文章编号: 1000−8152(2008)04−0780−03

一类复杂非线性系统的模糊控制

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摘要: 针对一类复杂非线性系统, 把模糊T–S模型和自适应模糊逻辑系统结合起来, 提出了一种跟踪控制方案. 首先, 应用模糊T–S模型对非线性系统建模, 设计观测器用来观测系统状态: 其次, 应用基于权值、中心和宽度3个参数可调节的自适应时延模糊逻辑系统补偿器来消除建模误差和不确定性. 文中证明了闭环系统满足期望的跟踪性能. 示例仿真结果表明了该方案的有效性.

关键词: 模糊T–S模型; 自适应模糊逻辑系统; 非线性系统; 不确定性; 时延; 跟踪控制

中图分类号: TP273　　**文献标识码:** A

Fuzzy control for a class of complex nonlinear systems

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Abstract: Combining fuzzy Takagi-Sugeno (T–S) model with adaptive fuzzy logic systems, we present a tracking control scheme for a class of complex nonlinear systems. Firstly, the fuzzy T–S model is used to approximate to the nonlinear systems, and an observer is designed to generate the system states. Secondly, the modeling errors and the uncertainty are eliminated by a compensator based on the adaptive time-delay fuzzy logic systems with three adjustable parameters: weights, centers and widths. It is proved that the closed loop system satisfies the desired tracking requirements. The simulation results demonstrate the efficacy of thee control scheme.

Key words: fuzzy T–S model; adaptive fuzzy logic systems; nonlinear systems; uncertainty; time-delay; tracking control

1 引言(Introduction)

在实际工程中, 许多非线性系统存在着时延现象和不确定性因素, 它们的存在使得系统性能恶化, 给非线性系统的跟踪控制设计造成了极大的困难.

基于模糊T–S模型的线性化方法是对非线性时延系统进行有效控制的一种方法, 已有成功的应用[1,2], 但对非线性时延系统的跟踪问题研究工作较少. 文[3]忽略了建模误差, 文[4]假定建模误差满足匹配条件, 且没考虑时延. 对于不确定性, 通常要求其满足特定约束条件[5]. 自适应模糊逻辑系统具有一致逼近特性, 已成功的应用于非线性系统中[6].

本文提出的跟踪控制方案, 不作任何假设. 采用模糊T–S模型对非线性时延系统建模, 构建自适应时延模糊逻辑系统补偿器来消除建模误差和不确定性. 控制方案使闭环系统满足期望的跟踪性能.

2 问题描述(Problem formulation)

考虑如下的复杂非线性系统:

$$\begin{cases} \dot{x} =Ax + B[f(x, x(t-\tau_1), \cdots, \\ \qquad x(t-\tau_r), u) + \widetilde{f}(x, x(t-\tau_1), \cdots, \\ \qquad x(t-\tau_r), u)] + d, \\ y = Cx. \end{cases} \tag{1}$$

其中: 系统状态$x \in \mathbb{R}^n$未知, $u \in \mathbb{R}^m$ 是控制输入, 系统输出$y \in \mathbb{R}^m$可量测, $x_1, x_2 \in \mathbb{R}^{n_1}, x_3, x_4 \in \mathbb{R}^{n_2}$, $x = [x_1^{\mathrm T}, x_2^{\mathrm T}, x_3^{\mathrm T}, x_4^{\mathrm T}]^{\mathrm T}$, $A = \mathrm{diag}\{A^1, A^2\}$, $A^1 = \begin{bmatrix} 0 & I_{n_1} \\ 0 & 0 \end{bmatrix}, A^2 = \begin{bmatrix} 0 & I_{n_2} \\ 0 & 0 \end{bmatrix}, B = \mathrm{diag}\{B^1, B^2\}$, $B^1 = [0\ I_{n_1}]^{\mathrm T}, B^2 = [0\ I_{n_2}]^{\mathrm T}$, 定常矩阵$C \in \mathbb{R}^{m\times n}$, f是已知光滑非线性向量函数, $\widetilde{f}$是不确定未知非线性向量函数, $\tau_i (i = 1, \cdots, r)$是时延, $d = [0, d_2^{\mathrm T}, 0, d_4^{\mathrm T}]^{\mathrm T}$是外部扰动, $n = 2m, m = n_1 + n_2$.
参考模型为

