

分散混杂自适应模糊 H_∞ 控制器及其在 自动化公路系统中的应用

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摘要: 本文针对一类SISO不确定非线性大系统, 提出了一种混杂间接和直接自适应分散模糊 H_∞ 控制器. 通过组合模糊系统和 H_∞ 跟踪技术开发的分散自适应模糊控制算法避免了控制设计中含有的符号函数. 两种自适应模糊控制器的组合消除了它们各自均不能够同时融合被控对象知识与控制知识的局限. 闭环大系统被证明是稳定的, 且具有 H_∞ 跟踪性能. 该算法应用于自动化公路系统中车辆的纵向跟随控制, 仿真结果表明混杂自适应模糊 H_∞ 控制系统的跟踪性能更好而相应的控制幅值却更小.

关键词: 非线性大系统; 混杂自适应模糊控制; 分散控制; H_∞ 跟踪性能; 自动化公路系统
中图分类号: TP273 **文献标识码:** A

Decentralized hybrid adaptive fuzzy H-infinity controller and its application to automated highroad systems

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Abstract: A novel decentralized hybrid indirect and direct adaptive fuzzy H-infinity controller is proposed for a class of uncertain large-scale single-input single-output(SISO) nonlinear systems in this paper. By the combination of fuzzy systems and H-infinity tracking technique, no sign function is utilized in the decentralized adaptive fuzzy control algorithm. The integration of two types of adaptive fuzzy controllers removes the limitation on the individual incorporation of plant knowledge and control knowledge. We prove that the closed-loop large-scale system is stable and possessed of H-infinity tracking performance. The algorithm is applied to the longitudinally following control of vehicles within automated highroad systems(AHS) and simulation results demonstrate better tracking properties of the hybrid adaptive fuzzy H-infinity control system with smaller control magnitudes.

Key words: large-scale nonlinear systems; hybrid adaptive fuzzy control(HAFC); decentralized control; H-infinity tracking performance; automated highroad systems

1 引言(Introduction)

近年来, 模糊控制被发现在处理复杂工程问题上具有优势^[1,2]. 自适应模糊控制分为间接与直接自适应两种结构. 文献[2,3]提出了非线性系统的间接自适应模糊控制(IAFC)算法, 而文献[2,4~7]则给出了直接自适应模糊控制(DAFC)方案. 为了克服IAFC只能融合被控对象知识而DAFC只能融合控制规则的局限性, 极少数学者提出了基于IAFC与DAFC组合的混杂自适应模糊控制(HAFC)算法^[2,8~11], 但这些控制设计存在如下问题: 1) 文献[2]的HAFC算法要求被控对象的输入增益仅是常数1, 而文献[8]的算法是建立在机器人固有的特殊物理结构之上, 故它

们均不能适用于一般的非线性系统. 2) 文献[9]虽然提出了一种输出反馈模糊神经控制算法, 其中控制器的执行需要依赖观测误差向量 \tilde{z} , 但观测误差向量在状态不可测的情况下是不可计算的; 给出的自适应律含有输入增益, 但输入增益事先又被假设是未知的. 由此可见, 文献[9]的HAFC算法比较有局限性. 3) 文献[10]所提HAFC算法是基于构造的Lyapunov函数不正确的求导得出的, 故该算法未获严格的理论证明, 有一定的局限性. 4) 在文献[11]中将其式(11)代入式(6)后不能确保跟踪误差 e 收敛于零, 故提出的理想控制器不正确, 又其本身就包含了组合系数 α , 这在理论上无法解释. 值得

指出的是, 现有国内外文献中, 关于HAFC的设计成果较少, 针对一般非线性系统的HAFC算法还有待进一步研究.

由于计算能力的局限与大范围测量的困难, 许多学者研究了大系统的分散控制算法^[12~15]. 其中, 文献[12, 13]提出了分散IAFC, 文献[13, 14]提出了分散DAFC, 文献[15]提出了分散HAFC. 但是, 文献[15]设计的控制器不但需要事先知道输入增益的边界, 而且还含有符号函数, 这会激发系统未建模高频动态, 甚至使控制系统失稳.

