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一类非线性MIMO系统的模糊自适应输出反馈控制

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摘 要: 针对一类MIMO非线性状态不可测系统, 提出一种基于观测器的模糊自适应输出反馈控制方法, 通过应用"主导输入"的概念, 并将自适应控制、H^∞控制与模糊逻辑系统相结合, 导出了输出反馈控制律以及参数的自适应律. 基于李亚普诺夫函数证明了该控制方法可保证闭环系统的全局稳定, 并获得了H^∞跟踪性能指标.

关键词: MIMO非线性系统; 观测器; 模糊自适应控制; H^∞控制
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Fuzzy Adaptive Output Feedback Control for Nonlinear MIMO Systems

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Abstract: The fuzzy adaptive control scheme based on observer is proposed for a class of MIMO nonlinear systems whose states are unavailable. By applying "dominant input" concept, and combining adaptive control and H^∞ control with fuzzy logic systems, the output feedback control law and parameter adaptive laws are derived. It is proved that the whole control scheme can guarantee the stability of the closed-loop system, and achieve H^∞ tracking performance based on Lyapunov function method.

Key words: Nonlinear MIMO systems; Observer; Fuzzy adaptive control; H^∞ control

1 引 言

不确定非线性多输入多输出系统的控制一直是一个难题. 近几年来, 随着模糊控制理论和神经网络技术的发展, 使这一研究领域变得活跃起来[1~7]. 文献[1~3]用模糊逻辑系统逼近系统中所有未知函数, 提出了一种模糊自适应控制方法. [4]用神经网络来逼近系统中所有未知函数, 提出了一种自适应神经网络控制方法. 在[1~3]的基础上, 通过引入"主导输入"的概念, [5,6]提出了一种直接和间接模糊自适应控制方法. 然而, 以上关于非线性多输入多输出的模糊自适应或神经网络控制方法都假设了系统的状态是可以直接测量的条件. 然而在实际中, 许多非线性系统的状态很难直接测量. 因此, 研究模糊自适应或神经网络的输出反馈控制的设计和系统的稳定性分析具有重要意义. 文献[7]针对一类多输入多输出非线性系统, 利用[1~3]的思想, 给出了一种基于观测器的模糊自适应输出控制算法及其稳定性分析.

本文针对状态不完全可测的MIMO非线性系统, 提出了一种新的基于观测器的模糊自适应输出反馈控制方法, 证明了闭环系统的稳定性和收敛性. 与文献[7]相比, 本文所给出的模糊自适应输出反馈控制方法具有以下优点: 1) 利用了文献[5,6]中所提出的"主导输入"的思想进行模糊自适应输出反馈控制的设计, 从而克服了[7]所提出的模糊自适应控制算法的复杂性[5,6]; 2) 模糊自适应观测器是针对系统

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的状态设计的,不是针对观测误差设计的,因此该控制算法更加直接,易于解决实际问题.

2　问题的描述

考虑一个MIMO非线性系统

$$
\begin{aligned}
&\dot{x}_{r_1 1} = x_{r_1 2},\\
&\quad\vdots\\
&\dot{x}_{r_1 (r_1-1)} = x_{r_1 r_1},\\
&\dot{x}_{r_1 r_1} = f_1(\underline{x}) + g_{11}(\underline{x})u_1 + \cdots + g_{1m}(\underline{x})u_m;\\
&\quad\vdots\\
&\dot{x}_{r_m 1} = x_{r_m 2},\\
&\quad\vdots\\
&\dot{x}_{r_m (r_m-1)} = x_{r_m r_m},\\
&\dot{x}_{r_m r_m} = f_m(\underline{x}) + g_{m1}(\underline{x})u_1 + \cdots + g_{mm}(\underline{x})u_m;\\
&y_1 = x_{r_1 1},\\
&\quad\vdots\\
&y_m = x_{r_m 1}.
\end{aligned}
\tag{1}
$$

式中:$[r_1, \cdots, r_m]$ 是系统的相对阶向量,$r_1 + \cdots + r_m = n$;$y = [y_1, \cdots, y_m]^{\mathrm T} \in R^m$ 为系统的输出向量,$\underline{x} = [x_{r_1 1}, \cdots, x_{r_1 r_1}, \cdots, x_{r_m 1}, \cdots, x_{r_m r_m}]^{\mathrm T} \in R^n$ 为系统状态向量,$u = [u_1, \cdots, u_m] \in R^m$ 为系统的输入控制向量,$f(\underline{x}) = [f_1(\underline{x}), \cdots, f_m(\underline{x})]^{\mathrm T}$ 为未知的非线性连续函数向量,$G(\underline{x}) = \begin{bmatrix} g_{11}(\underline{x}) & \cdots & g_{1m}(\underline{x}) \\ \vdots & \vdots & \vdots \\ g_{m1}(\underline{x}) & \cdots & g_{mm}(\underline{x}) \end{bmatrix}$ 为控制增益矩阵,其中 $G(x)$ 的每一个元素 $g_{ij}(x)$ 是连续的未知函数.

