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基于中间观测器的异构多智能体系统分布式故障估计

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摘　要: 针对由无人机和无人车组成的异构多智能体系统,提出一种新型的基于中间观测器的分布式故障估计方法,可以实现对节点及其邻居执行器故障和系统状态的同时估计. 首先,考虑到无人机在 XOY 平面与在 OZ 轴方向的运动相对独立,异构多智能体系统可以划分为由无人机和无人车组成的位置子系统的 XOY 平面以及无人机位置子系统的 OZ 轴;然后,设计基于中间变量的分布式故障估计观测器,不仅能同时估计出选定的智能体自身与其邻居的执行器故障和状态,也能克服观测器匹配条件的限制,并基于 H_∞ 性能指标求解观测器增益;最后,通过仿真实验验证所提出方法的可行性与有效性.

关键词: 无人机；无人车；异构多智能体系统；中间观测器；分布式故障估计；H_∞ 性能

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Intermediate observer-based distributed fault estimation for heterogeneous multi-agent systems

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Abstract: For heterogeneous multi-agent systems composed of UAVs and UGVs, this paper proposes a novel distributed fault estimation scheme based on intermediate observers, which can realize the simultaneous estimation of actuator faults and system states of the agent itself and its neighbors. Firstly, considering that the movement of UAVs in the XOY plane and the OZ axis directions is relatively independent, the heterogeneous multi-agent systems can be divided into the XOY plane of UAVs and UGVs' position subsystem, and the OZ axis of UAVs' position subsystem. Then, a distributed fault estimation observer based on intermediate variables is designed, so that the observer built on one agent can not only estimate the actuator faults and states of the selected agent itself and its neighbors, but also overcome the constraints of the observer matching conditions. Also, the gain matrices of the observer are solved based on the performance of H_∞. Finally, the feasibility and effectiveness of the proposed method are verified by simulation experiments.

Keywords: unmanned aerial vehicles；unmanned ground vehicles；heterogeneous multi-agent systems；intermediate observer；distributed fault estimation；H_∞ performance

0　引　言

随着现代工业的发展,现代工业控制系统变得越来越复杂,多智能体系统作为复杂系统的代表之一受到了研究人员的广泛关注[1-2]. 由无人机和无人车组成的异构多智能体系统由于包含性能不同的智能体,可以充分利用无人机和无人车的优势,弥补单种智能体的不足,完成更复杂的任务,因此,有关异构多智能体系统的研究也是当前的研究热点. 空地合作的异构多智能体系统拥有非常广泛的应用领域,例如侦察和监视[3]、目标跟踪[4] 和搜救[5] 等.

现代工业系统复杂度的提升对系统的可靠性与安全性提出了更高的要求,尤其对于多智能体系统而言,某个智能体上发生的故障可能会导致单个智能体功能的缺失,故障的影响会通过智能体间的连通拓扑结构进行传播,严重情况下导致系统的崩溃. 因此,对系统进行及时有效地故障诊断显得尤为重要[6-7]. 故障诊断包含3部分内容,分别是故障检测、分离和估计[8]. 近年来,针对多智能体系统的故障检测与分离

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的研究已经取得了不少成果[9-11],但相比于故障检测与分离,故障估计可获得的故障信息更多,包括故障的大小和波形[12-13]. 目前关于多智能体系统的故障估计,研究人员已经提出了不少方法. 文献[14]针对有向拓扑下的多智能体系统提出了具有可调参数的分布式故障估计观测器,基于相对输出设计具有可调参数的自适应观测器; 文献[15]对多智能体系统提出了分散式故障估计的方法,对每个智能体设计未知输入观测器,实现对状态和故障的同时估计. 然而,文献[14-15]所提出的方法都需要系统满足观测器匹配条件,但实际系统往往不满足该条件,这就导致了这些方法存在局限性. 为了克服观测器匹配条件的限制,文献[16-17]分别对线性系统和非线性系统设计了中间观测器,通过构建中间变量与对原状态和新定义的中间变量进行估计,基于状态和中间变量的估计值得到故障的估计值. 但是,前述研究均是针对同构多智能体系统展开的,有关异构多智能体系统故障估计的成果还很少.

在关于多智能体系统的研究中,分布式的结构备受青睐[18]. 集中式需要中心智能体与所有智能体进行信息交互,这对网络提出了很高的要求,继而中心智能体基于全局信息进行计算,并将决策发送回各个智能体;分散式虽然可以进行局部的数据计算,但依旧需要中心智能体进行网络调度;分布式结构则不需要中心智能体,也不需要全局信息,这种结构可以降低系统的计算压力,局部的故障对全局的影响也较小. 文献[14,19-20]均研究了多智能体系统分布式故障诊断的问题,其分布式思路是基于自身与邻居的相对信息定义相对输出估计误差,基于相对输出估计误差构建观测器. 其中,文献[14]在利用LMI求解观测器增益矩阵时,LMI的维数受系统中智能体的个数影响,矩阵计算量随着智能体数目增加而增加;文献[17]基于Schur分解定理,得到与单个系统维数相同的求解矩阵参数的LMI,矩阵计算量不受系统中智能体个数影响. 然而,文献[14, 16-17, 19-20]所提出的分布式故障诊断方法要实现对每个智能体的诊断,需要在每个智能体上都构建观测器,即要求每个智能体都具备计算能力,然而在实际系统中,会出现某些智能体不适合进行计算的情况. 因此,本文采用一种新的分布式结构,思路是在异构多智能体系统中选定一些关键节点,其相邻智能体将信息传递给该智能体,由关键节点完成估计并将估计信息传递回相邻智能体. 这种分布式框架既可以实现某个智能体上搭建的观测器,同时又能估计自身与其邻居的故障与状态信息,解决了某些智能体无法搭建观测器的问题.

基于上述分析,本文针对由无人机和无人车组成的异构多智能体系统,通过定义新的中间变量,设计分布式中间观测器以克服多数观测器要求的观测器匹配条件,并对传统中间观测器进行了改进[16-17]. 利用自身与邻居的信息,在某一智能体上构建的观测器能同时估计自身与其邻居的执行器故障与状态,并利用H_∞性能求解出所需的观测器增益矩阵,将观测器增益矩阵求解问题转化为线性矩阵不等式的有解问题,便于参数的获取.

与现有文献相比,本文的主要贡献包括:

1) 与文献[14-17]针对同构多智能体系统进行故障估计不同,本文解决了异构多智能体系统分布式故障估计的问题;

2) 与文献[16-17]中所采用的中间观测器相比,本文设计的观测器在对中间变量进行估计时引入了输出误差的微分项,改善了估计的性能;

3) 本文采用与文献[16-17, 19-21]不同的分布式思路,通过选定关键节点,基于局部与邻居的信息在关键节点上构建观测器,实现对关键节点与其邻居执行器故障与状态的同时估计.

1 预备知识和系统描述

首先介绍一些基本知识和引理;然后介绍异构多智能体系统的动力学模型. 为了实现对异构多智能体系统的分布式故障估计,对模型进行处理.