本文针对一类单输入单输出(SISO)不确定非线性大系统, 基于 H_∞ 跟踪与滑模控制技术提出了一种新型的分散HAFC算法. 主要工作如下: 1) 提出的分散 H_∞ 控制器不含有符号函数, 避免了控制信号的颤动; 2) 不需要输入增益的上下边界知识; 3) 控制器组合了IAFC与DAFC, 能够同时融合被控对象知识与控制规则来改善控制性能. 此外, 控制设计消除了文献[2, 8~11, 15]等存在的诸多缺点. 闭环大系统被证明所有信号最终有界, 输出误差具有 H_∞ 跟踪性能. 最后, 将该算法应用于自动化公路系统车辆的纵向跟随控制, 仿真的实验结果表明: 控制信号没有颤动, 分散HAFC系统的跟踪性能最好而所需的控制力最小.

2 问题陈述(Problem formulation)

考虑由 N 个子系统构成的一类仿射非线性大系统, 其第 i ($i = 1, \dots, N$)个子系统为

$$\begin{cases} \dot{y}_i^{(r_i)} = f_i(X_i) + g_i u_i + \Delta_i(X, t), \\ \dot{\psi}_i = W_i(X_i), \quad i = 1, \dots, N, \end{cases} \quad (1)$$

式中: $X_i = (y_i^T, \psi_i^T)^T \in \mathbb{R}^{n_i}$ 是子系统的状态向量, $y_i = (y_i, \dot{y}_i, \dots, y_i^{(r_i-1)})^T$, ψ_i 是可能的内状态, $X = (X_1^T, \dots, X_N^T)^T \in \mathbb{R}^n$; r_i 是相对阶, $u_i, y_i \in \mathbb{R}$ 分别是输入和输出变量; W_i 是连续映射, $f_i(X_i)$ 是未知但连续的非线性函数, g_i 是未知的常数. 不失一般性, 本文设 $g_i > 0$; $\Delta_i(X, t)$ 是子系统之间未知的非线性关联和外界扰动之和. 设参考输出为 y_{im} , 且 $y_{im}^{(k-1)}$ ($1 \leq k \leq n_i$) 均有界. 定义跟踪误差为 $e_i = y_{im} - y_i$, 记 $e_i = [e_i \ \dots \ e_i^{(r_i-1)}]^T$.

假设 1 相对阶 $r_i < n_i$ 时子系统 i 是指数最小相位的.

假设 2 $\Delta_i(X, t) \triangleq c_i(X) + d_i(t)$, 式中 $|c_i(X)| \leq \sum_{j=1}^N \gamma_{ij} \|e_j\|$, γ_{ij} 是未知关联强度系数, $d_i(t)$ 是部分关联与有界外界扰动之和.

控制任务 在相关假设条件下, 针对大系统(1)设计分散状态反馈HAFC

$$u_i = \alpha_i u_{ii} + (1 - \alpha_i) u_{id} + u_{ic}, \quad (2)$$

式中 u_{ii}, u_{id}, u_{ic} 分别是基本IAFC, DAFC与辅助的补

偿控制器. 对于设定的充分小衰减水平 $0 < \rho_i < 1$, 要求闭环大系统实现如下控制任务:

1) 获得 H_∞ 跟踪性能^[13, 14], 即

$$\begin{aligned} & \sum_{i=1}^N \ell_i \int_0^T e_i^T Q_i e_i d\tau \leq \\ & \sum_{i=1}^N \ell_i \left[\frac{\alpha_i \tilde{\theta}_{if}^T(0) \tilde{\theta}_{if}(0)}{\gamma_{if}} + \int_0^T \rho_i^2 D_i^2 dt + \right. \\ & \quad e_i^T(0) P_i e_i(0) + \frac{\alpha_i \tilde{g}_i^2}{\gamma_{ig}} + \\ & \quad \left. \frac{\tilde{\theta}_{iu}^T(0) \tilde{\theta}_{iu}(0)}{\gamma_{iu}} + \frac{\tilde{\eta}_i^2(0)}{\gamma_{i\eta}} \right], \end{aligned} \quad (3)$$

这里: $T \in [0, \infty]$, $\ell_i > 0$ 是常数; P_i, Q_i 是正定矩阵; $D_i \in L_2$ 是部分关联影响, 模糊逼近误差与外界扰动等的总和, 其余变量待定义.