$$\dot{x}_r(t) = A_r x_r(t) + r(t). \tag{2}$$

其中: $x_r(t)$是参考模型的状态, $r(t)$是有界输入,

收稿日期: 2006−05−08; 收修改稿日期: 2007−04−17.
基金项目: 国家自然科学基金资助项目(60234010); 中国航空科学基金资助项目(05E52031); 高校博士基金资助项目(JS06B23).

A_r是渐近稳定矩阵.

控制任务 设计控制器使非线性系统(1)稳定, 并使系统状态跟踪参考模型状态$x_r(t)$.

用模糊T–S模型来逼近非线性系统(1)的已知部分, 于是, 非线性系统(1)可改写为

$$\dot{x} = \sum_{i=1}^{L} \mu_i [A_i x(t) + \sum_{l=1}^{r} A_{il} x(t-\tau_l)] + \sum_{i=1}^{L} \mu_i B_i u(t) + B\Delta(x,\tau) + d, \tag{3}$$

$$\begin{cases} y(t) = Cx(t), \\ x(t) = 0, t \leqslant 0. \end{cases} \tag{4}$$

其中: A_i,B_i和A_{il}是适维矩阵, $B_i = [0\ \ b_{i1}^{\mathrm{T}}\ \ 0\ \ b_{i2}^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^{n\times m}$, μ_i是权重, 建模误差和不确定非线性部分为$\Delta(x,\tau) = \Delta(x, x(t-\tau_1), \cdots, x(t-\tau_r))$.

3 控制器的设计(Design of the controller)

把模糊输出反馈控制和基于自适应时延模糊逻辑系统的控制结合起来, 设计控制律

$$u(t) = u_l(t) - u_f(t). \tag{5}$$

其中: $u_l(t)$ 是模糊输出反馈控制器, $u_f(t)$ 是自适应时延模糊逻辑系统补偿器.

全局模糊观测器模型和输出反馈控制器模型:

$$\dot{\hat{x}} = \sum_{i=1}^{L} \mu_i [A_i \hat{x}(t) + \sum_{l=1}^{r} A_{il} \hat{x}(t-\tau_l)] + \sum_{i=1}^{L} \mu_i B_i u(t) + \sum_{i=1}^{L} \mu_i L_i (y(t) - \hat{y}(t)), \tag{6}$$

$$\hat{y}(t) = C\hat{x}(t), \tag{7}$$

$$u(t) = \sum_{i=1}^{L} \mu_i K_i (\hat{x}(t) - x_r(t)). \tag{8}$$

其中: $\hat{x}$是观测状态, L_i, K_i是适维矩阵, $u_l(t)$由式(8)给出.

选取自适应补偿器$u_f(t)$:

$$u_f(t) = \begin{cases} E^{-1}\hat{u}(\hat{x},\tau|\Theta,\alpha,\delta), & \text{若}E\text{非奇异}, \\ E^{\mathrm{T}}(I+EE^{\mathrm{T}})^{-1}\hat{u}(\hat{x},\tau|\Theta,\alpha,\delta), & \text{若}E\text{奇异}. \end{cases} \tag{9}$$

其中: $E=\sum\limits_{i=1}^{L} \mu_i E_i$, $E_i=\begin{bmatrix} b_{i1} \\ b_{i2} \end{bmatrix} \in \mathbb{R}^{m\times m}$, $\hat{u}(\hat{x},\tau|\Theta,\alpha,\delta)$由自适应模糊逻辑系统构建.

