsymbol{\Gamma}}_7 & \hat{\boldsymbol{\Gamma}}_8 & *\\ -\hat{\boldsymbol{M}} & \hat{\boldsymbol{R}}_1+\hat{\boldsymbol{M}} & -\hat{\boldsymbol{Q}}_1-\hat{\boldsymbol{R}}_1\end{pmatrix},$$

$$\hat{\boldsymbol{\Psi}}_2=\begin{bmatrix}\hat{\boldsymbol{R}}_2+\hat{\boldsymbol{N}} & 0 & 0\\ -\hat{\boldsymbol{N}} & 0 & 0\end{bmatrix},$$

$$\hat{\boldsymbol{\Psi}}_3=\begin{pmatrix}-\hat{\boldsymbol{R}}_2-\hat{\boldsymbol{N}}-\hat{\boldsymbol{N}}^{\mathrm{T}} & *\\ \hat{\boldsymbol{R}}_2+\hat{\boldsymbol{N}} & -\hat{\boldsymbol{Q}}_2-\hat{\boldsymbol{R}}_2\end{pmatrix},$$

$$\hat{\boldsymbol{\Psi}}_4=\begin{pmatrix}\overline{\boldsymbol{C}}^{\mathrm{T}} & 0 & 0\\ \hat{\boldsymbol{\Gamma}}_9 & 0 & 0\\ \hat{\boldsymbol{\Gamma}}_{10} & 0 & 0\end{pmatrix},$$

$$\hat{\boldsymbol{\Psi}}_5=\mathrm{diag}\{-\boldsymbol{I},-\boldsymbol{H}_1^{\mathrm{T}}\hat{\boldsymbol{\Omega}}\boldsymbol{H}_1,-\hat{\boldsymbol{\Gamma}}_{11}\},$$

$$\hat{\boldsymbol{\Gamma}}_3=\mathrm{diag}\{-\boldsymbol{I},-\boldsymbol{I}\},$$

$$\hat{\boldsymbol{\Gamma}}_6=\boldsymbol{I}_{2N}\otimes(\boldsymbol{A}\boldsymbol{X}+\boldsymbol{X}\boldsymbol{A}^{\mathrm{T}})+\hat{\boldsymbol{Q}}_1+\hat{\boldsymbol{Q}}_2-\hat{\boldsymbol{R}}_1-\hat{\boldsymbol{R}}_2,$$

$$\boldsymbol{Y}_1=\boldsymbol{I}_{2N}\otimes\boldsymbol{Y},\quad \boldsymbol{Y}_2=\boldsymbol{I}_N\otimes\boldsymbol{Y},$$

$$\hat{\boldsymbol{\Gamma}}_7=-\boldsymbol{Y}_1^{\mathrm{T}}\overline{\boldsymbol{L}}_1^{\mathrm{T}}\overline{\boldsymbol{B}}^{\mathrm{T}}-\bar{\sigma}\boldsymbol{Y}_1^{\mathrm{T}}\overline{\boldsymbol{W}}_2^{\mathrm{T}}\overline{\boldsymbol{B}}^{\mathrm{T}}+\hat{\boldsymbol{R}}_1+\hat{\boldsymbol{M}},$$

$$\hat{\boldsymbol{\Gamma}}_8=\lambda\boldsymbol{H}_1^{\mathrm{T}}\hat{\boldsymbol{\Omega}}\boldsymbol{H}_1-2\hat{\boldsymbol{R}}_1-\hat{\boldsymbol{M}}-\hat{\boldsymbol{M}}^{\mathrm{T}},$$

$$\hat{\boldsymbol{\Gamma}}_9=-\boldsymbol{Y}_2^{\mathrm{T}}\overline{\boldsymbol{L}}_2^{\mathrm{T}}\overline{\boldsymbol{B}}^{\mathrm{T}}-\bar{\sigma}\boldsymbol{Y}_2^{\mathrm{T}}\overline{\boldsymbol{B}}_1^{\mathrm{T}}\overline{\boldsymbol{B}}^{\mathrm{T}},$$