2) 闭环大系统稳定, 所有的信号最终有界, 即

$$X_i, e_i, \tilde{\theta}_{if}, \tilde{g}_i, \tilde{\theta}_{iu}, \tilde{\eta}_i, u_i \in L_\infty. \quad (4)$$

3 主要结果(Main results)

选取向量 $k_i = (k_{i1}, \dots, k_{i, r_i-1})^T$ 使得矩阵

$$A_i = \begin{bmatrix} \mathbf{0}_{(r_i-1) \times 1} & I_{r_i-1} \\ * & * \end{bmatrix}$$

是Hurwitz的, 其中 I_{r_i-1} 为单位矩阵, $(*, *) = -k_i^T$. 于是, 对于正定矩阵 $Q_i > 0$, 下列Lyapunov方程

$$A_i^T P_i + P_i A_i + 2Q_i = 0 \quad (5)$$

有唯一正定矩阵解 P_i . 当 $\Delta_i(X, t) = 0$ 时, 若 $f_i(X_i), g_i(X_i)$ 已知, 则存在理想控制律

$$u_i^* = \frac{1}{g_i} [k_i^T e_i + y_{im}^{(r_i)} - f_i(X_i)]. \quad (6)$$

若函数 $f_i(X_i), g_i(X_i)$ 皆未知, 则用单点模糊器, 乘积推理器与中心平均解模糊器设计模糊逻辑系统 $\hat{f}_i(X_i | \theta_{if}^*), \hat{u}_{id}(X_i | \theta_{iu}^*)$ 分别逼近 $f_i(X_i), u_i^*$, 这里最优参数 $\theta_{if}^*, \theta_{iu}^*$ 定义为:

$$\begin{aligned} \theta_{if}^* & \triangleq \arg \min_{\theta_{if} \in \Omega_{if}} \sup_{X_i \in U_{ic}} |\hat{f}_i(X_i | \theta_{if}) - f_i(X_i)|, \\ \theta_{iu}^* & \triangleq \arg \min_{\theta_{iu} \in \Omega_{iu}} \sup_{X_i \in U_{ic}} |u_i^* - \hat{u}_{id}(X_i | \theta_{iu})|, \end{aligned}$$

式中 U_{ic} 为 X_i 的可控区域.

定义模糊集合 $F_{i1f}^{l_1}, \dots, F_{inif}^{l_{n_i}}, F_{if}^{(l_1, \dots, l_{n_i})}, F_{i1u}^{l_1}, \dots, F_{inuu}^{l_{n_i}}, F_{iu}^{(l_1, \dots, l_{n_i})}$, 选择相应的隶属度函数, 建立模糊规则库如下:

$$\begin{aligned} R_{if}^{(l_1, \dots, l_{n_i})}: & \text{若 } x_{i1} \text{ 是 } F_{i1f}^{l_1} \text{ 且 } \dots \text{ 且 } x_{in_i} \text{ 是 } F_{inif}^{l_{n_i}}, \\ & \text{则 } \hat{f}_i(X_i | \theta_{if}) \text{ 是 } F_{if}^{(l_1, \dots, l_{n_i})}, \end{aligned} \quad (7a)$$

$$\begin{aligned} R_{iu}^{(l_1, \dots, l_{n_i})}: & \text{若 } x_{i1} \text{ 是 } F_{i1u}^{l_1} \text{ 且 } \dots \text{ 且 } x_{in_i} \text{ 是 } F_{inuu}^{l_{n_i}}, \\ & \text{则 } \hat{u}_{id}(x_i | \theta_{iu}) \text{ 是 } F_{iu}^{(l_1, \dots, l_{n_i})}, \end{aligned} \quad (7b)$$

其中:

$$\hat{f}_i(X_i|\theta_{if}) = \sum_{j=1}^{m_{if}} \theta_{if}^j \xi_{if}^j = \theta_{if}^T \xi_{if}(X_i),$$

$$\hat{u}_{id}(X_i|\theta_{iu}) = \sum_{j=1}^{m_{iu}} \theta_{iu}^j \xi_{iu}^j = \theta_{iu}^T \xi_{iu}(X_i),$$

$l_j = 1, \dots, m_{ij}; \theta_{if}, \theta_{iu}$ 分别为凸集

$$\Omega_{if} = \{\theta_{if} \mid \|\theta_{if}\| \leq M_{if}\},$$

$$\Omega_{iu} = \{\theta_{iu} \mid \|\theta_{iu}\| \leq M_{iu}\}$$

上的可调参数向量, $\|\cdot\|$ 是 2-范数; M_{if}, M_{iu} 是正的设计常数; m_{if}, m_{iu} 是模糊规则 “If-Then” 的总数; $\xi_{if}(X_i), \xi_{iu}(X_i)$ 是模糊基函数向量; 式(7a)基于被控对象知识, 用于 IAFC, 而式(7b)基于控制知识用于 DAFC. 因此, 分散 HAFC 是在同时融合式(7)中的两种模糊信息基础上构造的. 据式(6)知分散 IAFC 与 DAFC 的确定等效控制器为:

$$u_{ii} = \frac{1}{\hat{g}_i} [k_i^T \underline{e}_i + y_{im}^{(r_i)} - \hat{f}_i(X_i|\theta_{if})], \quad (8a)$$

$$u_{id} = \hat{u}_{id}(X_i|\theta_{iu}), \quad (8b)$$

式中 \hat{g}_i 是对 g_i 的估计.

