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多输入多输出非线性多时滞系统的直接自适应模糊跟踪控制

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摘 要: 针对多输入多输出非线性多时滞系统,提出了一种直接自适应模糊跟踪控制方案. 该方案有机综合了自适应控制和 H_∞控制,构建了一种自适应时滞模糊逻辑系统用来逼近有多重时滞的未知函数;设计了 H_∞补偿器来抵消模糊逼近误差和外部扰动. 根据跟踪误差给出了参数调节规律,构造了包含时滞的李亚普诺夫函数,从而证明了误差闭环系统满足期望的 H_∞跟踪性能. 仿真结果表明了该方案的可行性.

关键词: 非线性系统; 时滞; 模糊逻辑系统; 跟踪控制
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Direct adaptive fuzzy tracking control for MIMO nonlinear systems with multiple time delays

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Abstract: This paper presents a direct adaptive fuzzy tracking control scheme for MIMO nonlinear systems with multiple time delays. The scheme organically synthesizes adaptive control and H_∞ control. A kind of adaptive time-delay fuzzy logic systems are constructed and used to approximate the unknown functions with multiple time delays. An H_∞ compensator is designed to eliminate fuzzy approximation errors and external disturbances. The adjusting laws for parameters are derived by the tracking error. The Lyapunov function with time delays is constructed, and then it is proved that the error closed loop system satisfies the anticipant H_∞ tracking performance. The simulation results show the feasibility of the control scheme.

Key words: Nonlinear systems; Time delays; Fuzzy logic systems; Tracking control

1 引 言

自适应模糊控制作为一种研究非线性系统控制的有效方法引起了人们的广泛关注. 文献[1]首次提出了自适应模糊控制方案来控制非线性系统. 此后, [2,3]研究了多输入多输出非线性系统的自适应模糊控制器设计,可保证系统输出跟踪期望信号,但仅考虑了无时滞的情形. 在实际工程中存在着许多非线性时滞系统,时滞的存在使得系统性能恶化,从而非线性时滞系统的稳定性问题备受关注. [4-9]提出了基于自适应技术的非线性时滞系统的有效控制方案,通常,其控制方案要满足假设条件[4]、估计时滞部分的增益[5]、寻找时滞关联函数[6]以及寻求合适的李亚普诺夫函数来抵消时滞[7],然而,假设条件、增益、关联函数以及合适的李亚普诺夫函数不易满足或不易寻求. [8,9]的自适应技术结合了多种非线性技术,但多种技术的结合增加了控制器的设计难度.

本文针对多输入多输出非线性多时滞系统,给出了一种直接自适应模糊跟踪控制方案,该方案有机综合了自适应控制和 H_∞控制,并构建了一种自适应时滞模糊逻辑系统来逼近有时滞未知函数. 在自适应算法中,跟踪误差参与时滞模糊逻辑系统中的参数调节,应用 H_∞补偿器来抵消模糊逼近误差和外部扰动. 构造了包含时滞的李亚普诺夫函数,从

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而证明了误差闭环系统满足期望的 H_∞ 跟踪性能. 仿真结果表明了该方案的可行性.

2　问题描述

$$\begin{aligned}
&\dot{x}_1 = x_2,\\
&\cdots\\
&\dot{x}_{(\beta_1-1)} = x_{\beta_1},\\
&\dot{x}_{\beta_1} = \\
&f_1(x, x(t-\tau_1), \cdots, x(t-\tau_r)) + \\
&\sum_{i=1}^{m} g_{1i}(x, x(t-\tau_1), \cdots, x(t-\tau_r)) u_i + d_1;\\
&\dot{x}_{(\beta_1+1)} = x_{(\beta_1+2)},\\
&\cdots\\
&\dot{x}_{\beta_m} = \\
&f_m(x, x(t-\tau_1), \cdots, x(t-\tau_r)) + \\
&\sum_{i=1}^{m} g_{mi}(x, x(t-\tau_1), \cdots, x(t-\tau_r)) u_i + d_m;\\
&y_1 = x_1,\\
&\cdots\\
&y_m = x_{(n-\beta_m+1)};\\
&x(t) = \Xi(t),\ t \in [-\zeta, 0].
\end{aligned} \tag{1}$$

其中

$$x = [x_1, \cdots, x_1^{(\beta_1-1)}, \cdots, x_m, \cdots, x_m^{(\beta_m-1)}]^{\mathrm{T}} \in R^n,$$