1.1 预备知识

$\mathcal{G} = \{\mathcal{V}, \mathcal{E}, \mathcal{A}\}$被用来描述智能体之间的连通拓扑结构图. 其中:$\mathcal{V} = \{v_1, v_2, \ldots, v_N\}$代表非空点集,$\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$代表拓扑结构的边集,$\mathcal{A} = [a_{ij}]_{N\times N}$代表邻接矩阵. 边$(v_j, v_i) \in \mathcal{E}$指的是节点$v_i$可以收到$v_j$的信息,因此$v_j$被称做$v_i$的邻居. 如果$(v_j, v_i) \in \mathcal{E}$,则定义$a_{ij} > 0$,否则$a_{ij} = 0$. 另外,对于$i \in \{1, 2, \ldots, N\}$定义$a_{ii} = 0$. 对于无向图,有$a_{ij} = a_{ji}$. 拉普拉斯矩阵定义为$\mathcal{L} = \mathcal{D} - \mathcal{A}$. 定义$\bar{N}_i$代表智能体$i$自身与其邻居的集合, $|\bar{N}_i|$表示智能体i自身与其邻居集合的基数,即智能体i与其邻居的个数.

引理1 给定两个合适维度的向量X和Y,以下不等式成立:

$$X^{\mathrm{T}}Y + Y^{\mathrm{T}}X \leqslant \gamma^{-1}X^{\mathrm{T}}X + \gamma Y^{\mathrm{T}}Y, \tag{1}$$

其中γ是任意正实数.

1.2 异构多智能体系统的动力学模型

本文考虑的异构多智能体系统由多架无人机和多辆无人车组成. 所采用的无人机动力学模型基于

四旋翼无人机,无人车动力学模型基于两轮差速驱动式的移动机器人.

四旋翼无人机的动力学模型可以描述为

$$\begin{cases}\ddot{x}_i=(\cos\phi_i\sin\theta_i\cos\psi_i+\sin\phi_i\sin\psi_i)\dfrac{F_i}{M_i}-\dfrac{k_{xi}}{M_i}\dot{x}_i,\\ \ddot{y}_i=(\cos\phi_i\sin\theta_i\sin\psi_i-\sin\phi_i\cos\psi_i)\dfrac{F_i}{M_i}-\dfrac{k_{yi}}{M_i}\dot{y}_i,\\ \ddot{z}_i=(\cos\phi_i\cos\theta_i)\dfrac{F_i}{M_i}-g-\dfrac{k_{zi}}{M_i}\dot{z}_i,\\ \ddot{\phi}_i=\dot{\theta}_i\dot{\psi}_i\Big(\dfrac{I_{yi}-I_{zi}}{I_{xi}}\Big)-\dfrac{J_i}{I_{xi}}\dot{\theta}_i\Omega_i+\dfrac{\tau_{\phi i}}{I_{xi}}-\dfrac{k_{\phi i}}{I_{xi}}\dot{\phi}_i,\\ \ddot{\theta}_i=\dot{\phi}_i\dot{\psi}_i\Big(\dfrac{I_{zi}-I_{xi}}{I_{yi}}\Big)-\dfrac{J_i}{I_{yi}}\dot{\phi}_i\Omega_i+\dfrac{\tau_{\theta i}}{I_{yi}}-\dfrac{k_{\theta i}}{I_{yi}}\dot{\theta}_i,\\ \ddot{\psi}_i=\dot{\phi}_i\dot{\theta}_i\Big(\dfrac{I_{xi}-I_{yi}}{I_{zi}}\Big)+\dfrac{\tau_{\psi i}}{I_{zi}}-\dfrac{k_{\psi i}}{I_{zi}}\dot{\psi}_i.\end{cases} \tag{2}$$

其中: $X_{ai}(t)=[x_i(t),y_i(t),z_i(t)]^{\mathrm{T}}\in R^3$ 表示无人机的位置; $\phi_i(t),\theta_i(t),\psi_i(t)$ 分别表示横滚、俯仰、偏航角; I_{xi},I_{yi},I_{zi} 分别表示关于 x 轴、y 轴和 z 轴的机体转动惯量; M_i 和 J_i 分别表示质量和转动惯量; g 是重力加速度; $k_{xi},k_{yi},k_{zi},k_{\phi i},k_{\theta i},k_{\psi i}$ 表示相应轴的阻力系数; Ω_i 表示电机残差速度; F_i 是旋翼产生的升力; $\tau_{\phi i},\tau_{\theta i}$ 是由旋翼升力差异形成的升力扭矩; $\tau_{\psi i}$ 是反扭矩.

受文献[22]启发,为了简化问题,便于设计分布式观测器,本文将四旋翼的动态模型分成位置子系统和姿态子系统. 无人机的位置子系统可以改写为

$$\ddot{X}_{ai}(t)=U_{ai}(t)+f_{ai}(*,t). \tag{3}$$

其中

$$\begin{aligned}U_{ai}(t)=\Big[&(\cos\phi_i\sin\theta_i\cos\psi_i+\sin\phi_i\sin\psi_i)\frac{F_i}{M_i},\\ &(\cos\phi_i\sin\theta_i\sin\psi_i-\sin\phi_i\cos\psi_i)\frac{F_i}{M_i},\\ &(\cos\phi_i\cos\theta_i)\frac{F_i}{M_i}-g\Big]^{\mathrm{T}},\end{aligned}$$

$$f_{ai}(*,t)=\Big[-\frac{k_{xi}}{M_i}\dot{x}_i,-\frac{k_{yi}}{M_i}\dot{y}_i,-\frac{k_{zi}}{M_i}\dot{z}_i\Big]^{\mathrm{T}}.$$

无人车的动力学模型可以描述为

$$\begin{cases}\dot{x}_i(t)=v_i(t)\cos\theta_i(t),\\ \dot{y}_i(t)=v_i(t)\sin\theta_i(t),\\ \dot{\theta}_i(t)=\omega_i(t),\\ \dot{v}_i(t)=\dfrac{F_i(t)}{m_i},\\ \dot{\omega}_i(t)=\dfrac{\tau_i(t)}{J_{ri}}.\end{cases} \tag{4}$$

其中: $x_i(t)$ 和 $y_i(t)$ 分别表示第 i 个无人车在 OX 轴和 OY 轴方向上的位置; $\theta_i(t)$ 表示无人车的航向角; $v_i(t)$ 是无人车的线速度; $\omega_i(t)$ 是无人车的角速度; $F_i(t)$ 和 $\tau_i(t)$ 分别表示输入力和输入力矩; J_{ri} 和 m_i 分别表示第 i 个无人车的转动惯量和质量.