在各子系统之间存在相互关联与外界扰动影响的条件下, 设计补偿控制器为

$$u_{ic} = \left[\frac{1}{2}(\eta_i + \frac{1}{\rho_i^2}) \right] \underline{e}_i^T P_i B_i, \quad (9)$$

其中: η_i 是补偿子系统之间相互作用的增益, η_i^* 为期望增益; $\frac{1}{2\rho_i^2} \underline{e}_i^T P_i B_i$ 用于衰减部分关联影响、模糊逼近误差与外界扰动等建模误差的影响. 据式(6)和式(8a)的简单计算, 得

$$k_i^T \underline{e}_i + y_{im}^{(r_i)} = \alpha_i [\hat{f}_i(X_i|\theta_{if}) - f_i(X_i)] + f_i(X_i) + \alpha_i \hat{g}_i u_{ii} + (1 - \alpha_i) g_i u_i^*. \quad (10)$$

据式(1)(2)(10), 有

$$e_i^{(r_i)} = \alpha [\hat{f}_i(X_i|\theta_{if}) - f_i(X_i)] + \alpha_i (\hat{g}_i - g_i) u_{ii} + (1 - \alpha_i) [u_i^* - \hat{u}_{id}(X_i|\theta_{iu})] - g_i u_{ic} - \Delta_i(X, t) - k_i^T \underline{e}_i,$$

或等价于

$$\dot{e}_i = A_i \underline{e}_i + B_i [\alpha_i \tilde{\theta}_{if}^T \xi_{if}(X_i) + \alpha_i \tilde{g}_i u_{ii} + (1 - \alpha_i) \tilde{\theta}_{iu}^T \xi_{iu}(X_i) + \omega_i - g_i u_{ic} - \Delta_i(X, t)], \quad (11)$$

式中: $\tilde{\theta}_{if} = \theta_{if} - \theta_{if}^*, \tilde{g}_i = \hat{g}_i - g_i, \tilde{\theta}_{iu} = \theta_{iu}^* - \theta_{iu}$ 是参数估计误差;

$$\omega_i = \alpha [\hat{f}_i(X_i|\theta_{if}^*) - f_i(X_i)] + (1 - \alpha) [u_i^* - \hat{u}_{id}(X_i|\theta_{iu}^*)]$$

是最小模糊逼近误差.

记 $s_i = \underline{e}_i^T P_i B_i$, 利用 Lyapunov 综合法设计自适应算法如下:

$$\dot{\theta}_{if} = \begin{cases} -\gamma_{if} s_i \xi_{if}(X_i), \\ \|\theta_{if}\| < M_{if} \text{ 或} \\ (\|\theta_{if}\| = M_{if} \text{ 且 } s_i \theta_{if}^T \xi_{if}(X_i) \geq 0); \\ P[\gamma_{iu} s_i \xi_{iu}(X_i)], \\ (\|\theta_{if}\| = M_{if} \text{ 且 } s_i \theta_{if}^T \xi_{if}(X_i) < 0). \end{cases} \quad (12)$$

式中投影算子定义为

$$P[\gamma_{if} s_i \xi_{if}(X_i)] \triangleq -\gamma_{if} s_i (I - \frac{\theta_{if} \theta_{if}^T}{\|\theta_{if}\|^2}) \xi_{if}(X_i).$$

当 $\hat{g}_i = \varepsilon_i (0 < \varepsilon_i < 1)$ 时,

$$\dot{\hat{g}}_i = \begin{cases} -\gamma_{ig} s_i(t) u_{ii}, & s_i(t) u_{ii} < 0; \\ 0, & s_i(t) u_{ii} \geq 0, \end{cases} \quad (13)$$