$$\hat{\boldsymbol{\Gamma}}_{10}=\bar{\sigma}\boldsymbol{Y}_2^{\mathrm{T}}\overline{\boldsymbol{W}}_1^{\mathrm{T}}\overline{\boldsymbol{B}}^{\mathrm{T}},$$

$$\hat{\boldsymbol{\Gamma}}_{11}=-2\gamma_3(\boldsymbol{I}_N\otimes\boldsymbol{X})+\gamma_3^2\hat{\boldsymbol{I}},$$

$$\hat{\boldsymbol{\Gamma}}_2=\begin{bmatrix}\hat{\boldsymbol{\Psi}}_6 & \boldsymbol{\Psi}_7\end{bmatrix},$$

$$\hat{\boldsymbol{\Gamma}}_4=[\hat{\boldsymbol{\Gamma}}_{11},0,0,0,0,\hat{\boldsymbol{\Gamma}}_{12}],$$

$$\hat{\boldsymbol{\Psi}}_6=\begin{bmatrix}0 & 0 & 0 & \boldsymbol{F}\boldsymbol{H}_1(\boldsymbol{I}_{2N}\otimes\boldsymbol{X})\\ \mu\boldsymbol{H}_2(\boldsymbol{I}_{2N}\otimes\boldsymbol{X}) & 0 & 0 & 0\end{bmatrix},$$

$$\hat{\boldsymbol{\Gamma}}_{15}=\begin{bmatrix}\tau_M\boldsymbol{I}_{2N}\otimes\boldsymbol{A}\boldsymbol{X} & -\tau_M\overline{\boldsymbol{B}}\overline{\boldsymbol{L}}_1\boldsymbol{Y}_1-\tau_M\bar{\sigma}\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_2\boldsymbol{Y}_1 & 0\\ \eta_M\boldsymbol{I}_{2N}\otimes\boldsymbol{A}\boldsymbol{X} & -\eta_M\overline{\boldsymbol{B}}\overline{\boldsymbol{L}}_1\boldsymbol{Y}_1-\eta_M\bar{\sigma}\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_2\boldsymbol{Y}_1 & 0\\ 0 & \varepsilon\tau_M\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_2\boldsymbol{Y}_1 & 0\\ 0 & \varepsilon\eta_M\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_2\boldsymbol{Y}_1 & 0\end{bmatrix},$$

$$\hat{\boldsymbol{\Gamma}}_{16}=\begin{bmatrix}-\tau_M\overline{\boldsymbol{B}}\overline{\boldsymbol{L}}_2\boldsymbol{Y}_2-\tau_M\bar{\sigma}\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_1\boldsymbol{Y}_2 & \tau_M\overline{\boldsymbol{C}} & \tau_M\bar{\sigma}\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_1\boldsymbol{Y}_2\\ -\eta_M\overline{\boldsymbol{B}}\overline{\boldsymbol{L}}_2\boldsymbol{Y}_2-\eta_M\bar{\sigma}\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_1\boldsymbol{Y}_2 & \tau_M\overline{\boldsymbol{C}} & \eta_M\bar{\sigma}\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_1\boldsymbol{Y}_2\\ \varepsilon\tau_M\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_1\boldsymbol{Y}_2 & 0 & -\varepsilon\tau_M\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_1\boldsymbol{Y}_2\\ \varepsilon\eta_M\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_1\boldsymbol{Y}_2 & 0 & -\varepsilon\eta_M\overline{\boldsymbol{B}}\overline{\boldsymbol{W}}_1\boldsymbol{Y}_2\end{bmatrix},$$

$$\hat{\boldsymbol{\Gamma}}_5=\mathrm{diag}\{\boldsymbol{Z}_1,\boldsymbol{Z}_2,\boldsymbol{Z}_1,\boldsymbol{Z}_2\},$$

$$\boldsymbol{Z}_1=-2\gamma_1(\boldsymbol{I}_{2N}\otimes\boldsymbol{X})+\gamma_1^2\hat{\boldsymbol{R}}_1,$$

$$\boldsymbol{Z}_2=-2\gamma_2(\boldsymbol{I}_{2N}\otimes\boldsymbol{X})+\gamma_2^2\hat{\boldsymbol{R}}_2.$$