将系统(1) 写成如下形式:

$$
\begin{bmatrix} y_1^{(r_1)} \\ \vdots \\ y_m^{(r_m)} \end{bmatrix} = \begin{bmatrix} f_1(\underline{x}) \\ \vdots \\ f_m(\underline{x}) \end{bmatrix} + G(\underline{x}) \begin{bmatrix} u_1 \\ \vdots \\ u_m \end{bmatrix}. \tag{2}
$$

按照文献[5,6]的思想,可把式(1) 看成是 m 个多输入单输出子系统组成,其第 $i\,(i = 1, 2, \cdots, m)$ 个子系统为

$$
\begin{aligned}
y_i^{(r_i)} = {} & f_i(\underline{x}) + g_{i1}(\underline{x})u_1 + \cdots + \\
& g_{ii}(\underline{x})u_i + \cdots + g_{im}(\underline{x})u_m.
\end{aligned}
\tag{3}
$$

由于 m 个输入都影响这个子系统的输出,在这 m 个输入中选择一个起主导作用的输入,记为 u_i,其余看作系统的外来干扰,则有

$$
\begin{aligned}
& y_i^{(r_i)} = f_i(\underline{x}) + g_{ii}(\underline{x})u_i + d_{si},\quad i = 1, 2, \cdots, m,\\
& d_{si} = \sum_{j=1, j\neq i}^{m} g_{ij}(\underline{x})u_j.
\end{aligned}
\tag{4}
$$

这样就将一个多输入多输出系统分解成 m 个单输入单输出子系统.

如果定义

$$
A_i = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{r_i \times r_i},\quad B_i = \begin{bmatrix} 0 \\ 0 \\ \cdots \\ 1 \end{bmatrix}_{r_i \times 1},
$$

$$
C_i = [1\ \ 0\ \ \cdots\ \ 0]_{1 \times r_i}
$$

并记 $\underline{x}_i = (x_{r_i 1}, \cdots, x_{r_i r_i})^{\mathrm T}$,则式(4) 等价于

$$
\begin{aligned}
& \dot{\underline{x}}_i = A_i \underline{x}_i + B_i[f_i(\underline{x}) + g_{ii}(\underline{x})u_i + d_{si}],\ y_i = C_i \underline{x}_i,\\
& \qquad i = 1, 2, \cdots, m.
\end{aligned}
\tag{5}
$$

控制目标是设计一个自适应模糊输出反馈控制器,使系统(1) 的输出 $y = [y_1, \cdots, y_m]^{\mathrm T}$ 跟踪给定的有界参考信号 $y_m = [y_{m1}, \cdots, y_{mm}]^{\mathrm T}$,并且对于给定的干扰衰减水平 $\rho > 0$,获得 H^∞ 跟踪性能指标

$$
\begin{aligned}
& \int_0^T E_i^{\mathrm T} Q_i E_i \mathrm{d}t \leqslant \\
& E_i^{\mathrm T}(0) P_i E_i(0) + \frac{1}{r}\tilde{\theta}_i^{\mathrm T}(0)\tilde{\theta}_i(0) + \rho^2 \int_0^T w_i^2 \mathrm{d}t
\end{aligned}
\tag{6}
$$

式中:$T \in [0, \infty)$,$E_i = [\hat{e}_i, e_i]$ 为组合误差信号向量,$\tilde{\theta}_i$ 为参数逼近误差向量,w_i 是模糊逼近误差,Q_i 和 P_i 为适当维数的正定矩阵.