否则,

$$\dot{\hat{g}}_i = \begin{cases} -\gamma_{ig} s_i(t) u_{ii}, \\ \hat{g}_i < M_{ig} \text{ 或 } (\hat{g}_i = M_{ig} \hat{g}_i \text{ 且 } s_i(t) u_{ii} \geq 0); \\ -\gamma_{ig} s_i(t) u_{ii} [1 - \sigma_{ig} \hat{g}_i (\hat{g}_i - M_{ig})], \\ \text{其他,} \end{cases} \quad (14)$$

$$\dot{\theta}_{iu} = \begin{cases} \gamma_{iu} s_i \xi_{iu}(X_i), \\ \|\theta_{iu}\| < M_{iu} \text{ 或} \\ (\|\theta_{iu}\| = M_{iu} \text{ 且 } s_i \theta_{iu}^T \xi_{iu}(X_i) \leq 0); \\ P[\gamma_{iu} s_i \xi_{iu}(X_i)], \\ (\|\theta_{iu}\| = M_{iu} \text{ 且 } s_i \theta_{iu}^T \xi_{iu}(X_i) > 0. \end{cases} \quad (15)$$

式中投影算子定义为

$$P[\gamma_{iu} s_i \xi_{iu}(X_i)] \triangleq \gamma_{iu} s_i (I - \frac{\theta_{iu} \theta_{iu}^T}{\|\theta_{iu}\|^2}) \xi_{iu}(X_i),$$

$$\dot{\eta}_i = \begin{cases} \frac{\gamma_{in}}{2} s_i^2, \\ (|\eta_i| < M_{in}) \text{ 或 } (|\eta_i| = M_{in} \text{ 且 } \eta_i \leq 0); \\ \frac{\gamma_{in}}{2} s_i^2 [1 - \sigma_{in} (|\eta_i| - M_{in})], \\ \text{其他.} \end{cases} \quad (16)$$

定理 1 对于满足假设 1, 2 的大系统(1), 若采用分散 HAFC 设计式(2)(8)(9), 参数调节律用式(12)~(16), 则总体控制方案能够实现既定的控制任务式(3)和式(4).

证 令 $\tilde{\eta}_i = \eta_i - \eta_i^*$, 构造 Lyapunov 候选函数

$$V(t) = \sum_{i=1}^N \frac{\ell_i}{2} (\underline{e}_i^T P_i \underline{e}_i + \frac{\alpha_i \tilde{\theta}_{if}^T \tilde{\theta}_{if}}{\gamma_{if}} + \frac{\alpha_i \tilde{g}_i^2}{\gamma_{ig}} + \frac{(1 - \alpha_i) \tilde{\theta}_{iu}^T \tilde{\theta}_{iu}}{\gamma_{iu}} + \frac{\tilde{\eta}_i^2}{\gamma_{in}}). \quad (17)$$

对式(17)求导后联合式(5)(9)和式(11)~(15)得

$$\dot{V} = \sum_{i=1}^N \ell_i [\underline{e}_i^T P_i B_i (\omega_i - \frac{1}{2} g_i (\eta_i + \frac{1}{\rho_i^2}) \underline{e}_i^T P_i B_i - \Delta_i(X, t)) - \underline{e}_i^T Q_i \underline{e}_i + \frac{g_i \tilde{\eta}_i \dot{\tilde{\eta}}_i}{\gamma_{in}}]. \quad (18)$$

记 $D_i \triangleq \frac{1}{\sqrt{g_i}}[\omega_i - d_i(t)]$, 从而根据式(16)可将式(18)化为

$$\begin{aligned} \dot{V} = & \sum_{i=1}^N \ell_i \{ \underline{e}_i^T P_i B_i [-\frac{1}{2} g_i (\eta_i + \frac{1}{\rho_i^2}) \underline{e}_i^T P_i B_i - \\ & c_i(X) + D_i \sqrt{g_i}] - \underline{e}_i^T Q_i \underline{e}_i \} = \\ & \sum_{i=1}^N \ell_i \{ -\frac{1}{2} [\sqrt{\eta_i^*} g_i \underline{e}_i^T P_i B_i + \frac{c_i(X)}{\sqrt{\eta_i^*} g_i}]^2 + \\ & \underline{e}_i^T P_i B_i \sqrt{g_i} [D_i - \underline{e}_i^T P_i B_i \frac{1}{2\rho_i^2} \sqrt{g_i}] + \\ & \frac{c_i^2(X)}{2\eta_i^* g_i} - \underline{e}_i^T Q_i \underline{e}_i \} = \\ & \sum_{i=1}^N \ell_i \{ \frac{1}{2\eta_i^* g_i} (\sum_{j=1}^N \gamma_{ij} \|\underline{e}_j\|)^2 - \underline{e}_i^T Q_i \underline{e}_i + \\ & \underline{e}_i^T P_i B_i \sqrt{g_i} [D_i - \underline{e}_i^T P_i B_i \frac{\sqrt{g_i}}{2\rho_i^2}] \}. \end{aligned} \quad (19)$$