$u = [u_1, \cdots, u_m]^{\mathrm{T}}$ 和 $y = [y_1, \cdots, y_m]^{\mathrm{T}}$ 分别是系统的状态、输入和输出向量, 状态是可量测的; $\beta_1 + \beta_2 + \cdots + \beta_m = n$; f_i 和 $g_{ij}(i, j = 1, 2, \cdots, m)$ 为充分光滑函数; $d_i(i = 1, 2, \cdots, m)$ 是外部扰动; $\Xi(t)$ 连续, 表示系统的初始状态; $\tau_i(i = 1, 2, \cdots, r)$ 表示时滞; $\zeta = \max\{\tau_i \mid 1 \le i \le r\}$.

引进时滞算子 σ_i, 有

$$\sigma_i x(t) = x(t-\tau_i),\ i = 0, 1, \cdots, r.$$

其中: $\tau_0 = 0, \tau_i > 0$. 令 $\sigma = [\sigma_0\ \ \sigma_1\ \ \cdots\ \ \sigma_r]$, 于是非线性时滞向量函数和时滞矩阵函数可表示为如下形式:

$$\begin{aligned}
F\sigma(x) &\triangleq F(x, x(t-\tau_1), \cdots, x(t-\tau_r)) = \\
&[f_1(x, x(t-\tau_1), \cdots, x(t-\tau_r)), \cdots,\\
&f_m(x, x(t-\tau_1), \cdots, x(t-\tau_r))]^{\mathrm{T}},\\
G\sigma(x) &\triangleq G(x, x(t-\tau_1), \cdots, x(t-\tau_r)) = \\
&[G_1^{\mathrm{T}}(x, x(t-\tau_1), \cdots, x(t-\tau_r)), \cdots,\\
&G_m^{\mathrm{T}}(x, x(t-\tau_1), \cdots, x(t-\tau_r))]^{\mathrm{T}}.
\end{aligned}$$

其中

$$\begin{aligned}
&G_i(x, x(t-\tau_1), \cdots, x(t-\tau_r)) = \\
&[g_{i1}(x, x(t-\tau_1), \cdots, x(t-\tau_r)), \cdots,\\
&g_{im}(x, x(t-\tau_1), \cdots, x(t-\tau_r))]
\end{aligned}$$

是行向量. 从而非线性系统(1) 可改写为

$$\begin{aligned}
&\dot{x} = Ax + B[F\sigma(x) + G\sigma(x)u + d],\\
&y = Cx,\\
&x = \Xi(t),\ t \in [-\zeta, 0].
\end{aligned} \tag{2}$$

其中

$$\begin{aligned}
&A = \mathrm{diag}[A_1, A_2, \cdots, A_m],\\
&B = \mathrm{diag}[B_1, B_2, \cdots, B_m],\\
&C = \mathrm{diag}[C_1, C_2, \cdots, C_m],\\
&A_i = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0\\ \cdots & 0 & 1 & \ddots & \cdots\\ \cdots & \cdots & \ddots & \ddots & 0\\ 0 & 0 & \cdots & \ddots & 1\\ 0 & 0 & \cdots & \cdots & 0 \end{bmatrix} \in R^{\beta_i \times \beta_i},\\
&B_i = [0, \cdots, 0, 1]^{\mathrm{T}} \in R^{\beta_i \times 1},\\
&C_i = [1, 0, \cdots, 0] \in R^{1 \times \beta_i},\\
&d = [d_1, d_2, \cdots, d_m]^{\mathrm{T}},
\end{aligned}$$

$F\sigma(x)$ 是未知部分, $G\sigma(x)$ 是已知部分. 假定 $\forall x \in U_x$, U_x 是致密集, $G\sigma(x)$ 是非奇异的. 对给定的参考信号 $y_{r1}, \cdots, y_{rm}$, 定义跟踪误差为

$$\begin{aligned}
&e_1 = y_{r1} - y_1, \cdots, e_m = y_{rm} - y_m,\\
&y_r = [y_{r1}, \cdots, y_{rm}],\ y_r^{(\beta)} = [y_{r1}^{(\beta_1)}, \cdots, y_{rm}^{(\beta_m)}],\\
&Y_m = [y_{r1}, \cdots, y_{r1}^{(\beta_1-1)}, \cdots, y_{rm}, \cdots, y_{rm}^{(\beta_m-1)}]^{\mathrm{T}},\\
&e = [e_1, \cdots, e_1^{(\beta_1-1)}, \cdots, e_m, \cdots, e_m^{(\beta_m-1)}]^{\mathrm{T}}.
\end{aligned}$$

控制任务是求 1 个反馈控制 $u = u\sigma(x \mid \Theta, \alpha, \delta)$ 和 1 个调整参数 Θ, δ 的自适应律, 使得误差闭环系统满足期望的 H_∞ 跟踪性能并快速跟踪给定的参考信号.