则系统达到局部领导跟随一致.另外,若上述条件满足,则控制增益:

$$\boldsymbol{K}=\boldsymbol{Y}\boldsymbol{X}^{-1}. \tag{26}$$

证明 定义 $\boldsymbol{X}=\boldsymbol{P}^{-1}$,对不等式(16)左乘 $\boldsymbol{\Lambda}$,右乘 $\boldsymbol{\Lambda}^{\mathrm{T}}$,其中 $\boldsymbol{\Lambda}=\mathrm{diag}\{\boldsymbol{I}_{2N}\otimes\boldsymbol{X},\underbrace{\boldsymbol{I}_{2N}\otimes\boldsymbol{X},\cdots,\boldsymbol{I}_{2N}\otimes\boldsymbol{X}}_{8\text{个}},\underbrace{\boldsymbol{I}_{2N}\otimes\boldsymbol{I}_N,\cdots,\boldsymbol{I}_{2N}\otimes\boldsymbol{I}_N}_{6\text{个}}\}$. 定义 $\hat{\boldsymbol{Q}}_1=\boldsymbol{X}\boldsymbol{Q}_1\boldsymbol{X},\hat{\boldsymbol{Q}}_2=\boldsymbol{X}\boldsymbol{Q}_2\boldsymbol{X},\hat{\boldsymbol{R}}_1=\boldsymbol{X}\boldsymbol{R}_1\boldsymbol{X},\hat{\boldsymbol{R}}_2=\boldsymbol{X}\boldsymbol{R}_2\boldsymbol{X},\hat{\boldsymbol{M}}=\boldsymbol{X}\boldsymbol{M}\boldsymbol{X},\hat{\boldsymbol{N}}=\boldsymbol{X}\boldsymbol{N}\boldsymbol{X},\hat{\boldsymbol{\Omega}}=\boldsymbol{X}\boldsymbol{\Omega}\boldsymbol{X},\boldsymbol{Y}=\boldsymbol{K}\boldsymbol{X}$,则有

$$-\boldsymbol{R}_1^{-1}=-\boldsymbol{X}\hat{\boldsymbol{R}}_1^{-1}\boldsymbol{X},\ -\boldsymbol{R}_2^{-1}=-\boldsymbol{X}\hat{\boldsymbol{R}}_2^{-1}\boldsymbol{X}-\boldsymbol{I}=-\boldsymbol{X}\hat{\boldsymbol{I}}\boldsymbol{X}. \tag{27}$$

由式(27),利用引理2可得:

$$\begin{cases}-\boldsymbol{R}_1^{-1}\leqslant-2\gamma_1(\boldsymbol{I}_{2N}\otimes\boldsymbol{X})+\gamma_1^2\hat{\boldsymbol{R}}_1,\\ -\boldsymbol{R}_2^{-1}\leqslant-2\gamma_2(\boldsymbol{I}_{2N}\otimes\boldsymbol{X})+\gamma_2^2\hat{\boldsymbol{R}}_2,\\ -\boldsymbol{I}\leqslant-2\gamma_3(\boldsymbol{I}_{2N}\otimes\boldsymbol{X})+\gamma_3^2\hat{\boldsymbol{I}}.\end{cases} \tag{28}$$

由式(27)和式(28)可知,式(25)经变换可得到式(16),结合定理1和式(24),可得智能体系统达到局部领导跟随一致.由 $\boldsymbol{Y}=\boldsymbol{K}\boldsymbol{X}$ 可得智能体控制增益为 $\boldsymbol{K}=\boldsymbol{Y}\boldsymbol{X}^{-1}$,定理得证.

3 数值例子

下面将给出一个算例来证明本文提出方法的有效性.