为了避免非完整约束问题,选择无人车的前部中点为参考点,定义如下:

$$\begin{cases}x_i^h(t)=x_i(t)+L_i\cos\theta_i(t),\\ y_i^h(t)=y_i(t)+L_i\sin\theta_i(t),\end{cases} \tag{5}$$

其中 L_i 表示前部中点和两轮中点之间的距离. 定义无人车参考点的坐标 $X_i^h(t)=[x_i^h(t),y_i^h(t)]^{\mathrm{T}}$. 对式(5)取微分并将(4)代入,可得

$$\ddot{X}_i^h(t)=\begin{bmatrix}\ddot{x}_i^h(t)\\ \ddot{y}_i^h(t)\end{bmatrix}=\begin{bmatrix}u_{xi}(t)\\ u_{yi}(t)\end{bmatrix}. \tag{6}$$

其中虚拟控制输入定义为

$$\begin{cases}u_{xi}(t)=\cos\theta_i(t)\dfrac{F_i(t)}{m_i}-L_i\sin\theta_i(t)\dfrac{\tau_i(t)}{J_{ri}}-\\ \qquad v_i(t)\omega_i(t)\sin\theta_i(t)-L_i\omega_i^2(t)\cos\theta_i(t),\\ u_{yi}(t)=\sin\theta_i(t)\dfrac{F_i(t)}{m_i}+L_i\cos\theta_i(t)\dfrac{\tau_i(t)}{J_{ri}}+\\ \qquad v_i(t)\omega_i(t)\cos\theta_i(t)-L_i\omega_i^2(t)\sin\theta_i(t).\end{cases}$$

1.3 问题描述

针对无人机和无人车组成的异构多智能体系统,对其进行分布式故障估计的难点在于无人机和无人车有着不同的状态维度. 考虑到无人机在 XOY 平面与在 OZ 轴方向的运动相对独立,将无人机的 XOY 平面和 OZ 轴分开考虑,分别对无人机与无人车位置子系统的 XOY 平面和无人机位置子系统的 OZ 轴进行分布式观测. 无人机与无人车位置子系统的 XOY 平面运动模型统一成如下形式:

$$\begin{cases}\dot{p}_i(t)=v_i(t),\\ \dot{v}_i(t)=u_i^f(t)+f_i(x_i,t),\ i=1,2,\ldots,N.\end{cases} \tag{7}$$

其中: $p_i(t)\in R^2,v_i(t)\in R^2$ 分别表示第 i 个智能体的位置和速度; $u_i^f(t)\in R^2$ 表示执行器实际输出; $f_i(x_i,t)\in R^2$ 表示非线性项.

本文考虑的执行器故障是加性故障,执行器故障模型可以描述为

$$u_i^f(t)=u_i(t)+b_i(t). \tag{8}$$

其中: $u_i(t)\in R^2$ 为控制输入, $b_i(t)\in R^2$ 为加性故障.

假设1 非线性项 $f_i(x_i,t)$ 是已知的,且满足Lipschitz条件

$$\|f_i(x_i,t)-f_i(x_j,t)\|\leqslant\lambda_i\|x_i(t)-x_j(t)\|, \tag{9}$$

其中 λ_i 是Lipschitz常数.

无人机位置子系统 OZ 轴的模型也可以用式(7)的形式描述,此时 $p_i(t),v_i(t),u_i^f(t),u_i(t),f_i(x_i,t),$

$b_i(t) \in R$.

假设每个智能体能获取到的信息只有位置信息,速度信息不可知. 将式(7)改写成如下状态空间的形式:

$$\begin{cases}\dot{x}_i(t) = Ax_i(t) + B[u_i(t) + f_i(x_i, t) + b_i(t)],\\ y_i(t) = Cx_i(t).\end{cases} \tag{10}$$

其中: $x_i(t) = [{p_i}^{\mathrm{T}}(t), v_i^{\mathrm{T}}(t)]^{\mathrm{T}}, A \in R^{4\times 4}, B \in R^{4\times 2}$, $C \in R^{2\times 4}$ 均易根据式(7)推得.

注1 每个智能体能获取到的信息只有位置信息,因而根据式(7)推导出的状态空间模型(10)不满足文献[15]中的观测器匹配条件. 为了克服观测器匹配条件的限制,下文将设计中间观测器来实现分布式故障估计.

2 分布式观测器设计

为了实现分布式故障估计,首先考虑将第 i 个智能体与其邻居智能体的状态写成如下的紧致型:

$$x_{|\bar{N}_i|}(t) = [x_{i_1}^{\mathrm{T}}(t), x_{i_2}^{\mathrm{T}}(t), \ldots, x_{i_{|\bar{N}_i|}}^{\mathrm{T}}(t)]^{\mathrm{T}},$$

其中 $i = i_1$.

根据新定义的状态变量可以得到新的状态空间形式的系统描述,即

$$\begin{cases}\dot{x}_{|\bar{N}_i|}(t) = A_{|\bar{N}_i|}x_{|\bar{N}_i|}(t) + B_{|\bar{N}_i|}u_{|\bar{N}_i|}(t) + \\ \qquad B_{|\bar{N}_i|}f_{|\bar{N}_i|}(x_{|\bar{N}_i|}, t) + B_{|\bar{N}_i|}b_{|\bar{N}_i|}(t),\\ y_{|\bar{N}_i|}(t) = C_{|\bar{N}_i|}x_{|\bar{N}_i|}(t).\end{cases} \tag{11}$$

其中: $A_{|\bar{N}_i|} = I_{|\bar{N}_i|} \otimes A, B_{|\bar{N}_i|} = I_{|\bar{N}_i|} \otimes B, C_{|\bar{N}_i|} = I_{|\bar{N}_i|} \otimes C, u_{|\bar{N}_i|}(t) = [u_{i_1}^{\mathrm{T}}(t), u_{i_2}^{\mathrm{T}}(t), \ldots, u_{i_{|\bar{N}_i|}}^{\mathrm{T}}(t)]^{\mathrm{T}}$, $b_{|\bar{N}_i|}(t) = [b_{i_1}^{\mathrm{T}}(t), b_{i_2}^{\mathrm{T}}(t), \ldots, b_{i_{|\bar{N}_i|}}^{\mathrm{T}}(t)]^{\mathrm{T}}, f_{|\bar{N}_i|}(t) = [f_{i_1}^{\mathrm{T}}(t), f_{i_2}^{\mathrm{T}}(t), \ldots, f_{i_{|\bar{N}_i|}}^{\mathrm{T}}(t)]^{\mathrm{T}}$.

注2 这里将选定的智能体与其邻居的状态定义成新的状态变量,能够避免由于某些智能体无法构建观测器而无法估计故障的情况,可以实现构建在某个智能体上的观测器能够同时估计自身与其邻居的执行器故障与状态.

接着,为了克服观测器匹配条件的限制,引入如下的中间变量:

$$\xi_{|\bar{N}_i|}(t) = b_{|\bar{N}_i|}(t) - M_{|\bar{N}_i|}x_{|\bar{N}_i|}(t), \tag{12}$$

其中 $M_{|\bar{N}_i|}$ 是下文需要设计的参数.

根据式(11)和(12)可得

$$\begin{aligned}\dot{\xi}_{|\bar{N}_i|}(t) = &\ \dot{b}_{|\bar{N}_i|}(t) - M_{|\bar{N}_i|}(A_{|\bar{N}_i|}x_{|\bar{N}_i|}(t) + \\ & B_{|\bar{N}_i|}u_{|\bar{N}_i|}(t) + B_{|\bar{N}_i|}f_{|\bar{N}_i|}(x_{|\bar{N}_i|}, t) + \\ & B_{|\bar{N}_i|}b_{|\bar{N}_i|}(t)).\end{aligned} \tag{13}$$