3　自适应时滞模糊逻辑系统

构建自适应时滞模糊逻辑系统来逼近 m 维时滞向量函数 $u\sigma(x)$, 可调参数为权值 Θ, 中心 α 和幅度 δ, 形式如下:

$$\hat{u}\sigma(x \mid \Theta, \alpha, \delta) = \Psi_\sigma(x, \alpha, \delta)\Theta. \tag{3}$$

其中

$$\begin{aligned}
&\Psi_\sigma(x, \alpha, \delta) = \\
&\mathrm{diag}[\xi_{1\sigma}(x, \alpha_1, \delta_1), \cdots, \xi_{m\sigma}(x, \alpha_m, \delta_m)],\\
&\xi_{l\sigma}(x, \alpha, \delta) = (\xi_{l\sigma}^1, \cdots, \xi_{l\sigma}^M) \in R^{1 \times M},\\
&\xi_{l\sigma}^j = \frac{\prod_{i=1}^{n} \mu_{F_i^j}\sigma(x_i, \alpha_{kj}, \delta_{kj})}{\sum_{j=1}^{M}\left(\prod_{i=1}^{n} \mu_{F_i^j}\sigma(x_i, \alpha_{kj}, \delta_{kj})\right)},\\
&\mu_{F_i^j}\sigma(x_i, \alpha_{kj}, \delta_{kj}) = \prod_{i=0}^{n} \mu_{F_i^j}(x_i(t-\tau_i), \alpha_{kj}, \delta_{kj})),\\
&\tau_0 = 0,\ \tau_i > 0,\ i = 1, 2, \cdots, r,\\
&\Theta = [\theta_1^{\mathrm{T}}, \theta_2^{\mathrm{T}}, \cdots, \theta_m^{\mathrm{T}}]^{\mathrm{T}},\ \alpha = \mathrm{diag}[\alpha_1, \alpha_2, \cdots, \alpha_m],\\
&\delta = \mathrm{diag}[\delta_1, \delta_2, \cdots, \delta_m],
\end{aligned} \tag{4}$$

θ_i 是列向量, α_i 和 δ_j 是行向量.

定义参数误差

$$\tilde{\Theta} = \Theta - \Theta^* = (\theta_i - \theta_i^*)_{m\times 1},$$
$$\tilde{\alpha} = \alpha - \alpha^* = \mathrm{diag}(\alpha_1 - \alpha_1^*, \cdots, \alpha_m - \alpha_m^*),$$
$$\tilde{\delta} = \delta - \delta^* = \mathrm{diag}(\delta_1 - \delta_1^*, \cdots, \delta_m - \delta_m^*),$$

则自适应时滞模糊逻辑系统对时滞向量函数 $u_\sigma(x)$ 的逼近误差为

$$\hat{u}_\sigma(x \mid \Theta,\alpha,\delta) - u_\sigma(x) = (\Psi_\sigma(x) - \alpha\Psi_\sigma^\alpha(x) - \delta\Psi_\sigma^\delta(x))\tilde{\Theta} + (\tilde{\alpha}\Psi_\sigma^\alpha(x) + \tilde{\delta}\Psi_\sigma^\delta(x))\Theta + w. \tag{5}$$

其中

$$\Psi_\sigma(x) = \Psi_\sigma(x,\alpha,\delta),$$
$$\Psi_\sigma^\alpha(x) = \mathrm{diag}[\xi_{1\sigma}^\alpha(x,\alpha_1,\delta_1), \cdots, \xi_{m\sigma}^\alpha(x,\alpha_m,\delta_m)],$$
$$\Psi_\sigma^\delta(x) = \mathrm{diag}[\xi_{1\sigma}^\delta(x,\alpha_1,\delta_1), \cdots, \xi_{m\sigma}^\delta(x,\alpha_m,\delta_m)],$$

$\xi_{i\sigma}^\alpha(x,\alpha_i,\delta_i)$ 和 $\xi_{i\sigma}^\delta(x,\alpha_i,\delta_i)$ 分别表示 $\xi_{i\sigma}$ 关于 α_i 和 δ_i 的偏导数, w 是残差项.