考虑一个可被式(1)描述的4个跟随智能体和一个虚拟领导者组成的智能体系统,其中它的系统参数矩阵 $\boldsymbol{A}$ 和 $\boldsymbol{B}$ 如下[26]:

$$\boldsymbol{A}=\begin{bmatrix}-1.04 & 0 & -2.21\\ -1.25 & -0.53 & 0\\ 2.64 & -1.23 & -0.59\end{bmatrix},\quad \boldsymbol{B}=\begin{bmatrix}0\\1\\0\end{bmatrix}.$$

每个智能体的状态向量为 $\boldsymbol{x}_i(t)=(x_{i1}(t),x_{i2}(t),x_{i3}(t))^{\mathrm{T}}$,智能体的非线性动态假设为 $g(\boldsymbol{x}_i(t),t)=-0.1\sin(\boldsymbol{x}_i(t))$.智能体之间的通信拓扑如图2所示,从图2中可以得到其邻接矩阵和Laplacian矩阵如下:

$$\boldsymbol{W}=\begin{bmatrix}0&1&0&1\\1&0&0&1\\0&0&0&1\\1&1&1&0\end{bmatrix},\quad \boldsymbol{L}=\begin{bmatrix}2&-1&0&-1\\-1&2&0&-1\\0&0&1&-1\\-1&-1&-1&3\end{bmatrix}.$$

从图2中可以看到前两个智能体能够获取领导者的信息,故 $\hat{\boldsymbol{B}}=\mathrm{diag}\{1,1,0,0\}$.

给定时延上界 $\tau_M=0.2,\eta_M=0.1$.欺骗攻击发生的概率期望 $\bar{\sigma}=0.1$,标量 $\gamma_1=\gamma_2=\gamma_3=1,\mu=0.1$.利用定理2,求解线性矩阵不等式(25)可得:

$$\boldsymbol{\Omega}=\begin{bmatrix}28.5790 & 8.2001 & 7.6695\\ 8.2001 & 3.5377 & 1.6458\\ 7.6695 & 1.6458 & 7.7658\end{bmatrix},$$

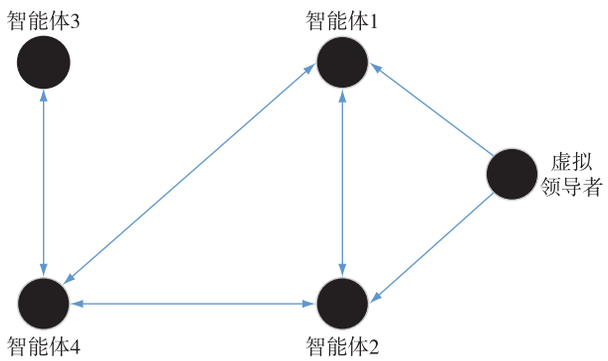


图 2　智能体间的通信拓扑

Fig. 2　Communication topology between agents

$$\boldsymbol{X}=\begin{bmatrix} 10.649\,0 & 1.524\,5 & -1.244\,1 \\ 1.524\,5 & 11.750\,2 & -2.746\,6 \\ -1.244\,1 & -2.746\,6 & 13.704\,0 \end{bmatrix},$$

$$\boldsymbol{Y}=[-0.470\,4, 1.103\,2, -0.289\,2].$$

由定理 2 中式(26) 可得:

$$\boldsymbol{K}=\boldsymbol{Y}\boldsymbol{X}^{-1}=[-0.059\,2, 0.100\,1, -0.006\,4].$$

采用上述参数,利用 MATLAB 仿真工具可得到仿真曲线图 3—6.其中,图 3 给出欺骗攻击的响应曲线;图 4 展示描述欺骗攻击是否发生的随机变量的伯努利分布情况;图 5 给出采用事件触发后的数据传输时刻及传输时间间隔;图 6 展示欺骗攻击下采用事件触发后的状态误差的响应曲线.