根据式(11)和(13),设计如下的中间观测器:

$$\begin{aligned}\dot{\hat{x}}_{|\bar{N}_i|}(t) = &\ A_{|\bar{N}_i|}\hat{x}_{|\bar{N}_i|}(t) + B_{|\bar{N}_i|}u_{|\bar{N}_i|}(t) + \\ & B_{|\bar{N}_i|}\hat{b}_{|\bar{N}_i|}(t) + B_{|\bar{N}_i|}f_{|\bar{N}_i|}(\hat{x}_{|\bar{N}_i|}, t) - \\ & K_{|\bar{N}_i|}(\hat{y}_{|\bar{N}_i|}(t) - y_{|\bar{N}_i|}(t)),\end{aligned} \tag{14a}$$

$$\begin{aligned}&\dot{\hat{\xi}}_{|\bar{N}_i|}(t) = \\ & - M_{|\bar{N}_i|}(A_{|\bar{N}_i|}\hat{x}_{|\bar{N}_i|}(t) + B_{|\bar{N}_i|}u_{|\bar{N}_i|}(t) + \\ & B_{|\bar{N}_i|}f_{|\bar{N}_i|}(\hat{x}_{|\bar{N}_i|}, t) + B_{|\bar{N}_i|}M_{|\bar{N}_i|}\hat{x}_{|\bar{N}_i|}(t)) - \\ & M_{|\bar{N}_i|}B_{|\bar{N}_i|}\hat{\xi}_{|\bar{N}_i|}(t) - L_{|\bar{N}_i|}(\dot{\hat{y}}_{|\bar{N}_i|}(t) - \dot{y}_{|\bar{N}_i|}(t)),\end{aligned} \tag{14b}$$

$$\hat{y}_{|\bar{N}_i|}(t) = C_{|\bar{N}_i|}\hat{x}_{|\bar{N}_i|}(t), \tag{14c}$$

$$\hat{b}_{|\bar{N}_i|}(t) = \hat{\xi}_{|\bar{N}_i|}(t) + M_{|\bar{N}_i|}\hat{x}_{|\bar{N}_i|}(t). \tag{14d}$$

其中 $\hat{x}_{|\bar{N}_i|}(t), \hat{\xi}_{|\bar{N}_i|}(t), \hat{b}_{|\bar{N}_i|}(t), \hat{y}_{|\bar{N}_i|}(t)$ 分别是对变量 $x_{|\bar{N}_i|}(t), \xi_{|\bar{N}_i|}(t), b_{|\bar{N}_i|}(t), y_{|\bar{N}_i|}(t)$ 的估计. $M_{|\bar{N}_i|}$ 参数设计为

$$M_{|\bar{N}_i|} = \kappa_{|\bar{N}_i|}B_{|\bar{N}_i|}^{\mathrm{T}}. \tag{15}$$

其中: $\kappa_{|\bar{N}_i|}$ 是选定的常数; $K_{|\bar{N}_i|} \in R^{4|\bar{N}_i|\times 2|\bar{N}_i|}$ 和 $L_{|\bar{N}_i|} \in R^{2|\bar{N}_i|\times 2|\bar{N}_i|}$ 是需要设计的观测器参数.

定义状态变量和中间变量的估计误差为 $\tilde{x}_{|\bar{N}_i|}(t) = \hat{x}_{|\bar{N}_i|}(t) - x_{|\bar{N}_i|}(t), \tilde{\xi}_{|\bar{N}_i|}(t) = \hat{\xi}_{|\bar{N}_i|}(t) - \xi_{|\bar{N}_i|}(t)$. 根据式(11)、(13)和(14)可以得到如下误差动态方程:

$$\begin{aligned}\dot{\tilde{x}}_{|\bar{N}_i|}(t) = &\ B_{|\bar{N}_i|}\tilde{\xi}_{|\bar{N}_i|}(t) + B_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) + (A_{|\bar{N}_i|} - \\ & K_{|\bar{N}_i|}C_{|\bar{N}_i|} + B_{|\bar{N}_i|}M_{|\bar{N}_i|})\tilde{x}_{|\bar{N}_i|}(t),\end{aligned} \tag{16a}$$

$$\begin{aligned}\dot{\tilde{\xi}}_{|\bar{N}_i|}(t) = &\ - M_{|\bar{N}_i|}(A_{|\bar{N}_i|} + B_{|\bar{N}_i|}M_{|\bar{N}_i|})\tilde{x}_{|\bar{N}_i|}(t) - \\ & M_{|\bar{N}_i|}B_{|\bar{N}_i|}(\tilde{\xi}_{|\bar{N}_i|}(t) + \tilde{f}_{|\bar{N}_i|}(t)) - \\ & \dot{b}_{|\bar{N}_i|}(t) - L_{|\bar{N}_i|}C_{|\bar{N}_i|}\dot{\tilde{x}}_{|\bar{N}_i|}(t),\end{aligned} \tag{16b}$$

其中 $\tilde{f}_{|\bar{N}_i|}(t) = f_{|\bar{N}_i|}(\hat{x}_{|\bar{N}_i|}, t) - f_{|\bar{N}_i|}(x_{|\bar{N}_i|}, t)$. 由于非线性项 $f_i(x_i, t)$ 满足Lipschitz条件,可以得到如下不等式:

$$\tilde{f}_{|\bar{N}_i|}(t)^{\mathrm{T}}\tilde{f}_{|\bar{N}_i|}(t) \leqslant \lambda_{|\bar{N}_i|}^2\tilde{x}_{|\bar{N}_i|}(t)^{\mathrm{T}}\tilde{x}_{|\bar{N}_i|}(t), \tag{17}$$

其中 $\lambda_{|\bar{N}_i|} = \max\{\lambda_{i_1}, \lambda_{i_2}, \ldots, \lambda_{i_{|\bar{N}_i|}}\}$.

定义 $e_{|\bar{N}_i|}(t) = [\tilde{x}_{|\bar{N}_i|}^{\mathrm{T}}(t), \tilde{\xi}_{|\bar{N}_i|}^{\mathrm{T}}(t)]^{\mathrm{T}}$, 式(16a)和(16b)可以改写为

$$\begin{aligned}&T_{|\bar{N}_i|}\dot{e}_{|\bar{N}_i|}(t) = \\ &\bar{A}_{|\bar{N}_i|}e_{|\bar{N}_i|}(t) + \bar{F}_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) + \bar{B}_{|\bar{N}_i|}\dot{b}_{|\bar{N}_i|}(t).\end{aligned} \tag{18}$$

其中

$$T_{|\bar{N}_i|} = \begin{bmatrix} I & 0 \\ L_{|\bar{N}_i|}C_{|\bar{N}_i|} & I \end{bmatrix},$$

$$\bar{F}_{|\bar{N}_i|} = \begin{bmatrix} B_{|\bar{N}_i|} \\ -M_{|\bar{N}_i|}B_{|\bar{N}_i|} \end{bmatrix},\ \bar{B}_{|\bar{N}_i|} = \begin{bmatrix} 0 \\ -I \end{bmatrix},$$

$$\bar{A}_{|\bar{N}_i|} = \begin{bmatrix} A_{|\bar{N}_i|} + B_{|\bar{N}_i|}M_{|\bar{N}_i|} - K_{|\bar{N}_i|}C_{|\bar{N}_i|} & B_{|\bar{N}_i|} \\ -M_{|\bar{N}_i|}(A_{|\bar{N}_i|} + B_{|\bar{N}_i|}M_{|\bar{N}_i|}) & -M_{|\bar{N}_i|}B_{|\bar{N}_i|} \end{bmatrix}.$$

根据文献[18],为了限制$\dot{b}_{|\bar{N}_i|}(t)$对$\tilde{b}_{|\bar{N}_i|}(t) = \hat{b}_{|\bar{N}_i|}(t) - b_{|\bar{N}_i|}(t)$的影响,基于下式设计观测器参数:

$$\min_{\gamma_{|\bar{N}_i|}>0, K_{|\bar{N}_i|}, L_{|\bar{N}_i|}} \gamma_{|\bar{N}_i|};$$

$$\text{s.t. } \|G_{\dot{b}_{|\bar{N}_i|}(t)\tilde{b}_{|\bar{N}_i|}(t)}(s)\|_\infty < \gamma_{|\bar{N}_i|}. \tag{19}$$

其中$\gamma_{|\bar{N}_i|}$是H_∞性能水平.