令$\tilde{x}(t) = [x^{\mathrm{T}}(t), x_r^{\mathrm{T}}(t), e^{\mathrm{T}}(t)]^{\mathrm{T}}$, 其中$e(t) = x(t) - \hat{x}(t)$; 令$\bar{w} = [\bar{w}_1^{\mathrm{T}}\ \ r^{\mathrm{T}}(t)\ \ \bar{w}_1^{\mathrm{T}}]^{\mathrm{T}}$, 其中$\bar{w}_1 = [0, (d_2 - w_{11})^{\mathrm{T}}, 0, (d_4 - w_{12})^{\mathrm{T}}]^{\mathrm{T}}$, $w_1 = [w_{11}^{\mathrm{T}}\ \ w_{12}^{\mathrm{T}}]^{\mathrm{T}}$. 由式(2)～(4)与(6)～(9), 并令$\bar{B} = [-B^{\mathrm{T}}\ \ 0\ \ -B^{\mathrm{T}}]^{\mathrm{T}}$, 得到闭环系统

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{L}\sum_{j=1}^{L} \mu_i\mu_j [\bar{A}_{il}\tilde{x}(t) + \sum_{l=1}^{r} \bar{A}_{il}\tilde{x}(t-\tau_l)] + \bar{B}[(\Psi(\hat{x},\tau) - \alpha\Psi_\alpha(\hat{x},\tau) - \delta\Psi_\delta(\hat{x},\tau))\tilde{\Theta} + (\tilde{\alpha}\Psi_\alpha(\hat{x},\tau) + \tilde{\delta}\Psi_\delta(\hat{x},\tau))\Theta] + \bar{w}. \tag{10}$$

其中:

$$\bar{A}_{ij} = \begin{bmatrix} A_i + B_iK_j & -B_iK_j & -B_iK_j \\ 0 & A_r & 0 \\ 0 & 0 & A_i - L_iC \end{bmatrix},$$

$$\bar{A}_{il} = \begin{bmatrix} A_{il} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & A_{il} \end{bmatrix}.$$

参数误差为$\tilde{\Theta}$, $\tilde{\alpha}$和$\tilde{\delta}$, $\Psi(\hat{x},\tau)$是模糊基函数矩阵, $\Psi_\alpha(\hat{x},\tau)$是$\Psi(\hat{x},\tau)$对$\alpha$的偏导, $\Psi_\delta(\hat{x},\tau)$是$\Psi(\hat{x},\tau)$对$\delta$的偏导.

若选择参数调节规律

$$\dot{\Theta} = -\eta_1(\Psi(\hat{x},\tau) - \alpha\Psi_\alpha(\hat{x},\tau) - \delta\Psi_\delta(\hat{x},\tau))^{\mathrm{T}}(\bar{B}^{\mathrm{T}}P\tilde{x}), \tag{11}$$

$$\dot{\alpha} = -\eta_2\bar{B}^{\mathrm{T}}P\tilde{x}(\Psi_\alpha(\hat{x},\tau)\Theta)^{\mathrm{T}}, \tag{12}$$

$$\dot{\delta} = -\eta_3\bar{B}^{\mathrm{T}}P\tilde{x}(\Psi_\delta(\hat{x},\tau)\Theta)^{\mathrm{T}}. \tag{13}$$

其中: η_1,η_2和η_3是正常数, P和Q是对称正定矩阵.