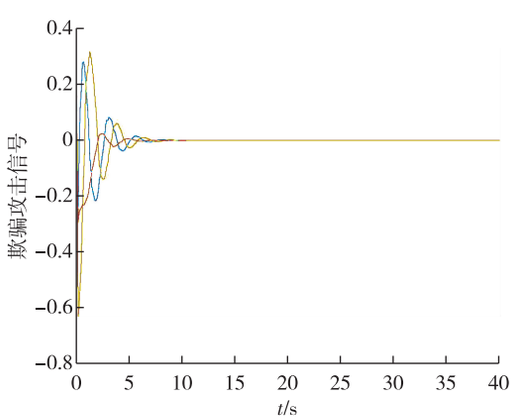


图 3　网络攻击信号的响应曲线

Fig. 3　The response signals of deception attacks

从图 5 可以看出,系统初始时刻因未稳定而触发频繁,相邻传输时刻之间间隔较短,后期系统趋于稳定,触发时刻减少,传输时刻之间间隔变长,能够大大减少数据的传输次数,进而节省有限的网络资源.从图 6 则可以看出智能体之间的状态误差最终趋于稳定,这表明本文的设计算法是有效的.

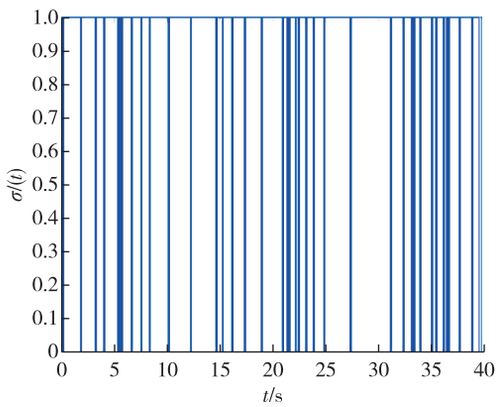


图 4　伯努利变量 $\sigma(t)$ 的分布序列

Fig. 4　The distribution sequence of $\sigma(t)$

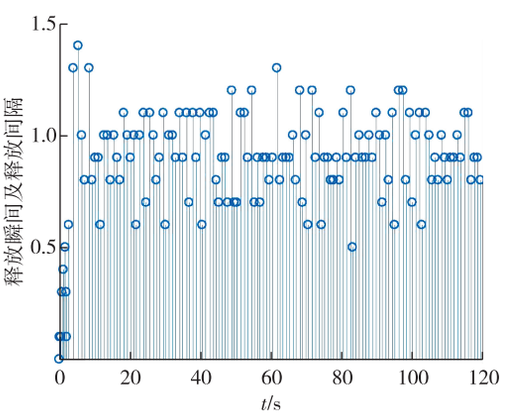


图 5　事件触发下数据释放间隔

Fig. 5　Data release interval under event triggering

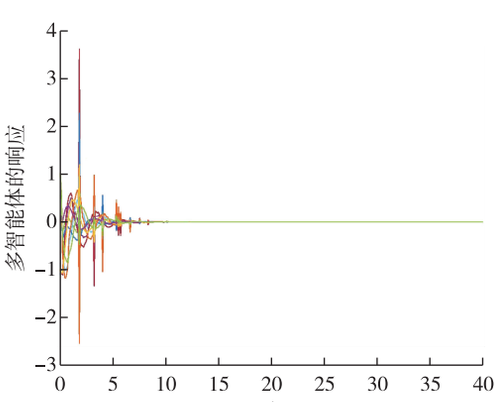


图 6　状态误差的响应曲线

Fig. 6　Response signals of state error

4　结论

本文针对基于事件触发和欺骗攻击的多智能体

一致性问题进行研究.通过引入事件触发机制缓解多智能体间无线通信网络传输压力,节省无线通信网络传输资源,延长续航时间.考虑欺骗攻击对智能体无线通信网络传输数据的影响,建立一类基于事件触发和欺骗攻击的多智能体系统的数学模型.基于此数学模型,通过利用 Lyapunov 稳定性理论和多智能体一致性理论给出系统达到一致性的充分性条件,并通过应用线性矩阵不等式技术得到控制器设计算法.最后,通过仿真算例验证本文设计方法的有效性.将来,针对威胁多智能体间无线通信网络安全的网络攻击,我们将对其进行攻击检测,进一步提高多智能体间无线通信网络的安全性和可靠性.