定理1　对于给定的常数$\kappa_{|\bar{N}_i|}, \gamma_{|\bar{N}_i|}$,如果存在对称正定矩阵$P_{|\bar{N}_i|1} \in R^{4|\bar{N}_i|\times 4|\bar{N}_i|}$和$P_{|\bar{N}_i|2} \in R^{2|\bar{N}_i|\times 2|\bar{N}_i|}$,矩阵$Q_{|\bar{N}_i|1} \in R^{4|\bar{N}_i|\times 2|\bar{N}_i|}$和$Q_{|\bar{N}_i|2} \in R^{2|\bar{N}_i|\times 2|\bar{N}_i|}$,正数$\mu_{|\bar{N}_i|}$使得下述LMI成立,则全局误差动态系统(18)在如式(19)定义的H_∞性能指标下是渐近稳定的.

$$\bar{\Lambda} = \begin{bmatrix} \bar{\Lambda}_1 & \bar{\Lambda}_2 & \bar{\Lambda}_3 \\ * & -\gamma_{|\bar{N}_i|} & 0 \\ * & * & -\mu_{|\bar{N}_i|} \end{bmatrix} < 0. \tag{20}$$

其中

$$\bar{\Lambda}_1 = \begin{bmatrix} \bar{\Lambda}_{11} & \Theta_{12} \\ * & \Theta_{22} \end{bmatrix},\ \bar{\Lambda}_2 = \begin{bmatrix} \bar{\Lambda}_{13} & M^{\mathrm{T}}_{|\bar{N}_i|} \\ -P_{|\bar{N}_i|2} & I \end{bmatrix},$$

$$\bar{\Lambda}_3 = \begin{bmatrix} \bar{\Lambda}_{15} & \bar{\Lambda}_{16} & 0 \\ 0 & 0 & \bar{\Lambda}_{27} \end{bmatrix};$$

$$\bar{\Lambda}_{11} = \Theta_{11} + 3\mu_{|\bar{N}_i|}\lambda^2_{|\bar{N}_i|},\ \bar{\Lambda}_{13} = -C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2},$$

$$\bar{\Lambda}_{15} = P_{|\bar{N}_i|1}B_{|\bar{N}_i|},\ \bar{\Lambda}_{16} = C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|},$$

$$\bar{\Lambda}_{27} = P_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}.$$

观测器参数

$$K_{|\bar{N}_i|} = (P_{|\bar{N}_i|1})^{-1}Q_{|\bar{N}_i|1},$$

$$L_{|\bar{N}_i|} = (P_{|\bar{N}_i|2})^{-1}Q_{|\bar{N}_i|2}.$$

证明　考虑如下Lyapunov函数:

$$V(t) = e^{\mathrm{T}}_{|\bar{N}_i|}(t)(T^{\mathrm{T}}_{|\bar{N}_i|}P_{|\bar{N}_i|}T_{|\bar{N}_i|})e_{|\bar{N}_i|}(t), \tag{21}$$

其中$P_{|\bar{N}_i|} = \mathrm{diag}\{P_{|\bar{N}_i|1}, P_{|\bar{N}_i|2}\} \in R^{6|\bar{N}_i|\times 6|\bar{N}_i|}$.

对式(21)求导,可得

$$\begin{aligned}
&\dot{V}(t) = \\
&2e^{\mathrm{T}}_{|\bar{N}_i|}(t)T^{\mathrm{T}}_{|\bar{N}_i|}P_{|\bar{N}_i|}(\bar{A}_{|\bar{N}_i|}e_{|\bar{N}_i|}(t) + \\
&\bar{F}_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) + \bar{B}_{|\bar{N}_i|}\dot{b}_{|\bar{N}_i|}(t)) = \\
&\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)\Theta_{11}\tilde{x}_{|\bar{N}_i|}(t) + 2\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)\Theta_{12}\tilde{\xi}_{|\bar{N}_i|}(t) + \\
&2\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)P_{|\bar{N}_i|1}B_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) - \\
&2\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) - \\
&2\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}\dot{b}_{|\bar{N}_i|}(t) - \\
&2\tilde{\xi}^{\mathrm{T}}_{|\bar{N}_i|}(t)P_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) - \\
&2\tilde{\xi}^{\mathrm{T}}_{|\bar{N}_i|}(t)P_{|\bar{N}_i|2}\dot{b}_{|\bar{N}_i|}(t) + \tilde{\xi}^{\mathrm{T}}_{|\bar{N}_i|}(t)\Theta_{22}\tilde{\xi}_{|\bar{N}_i|}(t).
\end{aligned} \tag{22}$$

其中

$$\begin{aligned}
&\Theta_{11} = \\
&\mathrm{He}(P_{|\bar{N}_i|1}A_{|\bar{N}_i|} - Q_{|\bar{N}_i|1}C_{|\bar{N}_i|} + P_{|\bar{N}_i|1}B_{|\bar{N}_i|}M_{|\bar{N}_i|} - \\
&C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}M_{|\bar{N}_i|}(A_{|\bar{N}_i|} + B_{|\bar{N}_i|}M_{|\bar{N}_i|})),\\
&\Theta_{12} = P_{|\bar{N}_i|1}B_{|\bar{N}_i|} - C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|} - \\
&\qquad (A_{|\bar{N}_i|} + B_{|\bar{N}_i|}M_{|\bar{N}_i|})^{\mathrm{T}}M^{\mathrm{T}}_{|\bar{N}_i|}P_{|\bar{N}_i|2},\\
&\Theta_{22} = \mathrm{He}(-P_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}).
\end{aligned}$$

根据式(17),可得如下不等式成立:

$$\begin{aligned}
&2\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)P_{|\bar{N}_i|1}B_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) \leqslant \\
&\mu^{-1}_{|\bar{N}_i|}\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)P_{|\bar{N}_i|1}B_{|\bar{N}_i|}B^{\mathrm{T}}_{|\bar{N}_i|}P_{|\bar{N}_i|1}\tilde{x}_{|\bar{N}_i|}(t) + \\
&\mu_{|\bar{N}_i|}\lambda^2_{|\bar{N}_i|}\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)\tilde{x}_{|\bar{N}_i|}(t),
\end{aligned} \tag{23a}$$

$$\begin{aligned}
&-2\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) \leqslant \\
&\mu^{-1}_{|\bar{N}_i|}\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}B^{\mathrm{T}}_{|\bar{N}_i|}M^{\mathrm{T}}_{|\bar{N}_i|} \times \\
&Q_{|\bar{N}_i|2}C_{|\bar{N}_i|}\tilde{x}_{|\bar{N}_i|}(t) + \mu_{|\bar{N}_i|}\lambda^2_{|\bar{N}_i|}\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)\tilde{x}_{|\bar{N}_i|}(t),
\end{aligned} \tag{23b}$$

$$\begin{aligned}
&-2\tilde{\xi}^{\mathrm{T}}_{|\bar{N}_i|}(t)P_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}\tilde{f}_{|\bar{N}_i|}(t) \leqslant \\
&\mu^{-1}_{|\bar{N}_i|}\tilde{\xi}^{\mathrm{T}}_{|\bar{N}_i|}(t)P_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}B^{\mathrm{T}}_{|\bar{N}_i|}M^{\mathrm{T}}_{|\bar{N}_i|}P_{|\bar{N}_i|2} \times \\
&\tilde{\xi}_{|\bar{N}_i|}(t) + \mu_{|\bar{N}_i|}\lambda^2_{|\bar{N}_i|}\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)\tilde{x}_{|\bar{N}_i|}(t).
\end{aligned} \tag{23c}$$