4 控制器设计

采用模糊控制律

$$u = \hat{u}_\sigma(x \mid \Theta,\alpha,\delta) - u_{\mathrm{com}}/G_\sigma(x). \tag{6}$$

其中

$$\hat{u}_\sigma(x \mid \Theta,\alpha,\delta) = \Psi_\sigma(x,\alpha,\delta)\Theta; \tag{7}$$

u_{com} 是 H_∞ 补偿器,用来补偿外部扰动和逼近误差.

采用式(7)来逼近 $F_\sigma(x)$ 和 $G_\sigma(x)$ 均已知时的控制律,即

$$\bar{u} = G_\sigma(x)^{-1}[-F_\sigma(x) + y_r^{(\beta)} + K^{\mathrm{T}}e], \tag{8}$$

其中 K^{T} 是反馈增益阵,使得 $A - BK^{\mathrm{T}}$ 的特征多项式是 Hurwitz 的.

最优逼近误差可定义为

$$w = -G_\sigma(x)[\hat{u}_\sigma(x \mid \Theta^*,\alpha^*,\delta^*) - \bar{u}].$$

令 $\bar{w} = w - d$,将式(6)代入(2),并由式(5),误差动态方程可改写为

$$\dot{e} = (A - BK^{\mathrm{T}})e - BG_\sigma(x)[(\Psi_\sigma(x) - \alpha\Psi_\sigma^\alpha(x) - \delta\Psi_\sigma^\delta(x))\tilde{\Theta} + (\tilde{\alpha}\Psi_\sigma^\alpha(x) + \tilde{\delta}\Psi_\sigma^\delta(x))\Theta] + B\bar{w} + Bu_{\mathrm{com}}. \tag{9}$$

根据跟踪误差 e,选择参数调整律

$$\dot{\Theta} = \eta_1(\Psi_\sigma(x) - \alpha\Psi_\sigma^\alpha(x) - \delta\Psi_\sigma^\delta(x))^{\mathrm{T}}(B^{\mathrm{T}}Pe), \tag{10}$$
$$\dot{\alpha} = \eta_2(B^{\mathrm{T}}Pe)\Psi_\sigma^\alpha(x)\Theta^{\mathrm{T}}, \tag{11}$$
$$\dot{\delta} = \eta_3(B^{\mathrm{T}}Pe)\Psi_\sigma^\delta(x)\Theta^{\mathrm{T}}, \tag{12}$$

其中 η_1, η_2 和 η_3 是正常数.

采用 H_∞ 补偿器 u_{com} 来补偿外部扰动和逼近误差, H_∞ 补偿器为

$$u_{\mathrm{com}} = -(1/\alpha)B^{\mathrm{T}}Pe. \tag{13}$$

其中对称正定矩阵 P 由下面的 Riccati 方程给出:

$$(A - BK^{\mathrm{T}})^{\mathrm{T}}P + P(A - BK^{\mathrm{T}}) + Q - \left(\frac{2}{\alpha} - \frac{1}{\rho^2}\right)PBB^{\mathrm{T}}P = 0, \tag{14}$$

$2\rho^2 \geq \alpha > 0$, Q 为对称正定矩阵.

定理1 对于 MIMO 非线性多时滞系统(1),选择模糊控制律(6),时滞模糊逻辑系统(7),参数调节律(10)～(12), H_∞ 补偿器(13),则误差闭环系统(9)满足 H_∞ 跟踪性能

$$\int_0^T e^{\mathrm{T}}\bar{Q}e\,\mathrm{d}t \leq e^{\mathrm{T}}(0)Pe(0) + \sum_{i=1}^r\int_{-\tau_i}^0 \Xi^{\mathrm{T}}(v)\Xi(v)\,\mathrm{d}v + \frac{1}{\eta_1}\tilde{\Theta}_1^{\mathrm{T}}(0)\tilde{\Theta}_1(0) + \frac{1}{\eta_2}\mathrm{tr}(\tilde{\alpha}^{\mathrm{T}}(0)\tilde{\alpha}(0)) + \frac{1}{\eta_3}\mathrm{tr}(\tilde{\delta}^{\mathrm{T}}(0)\tilde{\delta}(0)) + \rho^2\int_0^T(\bar{w}^{\mathrm{T}}\bar{w})\,\mathrm{d}t,$$

其中 $\bar{Q} = Q - rI > 0$.