令:

$$\begin{aligned} \Gamma_i &= (\gamma_{i1}, \dots, \gamma_{iN})^T, \quad E = (\|\underline{e}_1\|, \dots, \|\underline{e}_N\|)^T, \\ D &= \text{diag}\{\ell_1 \lambda_1, \dots, \ell_N \lambda_N\}, \quad M = \sum_{i=1}^N \ell_i \Gamma_i \Gamma_i^T, \end{aligned}$$

λ_{im} 为 $\frac{Q_i}{2}$ 具有最小模的特征值, $\eta^* = [\eta_1^* \dots \eta_N^*]^T$, $\eta_j^* = \eta^*(j = 1, \dots, N)$, $\Lambda = D - \frac{M}{2g_i \eta^*}$, $\eta^* = \arg \{\eta^{*T} \eta^* : \Lambda > 0\}$. 对于正定矩阵 $Q_i > 0$, 由 Gershgorin 定理, 存在 η^* 使 Λ 为(严格)对角占优矩阵^[14], 故 $\Lambda > 0$. 据此, 式(19)变为

$$\begin{aligned} \dot{V} \leq & \sum_{i=1}^N \ell_i \{ -\lambda_{im} \|\underline{e}_i\|^2 + \frac{1}{2\eta_i^* g_i} E^T \Gamma_i \Gamma_i^T E - \frac{1}{2} \underline{e}_i^T Q_i \underline{e}_i + \\ & \underline{e}_i^T P_i B_i \sqrt{g_i} [D_i - \underline{e}_i^T P_i B_i \frac{1}{2\rho_i^2} \sqrt{g_i}] \} = \\ & \sum_{i=1}^N \ell_i \{ -\frac{1}{2} \underline{e}_i^T Q_i \underline{e}_i + \underline{e}_i^T P_i B_i \sqrt{g_i} [D_i - \\ & \underline{e}_i^T P_i B_i \frac{1}{2\rho_i^2} \sqrt{g_i}] \} - E^T D E + E^T M E \frac{1}{2\eta_i^* g_i} \leq \\ & \sum_{i=1}^N \ell_i [-\frac{1}{2} \underline{e}_i^T Q_i \underline{e}_i - \frac{1}{2} (\underline{e}_i^T P_i B_i \frac{1}{\rho_i} \sqrt{g_i} - \rho_i D_i)^2 + \\ & \frac{1}{2} D_i^2 \rho_i^2] \leq \sum_{i=1}^N \frac{\ell_i}{2} (D_i^2 \rho_i^2 - \underline{e}_i^T Q_i \underline{e}_i). \end{aligned} \quad (20)$$

对式(20)的两边从0到T积分, 得

$$\begin{aligned} \sum_{i=1}^N \ell_i \int_0^T \underline{e}_i^T Q_i \underline{e}_i d\tau \leq & \sum_{i=1}^N \frac{\ell_i}{2} \rho_i^2 \int_0^T D_i^2 dt - V(T) + V(0) \leq \\ & \sum_{i=1}^N \frac{\ell_i}{2} \int_0^T \rho_i^2 D_i^2 dt + V(0). \end{aligned} \quad (21)$$

据式(17)(21), 得到式(3). 式(4)的证明仿照文献[13]的方法可得. 证毕.

4 应用(Application)

先进车辆控制系统是智能交通系统(intelligent transport systems, ITS)必须具有的3个公共组成部分之一, 其最终发展是自动公路系统(automated highway system, AHS). AHS中的车辆跟随控制分为纵向控制和侧向控制. 本文基于提出的分散HAFc算法研究车辆纵向跟随的分散控制器设计. 车队纵向跟随系统车辆*i*的动态模型^[14]为

$$\begin{cases} \dot{\psi}_i = v_i - v_{i-1}, \\ \dot{v}_i = \frac{1}{m}(-av_i^2 - d + f_i), \\ \dot{f}_i = \frac{1}{\tau}(-f_i + u_i), \\ y_i = \psi_i + L + \rho v_i, \end{cases} \quad (22)$$

其中: $\psi_i = x_i - x_{i-1}$, y_i 为输出, $u_i > 0$ 表示节流阀或风门输入, $u_i < 0$ 则为刹车输入. 每10mph预留一车长的车间距是比较适合行人的标准驾驶规则之一, 可取 $\rho = 0.9$. 式中变量含义与参数取值见表1.