根据式(23),(22)可写成如下形式:

$$\begin{aligned}
&\dot{V}(t) \leqslant \\
&\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)(\Theta_{11} + 3\mu_{|\bar{N}_i|}\lambda^2_{|\bar{N}_i|} + \\
&\mu^{-1}_{|\bar{N}_i|}P_{|\bar{N}_i|1}B_{|\bar{N}_i|}B^{\mathrm{T}}_{|\bar{N}_i|}P_{|\bar{N}_i|1} + \\
&\mu^{-1}_{|\bar{N}_i|}C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}B^{\mathrm{T}}_{|\bar{N}_i|} \times \\
&M^{\mathrm{T}}_{|\bar{N}_i|}Q_{|\bar{N}_i|2}C_{|\bar{N}_i|})\tilde{x}_{|\bar{N}_i|}(t) + \tilde{\xi}^{\mathrm{T}}_{|\bar{N}_i|}(t)(\Theta_{22} + \\
&\mu^{-1}_{|\bar{N}_i|}P_{|\bar{N}_i|2}M_{|\bar{N}_i|}B_{|\bar{N}_i|}B^{\mathrm{T}}_{|\bar{N}_i|}M^{\mathrm{T}}_{|\bar{N}_i|}P_{|\bar{N}_i|2})\tilde{\xi}_{|\bar{N}_i|}(t) + \\
&2\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)\Theta_{12}\tilde{\xi}_{|\bar{N}_i|}(t) - 2\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)C^{\mathrm{T}}_{|\bar{N}_i|}Q^{\mathrm{T}}_{|\bar{N}_i|2}\dot{b}_{|\bar{N}_i|}(t) - \\
&2\tilde{\xi}_{|\bar{N}_i|}(t)^{\mathrm{T}}P_{|\bar{N}_i|2}\dot{b}_{|\bar{N}_i|}(t).
\end{aligned} \tag{24}$$

分两种情况考虑.

情况1　$\dot{b}_{|\bar{N}_i|}(t) = 0$.

式(24)可以整理为

$$\begin{aligned}
&\dot{V}(t) \leqslant \\
&\tilde{x}^{\mathrm{T}}_{|\bar{N}_i|}(t)(\Theta_{11} + 3\mu_{|\bar{N}_i|}\lambda^2_{|\bar{N}_i|} + \\
&\mu^{-1}_{|\bar{N}_i|}P_{|\bar{N}_i|1}B_{|\bar{N}_i|}B^{\mathrm{T}}_{|\bar{N}_i|}P_{|\bar{N}_i|1} +
\end{aligned}$$

$$\mu_{|\bar N_i|}^{-1}C_{|\bar N_i|}^{\mathrm T}Q_{|\bar N_i|2}^{\mathrm T}M_{|\bar N_i|}B_{|\bar N_i|}B_{|\bar N_i|}^{\mathrm T}\times M_{|\bar N_i|}^{\mathrm T}Q_{|\bar N_i|2}C_{|\bar N_i|})\tilde x_{|\bar N_i|}(t)+\tilde\xi_{|\bar N_i|}^{\mathrm T}(t)(\varTheta_{22}+\mu_{|\bar N_i|}^{-1}P_{|\bar N_i|2}M_{|\bar N_i|}B_{|\bar N_i|}B_{|\bar N_i|}^{\mathrm T}M_{|\bar N_i|}^{\mathrm T}P_{|\bar N_i|2})\tilde\xi_{|\bar N_i|}(t)+2\tilde x_{|\bar N_i|}^{\mathrm T}(t)\varTheta_{12}\tilde\xi_{|\bar N_i|}(t)\leqslant \begin{bmatrix}\tilde x_{|\bar N_i|}(t)\\ \tilde\xi_{|\bar N_i|}(t)\end{bmatrix}^{\mathrm T}\begin{bmatrix}\varXi_{11} & \varXi_{12}\\ * & \varXi_{22}\end{bmatrix}\begin{bmatrix}\tilde x_{|\bar N_i|}(t)\\ \tilde\xi_{|\bar N_i|}(t)\end{bmatrix}. \tag{25}$$

其中

$$\varXi_{11}=\varTheta_{11}+3\mu_{|\bar N_i|}\lambda_{|\bar N_i|}^2+\mu_{|\bar N_i|}^{-1}P_{|\bar N_i|1}B_{|\bar N_i|}B_{|\bar N_i|}^{\mathrm T}P_{|\bar N_i|1}+\mu_{|\bar N_i|}^{-1}C_{|\bar N_i|}^{\mathrm T}Q_{|\bar N_i|2}^{\mathrm T}M_{|\bar N_i|}B_{|\bar N_i|}B_{|\bar N_i|}^{\mathrm T}M_{|\bar N_i|}^{\mathrm T}Q_{|\bar N_i|2}C_{|\bar N_i|},$$

$$\varXi_{12}=\varTheta_{12},$$

$$\varXi_{22}=\varTheta_{22}+\mu_{|\bar N_i|}^{-1}P_{|\bar N_i|2}M_{|\bar N_i|}B_{|\bar N_i|}B_{|\bar N_i|}^{\mathrm T}\times M_{|\bar N_i|}^{\mathrm T}P_{|\bar N_i|2}.$$

如果 $\begin{bmatrix}\varXi_{11} & \varXi_{12}\\ * & \varXi_{22}\end{bmatrix}<0$ 成立,可得 $\dot V(t)<0$,此时全局误差动态方程(18)在 $\dot b_{|\bar N_i|}(t)=0$ 的情况下是渐近稳定的.

情况2 $\dot b_{|\bar N_i|}(t)\neq 0$.

定义 $J(t)=\dot V(t)+\gamma_{|\bar N_i|}^{-1}\tilde b_{|\bar N_i|}^{\mathrm T}(t)\tilde b_{|\bar N_i|}(t)-\gamma_{|\bar N_i|}\dot b_{|\bar N_i|}^{\mathrm T}(t)\dot b_{|\bar N_i|}(t)$,根据式(24),可得

$$J(t)=\dot V(t)+\gamma_{|\bar N_i|}^{-1}(\tilde\xi_{|\bar N_i|}(t)+M_{|\bar N_i|}\tilde x_{|\bar N_i|}(t))^{\mathrm T}\times(\tilde\xi_{|\bar N_i|}(t)+M_{|\bar N_i|}\tilde x_{|\bar N_i|}(t))-\gamma_{|\bar N_i|}\dot b_{|\bar N_i|}^{\mathrm T}(t)\times\dot b_{|\bar N_i|}(t)=\dot V(t)+\gamma_{|\bar N_i|}^{-1}(\tilde x_{|\bar N_i|}^{\mathrm T}(t)M_{|\bar N_i|}^{\mathrm T}M_{|\bar N_i|}\tilde x_{|\bar N_i|}(t)+2\tilde x_{|\bar N_i|}^{\mathrm T}(t)M_{|\bar N_i|}^{\mathrm T}\tilde\xi_{|\bar N_i|}(t)+\tilde\xi_{|\bar N_i|}^{\mathrm T}(t)\tilde\xi_{|\bar N_i|}(t))-\gamma_{|\bar N_i|}\dot b_{|\bar N_i|}^{\mathrm T}(t)\dot b_{|\bar N_i|}(t). \tag{26}$$