3　自适应模糊输出反馈控制器的设计

设模糊逻辑系统的形式为

$$
\begin{aligned}
& \hat{f}_i(\underline{x} \mid \theta_i) = \theta_i^{\mathrm T} \zeta(\underline{x}),\\
& \hat{g}_{ii}(\underline{x} \mid \theta_{ii}) = \theta_{ii}^{\mathrm T} \zeta(\underline{x}),\quad i = 1, 2, \cdots, m.
\end{aligned}
$$

其中:$\theta_i = (\theta_{i1}, \cdots, \theta_{iM})^{\mathrm T}$,$\theta_{ii} = (\theta_{ii1}, \cdots, \theta_{iiM})^{\mathrm T}$ 为可调参数向量.$\zeta(\underline{x}) = (\zeta_1(\underline{x}), \cdots, \zeta_M(\underline{x}))^{\mathrm T}$ 为模糊基向量函数.根据模糊逻辑系统具有逼近非线性连续函数的性质,用模糊逻辑系统 $\hat{f}_i(\underline{x} \mid \theta_i)$,$\hat{g}_{ii}(\underline{x} \mid \theta_{ii})$ 分别逼近未知函数 $f_i(\underline{x})$,$g_{ii}(\underline{x})$.设计模糊自适应观测器为

$$
\begin{aligned}
& \dot{\hat{\underline{x}}}_i = A_i \hat{\underline{x}}_i + B_i[\hat{f}_i(\hat{\underline{x}} \mid \theta_i) + \hat{g}_{ii}(\hat{\underline{x}} \mid \theta_{ii})u_i - \\
& \qquad u_{ai} - u_{si}] + K_{0i}(y_i - C_i \hat{\underline{x}}_i),\\
& \hat{y}_i = C_i \hat{\underline{x}}_i.
\end{aligned}
\tag{7}
$$

式中:$K_{0i} = [k_{i,r_i} \cdots k_{i,1}]^{\mathrm T}$ 为观测器增益矩阵,K_{0i} 的选择使得 $A_i - K_{0i}C_i$ 为稳定的矩阵.

定义观测误差向量为

$$
\underline{e}_i = \underline{x}_i - \hat{\underline{x}}_i,\quad \tilde{y}_i = y_i - \hat{y}_i,
$$

则由式(5) 和(7) 得

$$
\begin{aligned}
& \dot{\underline{e}}_i = (A_i - K_{0i}C_i)\underline{e}_i + B_i[(f_i(\underline{x}) - \hat{f}_i(\hat{\underline{x}} \mid \theta_i)) + \\
& \qquad (g_{ii}(\underline{x}) - \hat{g}_{ii}(\hat{\underline{x}} \mid \theta_{ii}))u_i + d_{si} + u_{ai} + u_{si}],\\
& \tilde{y}_i = C_i \underline{e}_i.
\end{aligned}
\tag{8}
$$

令 $\underline{x}$ 和 $\hat{\underline{x}}$ 分别属于紧集 $U_{\underline{x}}$ 和 $U_{\hat{\underline{x}}}$,其中

$$
U_{\underline{x}} = \{\underline{x} \in R^n : \|\underline{x}\| \leqslant m_{\underline{x}} < \infty\}, \tag{9}
$$

$$
U_{\hat{\underline{x}}} = \{\hat{\underline{x}} \in R^n : \|\hat{\underline{x}}\| \leqslant m_{\hat{\underline{x}}} < \infty\}. \tag{10}
$$

定义最优参数估计值为

$$\theta_i^* = \arg\min_{\theta_i\in\Omega_i}\Big[\sup_{x\in U_x,\ \hat{x}\in U_{\hat{x}}}\|\hat{f}_i(\hat{x}|\theta_i) - f_i(x)\|\Big],\quad i = 1, 2, \cdots, m,$$

$$\theta_{ii}^* = \arg\min_{\theta_{ii}\in\Omega_{ii}}\Big[\sup_{x\in U_x,\ \hat{x}\in U_{\hat{x}}}\|\hat{g}_i(\hat{x}|\theta_{ii}) - g_i(x)\|\Big],\quad i = 1, 2, \cdots, m. \tag{11}$$

Ω_i 和 Ω_{ii} 分别表示有界的闭子集.

定义最小逼近误差为

$$w_i = (f_i(x) - \hat{f}_i(\hat{x}|\theta_i^*)) + (g_{ii}(x) - \hat{g}_{ii}(\hat{x}|\theta_{ii}^*))u_i,$$

则式(8) 可以表示为

$$\dot{e}_i = (A_i - K_{0i}C_i)e_i + B_i(\tilde{\theta}_{i}^{\mathrm{T}}\zeta(\hat{x}) + \tilde{\theta}_{ii}^{\mathrm{T}}\zeta(\hat{x})u_i) + B_iu_{ai} + B_iu_{si} + B_iw_i', \tag{12}$$

式中 $w_i' = w_i + d_{si}$.