参考文献

References

[1] Yang Y Z,Zheng Z J,Bian K G,et al.Real-time profiling of fine-grained air quality index distribution using UAV sensing[J].IEEE Internet of Things Journal,2018,5(1):186-198

[2] Chebrolu N,Labe T,Stachniss C.Robust long-term registration of UAV images of crop fields for precision agriculture[J].IEEE Robotics and Automation Letters,2018,3(4):3097-3104

[3] Harikumar K, Senthilnath J, Sundaram S. Multi-UAV oxyrrhis marina-inspired search and dynamic formation control for forest firefighting[J].IEEE Transactions on Automation Science and Engineering, 2019, 16(2):863-873

[4] 许文盈,曹进德.基于事件驱动机制的多智能体系统协调控制研究综述[J].南京信息工程大学学报(自然科学版),2018,10(4):395-400
XU Wenying,CAO Jinde.An overview of recent progress in the study of event-triggered coordinated schemes of multi-agent systems[J].Journal of Nanjing University of Information Science & Technology(Natural Science Edition),2018,10(4):395-400

[5] 胡鸿翔,梁锦,温广辉,等.多智能体系统的群集行为研究综述[J].南京信息工程大学学报(自然科学版),2018,10(4):415-421
HU Hongxiang, LIANG Jin, WEN Guanghui, et al. A survey of development on swarming behavior for multi-agent systems[J].Journal of Nanjing University of Information Science & Technology(Natural Science Edition),2018,10(4):415-421

[6] Wan Y,Cao J D.Distributed robust stabilization of linear multi-agent systems with intermittent control[J].Journal of the Franklin Institute,2015,352(10):4515-4527

[7] 潘欢,胡钢墩,薛丽.基于输出反馈的分数阶奇异线性多智能体系统领导者-跟随一致性[J].南京信息工程大学学报(自然科学版),2018,10(4):422-427
PAN Huan,HU Gangdun,XUE Li.Leader-following consensus of fractional-order singular linear multi-agent systems based on output feedback[J].Journal of Nanjing University of Information Science & Technology(Natural Science Edition),2018,10(4):422-427

[8] 陈军统,徐振华,项秉铜,等.具有控制器增益随机不确定性的多智能体一致性控制[J].南京信息工程大学学报(自然科学版),2018,10(2):173-177
CHEN Juntong, XU Zhenhua, XIANG Bingtong, et al. Leader-follower consensus of multi-agent systems with stochastic uncertainty of controller gain[J].Journal of Nanjing University of Information Science & Technology(Natural Science Edition),2018,10(2):173-177

[9] Akashi S,Ishii H,Cetinkaya A.Self-triggered control with tradeoffs in communication and computation[J].Automatica,2018,94:373-380

[10] Peng C,Yang M J,Zhang J,et al.Network-based H_∞ control for T-S fuzzy systems with an adaptive event-triggered communication scheme[J].Fuzzy Sets and Systems,2017,329:61-76

[11] Yi X L,Liu K,Dimarogonas D V,et al.Dynamic event-triggered and self-triggered control for multi-agent systems[J].IEEE Transactions on Automatic Control,2018.DOI:10.1109/TAC.2018.2874-703

[12] Yue D,Tian E G,Han Q L.A delay system method for designing event-triggered controllers of networked control systems[J].IEEE Transactions on Automatic Control,2013,58(2):475-481

[13] Ge X H,Han Q L.Distributed formation control of networked multi-agent systems using a dynamic event-triggered communication mechanism[J].IEEE Transactions on Industrial Electronics,2017,64(10):8118-8127

[14] Peng C,Wu M,Xie X P,et al.Event-triggered predictive control for networked nonlinear systems with imperfect premise matching[J].IEEE Transactions on Fuzzy Systems,2018,26(5):2797-2806