在零初始条件下,有

$$\int_0^t J(s)\mathrm ds=V(t)+\int_0^t\gamma_{|\bar N_i|}^{-1}\tilde b_{|\bar N_i|}^{\mathrm T}(s)\tilde b_{|\bar N_i|}(s)\mathrm ds-\int_0^t\gamma_{|\bar N_i|}\dot b_{|\bar N_i|}^{\mathrm T}(s)\dot b_{|\bar N_i|}(s)\mathrm ds.$$

此时,$J(t)<0$ 意味着 $\int_0^t\gamma_{|\bar N_i|}^{-1}\tilde b_{|\bar N_i|}^{\mathrm T}(s)\tilde b_{|\bar N_i|}(s)\mathrm ds<\int_0^t\gamma_{|\bar N_i|}\dot b_{|\bar N_i|}^{\mathrm T}(s)\dot b_{|\bar N_i|}(s)\mathrm ds$. 根据式(24),可得

$$J(t)\leqslant\begin{bmatrix}\tilde x_{|\bar N_i|}(t)\\ \tilde\xi_{|\bar N_i|}(t)\\ \dot b_{|\bar N_i|}(t)\end{bmatrix}^{\mathrm T}\varLambda\begin{bmatrix}\tilde x_{|\bar N_i|}(t)\\ \tilde\xi_{|\bar N_i|}(t)\\ \dot b_{|\bar N_i|}(t)\end{bmatrix}. \tag{27}$$

其中

$$\varLambda=\begin{bmatrix}\varLambda_{11} & \varLambda_{12} & \varLambda_{13}\\ * & \varLambda_{22} & -P_{|\bar N_i|2}\\ * & * & -\gamma_{|\bar N_i|}\end{bmatrix};$$

$$\varLambda_{11}=\varXi_{11}+\gamma_{|\bar N_i|}^{-1}M_{|\bar N_i|}^{\mathrm T}M_{|\bar N_i|},$$

$$\varLambda_{12}=\varXi_{12}+\gamma_{|\bar N_i|}^{-1}M_{|\bar N_i|}^{\mathrm T},$$

$$\varLambda_{13}=-C_{|\bar N_i|}^{\mathrm T}Q_{|\bar N_i|2}^{\mathrm T},\ \varLambda_{22}=\varXi_{22}+\gamma_{|\bar N_i|}^{-1}.$$

根据Schur补引理,$\varLambda<0$ 等价于 $\bar\varLambda<0$. 同时,如果式(20)成立,也可以得到 $\begin{bmatrix}\varXi_{11} & \varXi_{12}\\ * & \varXi_{22}\end{bmatrix}<0$ 成立,从而全局误差动态方程(18)在如式(19)定义的 H_∞ 性能指标下是渐近稳定的. □

注3 根据构建的中间观测器(14a),(14b)和(14d),可以得到如下故障估计算法:

$$\dot{\hat b}_{|\bar N_i|}(t)=-L_{|\bar N_i|}(\dot{\hat y}_{|\bar N_i|}(t)-\dot y_{|\bar N_i|}(t))-K_{|\bar N_i|}(\hat y_{|\bar N_i|}(t)-y_{|\bar N_i|}(t)).$$

本文所提出中间观测器的故障估计算法同时包含比例项和积分项,形式如下:

$$\hat b_{|\bar N_i|}(t)=-L_{|\bar N_i|}(\hat y_{|\bar N_i|}(t)-y_{|\bar N_i|}(t))-\int_{t_f}^t K_{|\bar N_i|}(\hat y_{|\bar N_i|}(t)-y_{|\bar N_i|}(t))\mathrm ds,$$

其中 t_f 是故障发生的时间. 与文献[16]只包含输出估计误差的积分项相比,比例项的引入有利于提高故障估计的快速性,有助于改善故障估计的性能.

注4 在文献[16-17]中所采用的分布式结构下,某个智能体上构建的观测器只能估计出其自身的故障信息. 考虑到在实际中某些智能体无法构建观测器,本文对分布式结构进行了改进,实现了在某个智能体上构建的观测器能同时估计出自身与其邻居的故障与状态信息. 这里提出一种简单选定构建观测器的智能体方法,具体步骤如下.

step 1: 选择邻居数最多且能构建观测器的智能体为关键节点.

step 2: 在拓扑结构中去掉关键节点与其相邻节点,在剩下的通讯拓扑中根据step 1中同样的方法继续选择关键节点.

step 3: 如果拓扑中还剩下没有邻居且无法构建观测器的节点 i,则选定 i 的邻居 j 为关键节点.

至此,选择需要构建观测器的智能体步骤完成.

3 仿 真

考虑异构多智能体系统由2架无人机和2辆无人车组成,拓扑网络如图1所示. 其中:1和2代表无

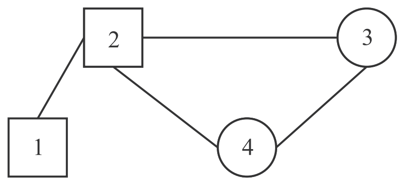

图1 连通拓扑图

人车, 3和4代表无人机. 仿真中所参考的无人机和无人车参数可以在文献[22]中找到.

假设4个智能体发生如下故障:

$$b_{1x}=\begin{cases}0,\ 0\leqslant t\leqslant 4\,\mathrm{s},\ 7\,\mathrm{s}<t\leqslant 10\,\mathrm{s};\\ 0.3t,\ 4\,\mathrm{s}<t\leqslant 7\,\mathrm{s};\end{cases}$$

$$b_{2x}=\begin{cases}0,\ 0\leqslant t\leqslant 2\,\mathrm{s},\ 8\,\mathrm{s}<t\leqslant 10\,\mathrm{s};\\ 2,\ 2\,\mathrm{s}<t\leqslant 4\,\mathrm{s};\\ \sin(6t-1),\ 4\,\mathrm{s}<t\leqslant 8\,\mathrm{s};\end{cases}$$

$$b_{3z}=-0.3\cos(4t);$$

$$b_{4z}=-0.5\sin(3.5t).$$

为使图1所示的异构多智能体系统能够在只有位置信息可知、速度信息不可知且出现执行器故障的情况下实现编队, 控制输入信号采用文献[23]所设计的方法.

正如前文所述, 为了实现对无人机和无人车组成的异构多智能体系统的分布式故障估计, 需要对无人机和无人车的XOY平面与无人机的OZ轴分开进行分布式故障估计. 对于XOY平面的分布式故障估计, 考虑在2号智能体上构建观测器, 设定$\kappa_{|\bar{N}_2|}=5$, H_∞性能指标设定为$\gamma_{|\bar{N}_2|}=5.1$; 对于无人机OZ轴的分布式故障估计, 考虑在4号智能体上构建观测器, 设定$\kappa_{|\bar{N}_4|}=5$, H_∞性能指标设定为$\gamma_{|\bar{N}_4|}=4.8$.