表1 车辆变量与参数

Table 1 Variables and parameters of vehicles

变量	含义
x/m	车辆位置
$v/(m \cdot s^{-1})$	车辆速度
f/N	车辆纵向牵引力
$L = 2/m$	附加的车间距正常数
$m = 1300/kg$	车辆质量
$a = 0.3/(N \cdot s^2 \cdot m^{-1})$	空气动力
$d = 100/N$	摩擦力
$\tau = 0.2/s$	发车/刹车常数

由于

$$y_i^{(2)} = \frac{1}{m}(f_i - av_i^2 - d) - \frac{\rho}{m}(2av_i \dot{v}_i + \frac{f_i}{\tau}) + \frac{\rho}{m\tau} u_i - \dot{v}_{i-1},$$

故相对阶 $r_i = 2$. 用Lyapunov函数法可检验零动态是指数稳定的, 这符合假设1. 令车辆*i*的状态向量为

$$X_i = \begin{bmatrix} x_{i1} \\ x_{i2} \\ x_{i3} \end{bmatrix} = \Phi(\psi_i, v_i, f_i) = \begin{bmatrix} y_i \\ L f_i y_i \\ v_i \end{bmatrix},$$

式中: 向量场 $f_i = \begin{bmatrix} v_i \\ \frac{1}{m}(f_i - av_i^2 - d) \\ -\frac{1}{\tau} f_i \end{bmatrix}$, $L f_i y_i$ 表示 y_i 关于 f_i 的Lie导数. Jacobian矩阵 $\frac{\partial \Phi}{\partial(\psi_i, v_i, f_i)}$ 可逆, 故 Φ

为拓扑同胚, 可将式(22)化为与式(1)等价的正则形式

$$\begin{cases} \dot{x}_{i1} = x_{i2}, \\ \dot{x}_{i2} = \left(\frac{1}{\rho} - \frac{1}{\tau}\right)(x_{i2} - x_{i3}) - \frac{2ax_{i2}x_{i3}}{m} + \\ \frac{a}{m}\left(2 - \frac{\rho}{\tau}\right)x_{i3}^2 - \frac{\rho d}{m\tau} + \frac{\rho u_i}{m\tau} + \\ \left(\frac{1}{\rho} - \frac{1}{\tau} - \frac{2ax_{i3}}{m}\right)x_{i-1,3} - \dot{x}_{i-1,3}, \\ \dot{x}_{i3} = \frac{1}{\rho}(x_{i2} - x_{i3} + x_{i-1,3}). \end{cases} \quad (23)$$

显然, 后者为系统内动态. 因期待输出 $y_i = x_{i1} = 0$, 故选 $y_{im} = 0$.

仿真步骤如下:

a) 选取反馈增益 $k_i = (1, 2)^T$, $Q_i = \text{diag}\{5, 5\}$,

求解式(5)得到 $P_i = \begin{bmatrix} 15 & 5 \\ 5 & 5 \end{bmatrix}$. 设计常数 $M_{ia} = 50$,

$M_{iu} = 100$, $\gamma_{ia} = 4$, $\gamma_{iu} = 4$, $\gamma_{ig} = 3$, $\gamma_{in} = 3$; $\varepsilon_i = 0.01$; 初值 $\theta_{ia}(0), \theta_{iu}(0)$ 在 $[-\pi, 4]$ 上随机取值, $\eta_i(0)$ 在 $[2\pi, 3\pi]$ 上随机取值; 选取初始状态 $X_i(0) = (\frac{\pi}{6}, \frac{\pi}{3}, 57)^T$; 领头车辆速度 $v_0 = 55 + 6 \sin \frac{\pi t}{4}$.

b) 选取状态变量隶属函数

$$\begin{aligned} \mu_{F_{1ja}}(x_{ik}) &= \mu_{F_{1ju}}(x_{ik}) = \\ \exp\left\{-\frac{[x_{ik} + \pi/3 - (j-1)\pi/9]^2}{(\pi/18)^2}t\right\}, \end{aligned}$$

式中: $i = 1, 2, 3, 4$; $j = 1, \dots, 7$; $k = 1, 2, 3$.

c) 以相连的4辆车为一个车队大系统($N = 4$), 计算大系统第 i 个分散HAFC(式(2)), 将其作用于子系统(23). 令 $\alpha_i = 0.5$, $\rho_i = 0.003$, 仿真结果如图1~4所示.