定理 1 对非线性系统(1), 选择控制律(5), 输出反馈控制器(8), 自适应时延模糊逻辑系统补偿器(9), 参数调节规律(11)(12)和(13), 则闭环系统(10)满足跟踪性能

$$\int_0^{\mathrm{T}} (x(t) - x_r(t))^{\mathrm{T}}Q(x(t) - x_r(t))\mathrm{d}t \leqslant \tilde{x}^{\mathrm{T}}(0)P\tilde{x}(0) + \frac{1}{\eta_1}\tilde{\Theta}^{\mathrm{T}}(0)\tilde{\Theta}(0) + \frac{1}{\eta_2}\mathrm{tr}(\tilde{\alpha}^{\mathrm{T}}(0)\tilde{\alpha}(0)) + \frac{1}{\eta_3}\mathrm{tr}(\tilde{\delta}^{\mathrm{T}}(0)\tilde{\delta}(0)) + \rho^2\int_0^T (\bar{w}^{\mathrm{T}}\bar{w})\mathrm{d}t, \tag{14}$$

其中ρ是正常数.

证 选取Lyapunov函数

$$V = \frac{1}{2}\tilde{x}^{\mathrm{T}}P\tilde{x} + \frac{1}{2}\sum_{l=1}^{r}\int_{t-\tau_l}^{t} \alpha_l\tilde{x}^{\mathrm{T}}(v)\tilde{x}(v)\mathrm{d}v + \frac{1}{2\eta_1}\tilde{\Theta}^{\mathrm{T}}\tilde{\Theta} + \frac{1}{2\eta_2}\mathrm{tr}(\tilde{\alpha}^{\mathrm{T}}\tilde{\alpha}) + \frac{1}{2\eta_3}\mathrm{tr}(\tilde{\delta}^{\mathrm{T}}\tilde{\delta}).$$

4 仿真算例(Simulation results)

设复杂非线性系统为具有不确定性和时延的机械臂系统[6]:

$$\ddot{q}(t) + C(q,\dot{q})\dot{q}(t) + g(q) = B(q)\tau(t) + \sum_{i=1}^{r}\xi_i(t)q(t-\tau_i) + d'.$$

参考模型为$\dot{x}_r(t) = A_rx_r(t) + r(t)$. 其中: $A_r =$

$\mathrm{diag}\{A_{r1}, A_{r2}\}$, $A_{r1} = A_{r2} = \begin{bmatrix} 0 & 1 \\ -6 & -5 \end{bmatrix}$, $r(t) = [0, 4\sin\, t, 0, 4\cos\, t]^{\mathrm{T}}$. 采用定理1的方法, 仿真结果如图1所示. 图中(a)(b)(c)和(d)依次是状态x_1,x_2,x_3和x_4的响应曲线.

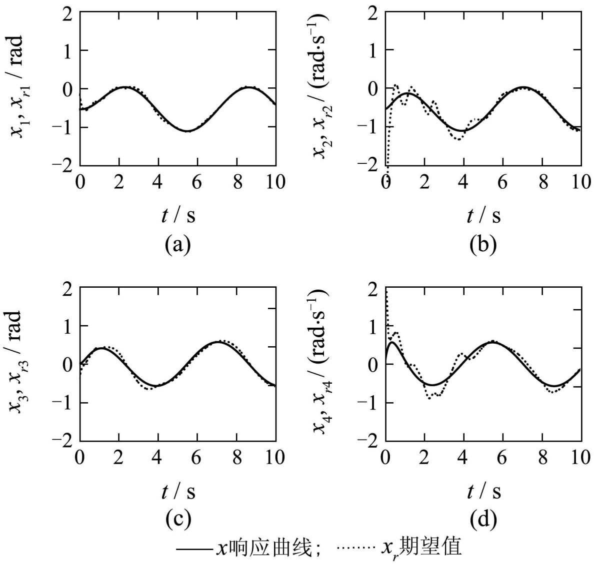

图 1 状态x_1, x_2, x_3, x_4的响应曲线(虚线)及期望值$x_{r1}, x_{r2}, x_{r3}, x_{r4}$(实线)

Fig. 1 The responses of states x_1, x_2, x_3 and x_4(doted lines), and the anticipant valuex_{r1}, x_{r2}, x_{r3} and x_{r4} (solid lines)

5 结论(Conclusion)

本文综合了两种模糊逻辑方式, 提出的控制方案能快速跟踪期望信号.

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