图2和图3是异构多智能体系统XOY平面状态和执行器故障的估计结果, 其中图2是2号智能体XOY平面的状态及其估计值, 由于1号、3号、4号智能体可以得到相似的状态估计结果, 出于篇幅限制考虑, 这里只展示2号智能体的状态估计结果. 图3是1号、2号智能体XOY平面故障真实值和估计值的对比图. 图4和图5是3号、4号智能体OZ轴的状态和执行器故障估计结果, 其中图4是4号智能体OZ轴状态及其估计值, 同样出于篇幅限制, 只展示了4号智能体的OZ轴状态估计结果; 图5是3号、4号智能体OZ轴故障真实值与估计值的对比图. 可以看出, 本文提出的方法可以同时对构建观测器的智能体与其邻居的执行器故障和状态进行准确估计.

为了证明本文所改进的中间观测器优点, 在图6中将本文方法与文献[16]中的传统中间观测器方法进行对比, 实线是引入了输出估计误差微分项的中间观测器得到的故障估计误差曲线, 虚线是文献[16]中只有输出估计误差比例项的传统中间观测器得到的故障估计曲线. 可以看到, 在引入了输出估计误差微分项后, 故障估计响应更快, 故障估计的性能得到了提高.

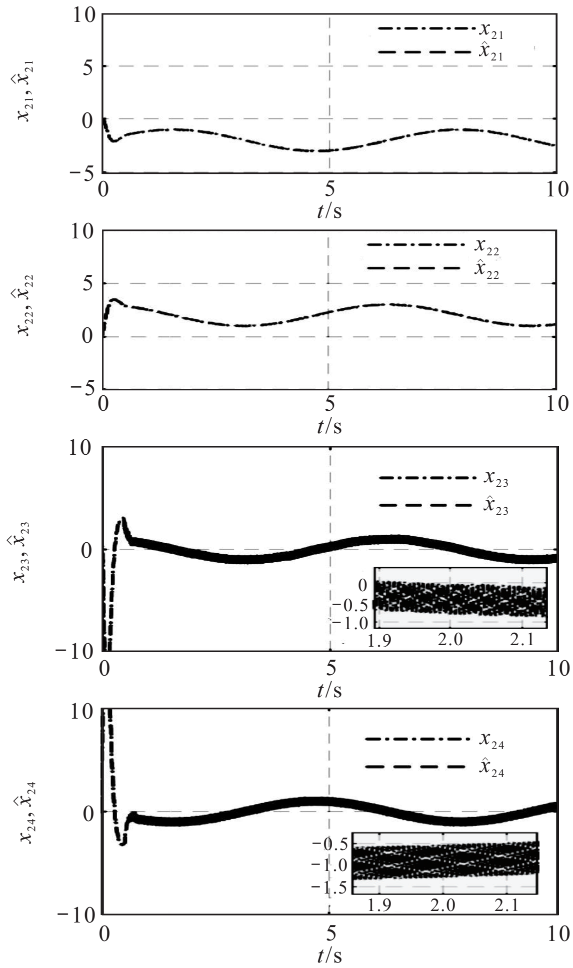

图 2　2号智能体XOY平面状态及其估计值

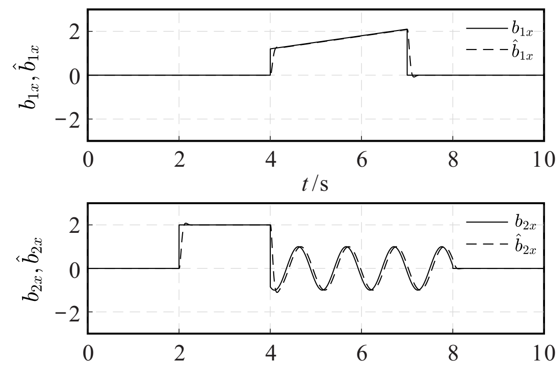

图 3　1号、2号智能体XOY平面故障及其估计值

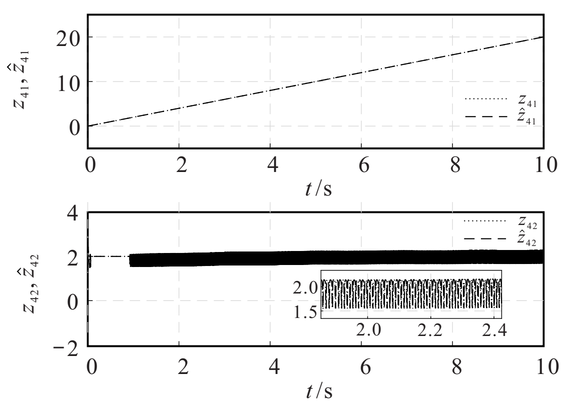

图 4　4号智能体OZ轴状态及其估计值

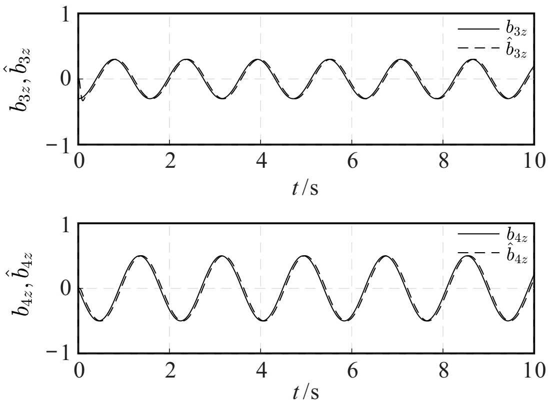

图 5 3号、4号智能体OZ轴故障及其估计值

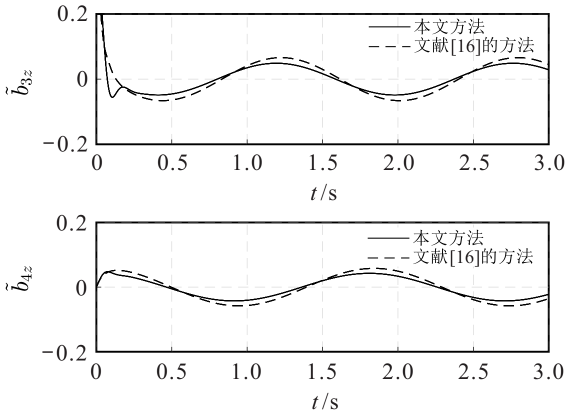

图 6 3号、4号智能体OZ轴故障估计误差

4 结论

本文针对由无人机和无人车组成的异构多智能体系统,因其无法满足常见观测器中需要的观测器匹配条件,提出了基于中间观测器的分布式故障估计方法. 无人机和无人车有着不同的状态维度,考虑到无人机在XOY平面和在OZ轴方向上的运动相对独立,对无人机和无人车位置子系统的XOY平面以及无人机的OZ轴分别进行分布式故障估计,在新的分布式框架下实现了构建在某个智能体上的观测器可以同时观测自身与邻居的执行器故障与状态,并基于H_∞性能求解观测器的增益矩阵,将增益矩阵的求解问题转化为线性矩阵不等式的有解问题,提升了所提出方法的鲁棒性. 最后通过仿真实验,验证了本文方法的有效性. 本文解决了异构多智能体系统故障估计的问题,该工作可以为容错控制提供有效的故障信息,未来将研究异构多智能体系统的主动容错控制问题.

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