证明 选取 Lyapunov 函数

$$V = \frac{1}{2}e^{\mathrm{T}}Pe + \frac{1}{2}\sum_{i=1}^r\int_{t-\tau_i}^t e^{\mathrm{T}}(v)e(v)\,\mathrm{d}v + \frac{1}{2\eta_1}\tilde{\Theta}^{\mathrm{T}}\tilde{\Theta} + \frac{1}{2\eta_2}\mathrm{tr}(\tilde{\alpha}^{\mathrm{T}}\tilde{\alpha}) + \frac{1}{2\eta_3}\mathrm{tr}(\tilde{\delta}^{\mathrm{T}}\tilde{\delta}),$$

可证得 H_∞ 的跟踪性能. □

5 仿真算例

设多输入多输出非线性多时滞系统为两连杆机械臂系统[5]

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

其中

$$C(q,\dot{q}) = H^{-1}(q)C'(q,\dot{q}),$$
$$g(q) = 0,\ B(q) = H^{-1}(q),$$

$q = [q_1, q_2]^{\mathrm{T}}$, $\xi_i(t)$ 未知有界, $\tau_i(i = 1,2,\cdots,r)$ 表示时滞, $d' = H^{-1}(q)d$ 是外部扰动, $d = [d_1, d_2]^{\mathrm{T}}$.

令 $x_1 = q_1$, $x_2 = \dot{q}_1$, $x_3 = q_2$, $x_4 = \dot{q}_2$, $y_1 = x_1$, $y_2 = x_3$, $r = 2$, $\tau_1 = 0.8$, $\tau_2 = 1.2$, d 是零均值、方差为 0.1 的白噪声, $\Xi(t) = [0.4\ \ 0\ \ -0.4\ \ 0]$,选取

$$K^{\mathrm{T}} = \begin{bmatrix} 2 & 2 & 0 & 0 \\ 0 & 0 & 3 & 3 \end{bmatrix},$$
$$Q = \mathrm{diag}[12, 12, 12, 12],$$
$$\rho = 0.1,\ \alpha = 0.01,\ \xi_1(t) = 0.5 + 10\sin t,$$
$$\xi_2(t) = 0.5(1 - \exp(-t))/(1 + \exp(-t)).$$

跟踪信号 y_{r1} 和 y_{r2} 满足

$$\ddot{y}_{r1} = -5y_{r1} - 4\dot{y}_{r1} + r_1(t),$$
$$\ddot{y}_{r2} = -5y_{r2} - 4\dot{y}_{r2} + r_2(t),$$

其中 $r_1(t)$ 和 $r_2(t)$ 均是幅值为 1,周期为 2π 的方波信号. 采用本文方法,可得仿真结果如图 1 和图 2 所

示.

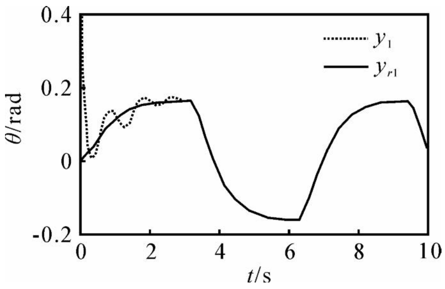

图 1　输出 y_1 和期望值 y_{r1}

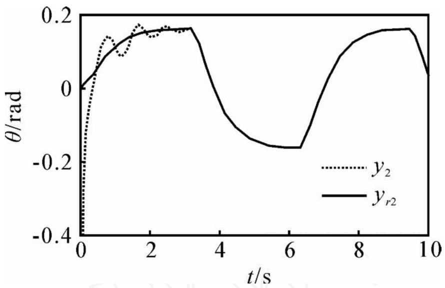

图 2　输出 y_2 和期望值 y_{r2}

6　结　　论

本文综合了自适应控制和 H_∞控制,提出了一种直接自适应模糊跟踪控制方案. 构建自适应时滞模糊逻辑系统用来逼近时滞未知函数,用 H_∞补偿器抵消模糊逼近误差和系统的外部扰动. 仿真结果表明了该方案的有效性.

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