[15] Liu J L,Gu Y Y,Cao J,et al.Distributed event-triggered H filtering over sensor networks with sensor saturations and cyber-attacks[J].ISA Transactions,2018,81:63-75

[16] Liu J L,Wei L L,Xie X P,et al.Quantized stabilization for T-S fuzzy systems with hybrid-triggered mechanism and stochastic cyber-attacks[J].IEEE Transactions on Fuzzy Systems,2018,26(6):3820-3834

[17] 刘金良,汤佳,费树岷.基于事件触发和量化的时滞神经网络系统状态估计[J].中国科学(信息科学),2016,46(11):1555-1568
LIU Jinliang,TANG Jia,FEI Shumin.Event-based state estimation for delayed neural network systems with quantization[J].Science China Information Sciences,2016,46(11):1555-1568

[18] Zhu M H,Martinez S.On the performance analysis of resilient networked control systems under replay attacks[J].IEEE Transactions on Automatic Control,2014,59(3):804-808

[19] Amin S,Schwartz G A,Shankar S S.Security of interdependent and identical networked control systems[J].Automatica,2013,49(1):186-192

[20] Zha L J,Tian E G,Xie X P,et al.Decentralized event-triggered H_∞ control for neural networks subject to cyber-attacks[J].Information Sciences,2018,457/458:141-155

[21] Ding D R,Wang Z D,Han Q L,et al.Security control for discrete-time stochastic nonlinear systems subject to deception attacks[J].IEEE Transactions on Systems,Man,and Cybernetics(Systems),2018,48(5):779-789
[22] Ding D R,Wang Z D,Ho D W C,et al.Distributed recursive filtering for stochastic systems under uniform quantizations and deception attacks through sensor networks[J].Automatica,2017,78:231-240
[23] Yin X X,Yue D,Hu S L.Adaptive periodic event-triggered consensus for multi-agent systems subject to input saturation[J].International Journal of Control,2016,89(4):653-667
[24] Liu J L,Gu Y Y,Xie X P,et al.Hybrid-driven-based H_∞ control for networked cascade control systems with actuator saturations and stochastic cyber attacks[J].IEEE Transactions on Systems,Man,and Cybernetics(Systems),2018:1-12.DOI:10.1109/TSMC.2018.2875484
[25] 刘金良,田恩刚,顾洲.多自由度遥操作机器人可靠性控制研究[J].中国科学(信息科学),2012,42(9):1158-1169
LIU Jinliang,TIAN Engang,GU Zhou.Reliable control for tele-robotics with multi degree of freedom[J].Science China Information Sciences,2012,42(9):1158-1169
[26] Zhu W,Jiang Z P.Event-based leader-following consensus of multi-agent systems with input time delay[J].IEEE Transactions on Automatic Control,2015,60(5):1362-1367

Event-based consensus of multi-agent systems with deception attacks

WANG Yuda[1] ZHA Lijuan[1,2] LIU Jinliang[1] FEI Shumin[3]
1 College of Information Engineering,Nanjing University of Finance and Economics,Nanjing 210023
2 School of Mathematics,Southeast University,Nanjing 210096
3 School of Automation,Southeast University,Nanjing 210096

Abstract This paper is concerned with the consensus problem of multi-agent systems with event-triggered scheme and deception attacks.In order to alleviate the wireless communication network load,an event-triggered scheme is introduced to reduce the amount of redundant data.Due to wireless communication networks between agents are vulnerable to cyber attacks,this paper considers the influence of deception attacks.By taking the effects of deception attacks into account,the mathematical model of multi-agent systems with event-triggered scheme and deception attacks is established.Based on the constructed model,through the utilization of Lyapunov stability theory,multi-agent approach and linear matrix inequalities,the sufficient conditions are acquired which can guarantee consensus of the system and the designed algorithm of the controller is obtained,respectively.Finally,the feasibility of the proposed method is verified by a simulated example.

Key words multi-agent systems;consensus;event-triggered scheme;deception attacks