从图1, 2可看出, 车队纵向跟随车间距的稳态误差在分散HAFC的驱动下趋近于0, HAFC能够提供较好的跟踪效果, 且控制信号没有发生颤动. 就不同 α_i 比较而言, $\alpha_i = 0.5$ 时HAFC系统的跟踪性能最好(图3), 而相应的控制输入幅值也最小(图4).

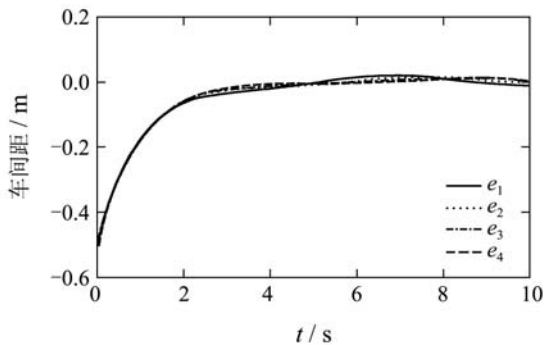


图1 紧后4辆车的车间距误差
Fig. 1 Intervernicle spacing errors of the four subsequent vehicles

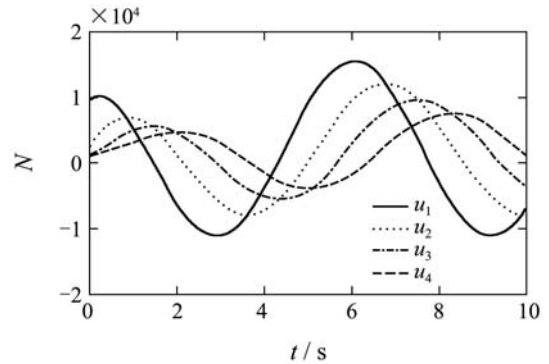


图2 车辆1~4的输入信号

Fig. 2 Input signals of vehicles 1~4

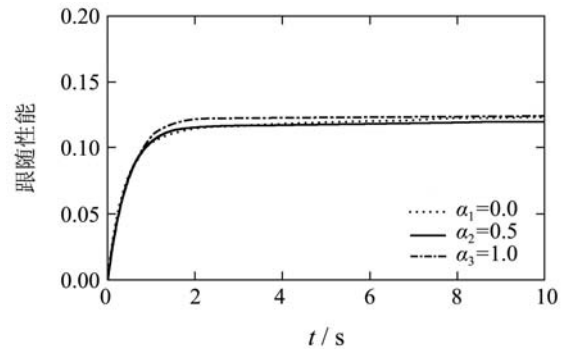


图3 不同 α_i 下车辆的跟随性能

Fig. 3 Following performance $\int_0^{10} e_i^2(t)dt$ of vehicles under different α_i

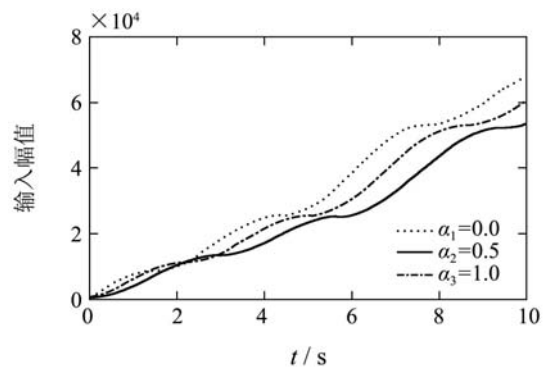


图4 不同 α_i 下车辆的输入幅值

Fig. 4 Input magnitude $\int_0^{10} |u_i(t)|dt$ of vehicles under different α_i

5 结论(Conclusion)

本文研究了一类不确定非线性大系统分散混杂自适应模糊H_∞跟踪控制算法. 该算法处理了现有HAFC设计^[2,8~11]存在的问题, 消除了文献[15]的控制器设计存在符号函数和需要知道输入增益边界的缺点. 算法应用的仿真结果验证了其有效性, 同时表明提出的HAFC系统在跟踪准确性和控制幅度上优于IAFC和DAFC系统, 在工程上具有较大的应用价值.

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