设 $y_{mi} = (y_{mi}, \dot{y}_{mi}, \cdots, y_{mi}^{(r_i-1)})^{\mathrm{T}}$, $\hat{e}_i = y_{mi} - \hat{x}_i$, 模糊控制器的设计为

$$u_i = \frac{1}{\hat{g}_{ii}(\hat{x}|\theta_{ii})}\big(-\hat{f}_i(\hat{x}|\theta_i) + y_{mi}^{(r_i)} + K_{ic}^{\mathrm{T}}\hat{e}_i + u_{ai} + u_{si}\big), \tag{13}$$

$$u_{ai} = -\frac{1}{r}B_i^{\mathrm{T}}P_{i2}e_i, \tag{14}$$

$$u_{si} = K_{0i}P_{1i}\hat{e}_i. \tag{15}$$

把式(13) 代入式(7) 得

$$\dot{\hat{e}}_i = (A_i - B_iK_{ci}^{\mathrm{T}})\hat{e}_i - K_{0i}C_ie_i. \tag{16}$$

假设 1　对于给定的正定矩阵 Q_{1i} 和 Q_{2i}, 下面的矩阵方程存在正定解 P_{1i} 和 P_{2i}:

$$(A_i - B_iK_{ci}^{\mathrm{T}})^{\mathrm{T}}P_{1i} + P_{1i}(A_i - B_iK_{ci}^{\mathrm{T}}) = -Q_{1i}; \tag{17}$$

$$(A_i - C_iK_{0i})^{\mathrm{T}}P_{2i} + P_{2i}(A_i - C_iK_{0i}) - P_{2i}B_i\left(\frac{2}{r} - \frac{1}{\rho^2}\right)B_i^{\mathrm{T}}P_{2i} = -Q_{2i},$$
$$P_{2i}B_i = C_i^{\mathrm{T}}. \tag{18}$$

假设 2　设模糊逼近误差 w_i' 是平方可积, 即

$$\int_0^\infty |w_i'|^2\mathrm{d}t < \infty.$$

定理 1　对于非线性系统(4), 如满足前面的假设, 并取模糊控制器为

$$u_i = \frac{1}{\hat{g}_{ii}(\hat{x}|\theta_{ii})}\big(-\hat{f}_i(\hat{x}|\theta_i) + y_{mi}^{(r_i)} + K_{ci}^{\mathrm{T}}\hat{e}_i + u_{ai} + u_{si}\big), \tag{19}$$

$$u_{ai} = -\frac{1}{r}B_i^{\mathrm{T}}P_{i2}e_i = -\frac{\tilde{y}_i}{r}, \tag{20}$$

$$u_{si} = K_{0i}P_{1i}\hat{e}_i, \tag{21}$$

参数向量的自适应律为

$$\dot{\theta}_i = \gamma_{1i}e_i^{\mathrm{T}}P_{2i}B_i\zeta(\hat{x}) = \gamma_{1i}\tilde{y}_i\zeta(\hat{x}), \tag{22}$$

$$\dot{\theta}_{ii} = \gamma_{2i}e_i^{\mathrm{T}}P_{2i}B_i\zeta(\hat{x})u_i = \gamma_{2i}\tilde{y}_i\zeta(\hat{x})u_i, \tag{23}$$

则整个闭环系统稳定且 $\lim_{t\to\infty}e_i = \lim_{t\to\infty}\hat{e}_i = 0$.

证明　取李亚普诺夫函数为

$$V_i = \frac{1}{2}\hat{e}_i^{\mathrm{T}}P_{1i}\hat{e}_i + \frac{1}{2}e_i^{\mathrm{T}}P_{2i}e_i + \frac{1}{2\gamma_{1i}}\tilde{\theta}_i^{\mathrm{T}}\tilde{\theta}_i + \frac{1}{2\gamma_{2i}}\tilde{\theta}_{ii}^{\mathrm{T}}\tilde{\theta}_{ii}. \tag{24}$$

求 V_i 对时间的导数, 并由式(12) 和(16) 得

$$\dot{V}_i = \frac{1}{2}\hat{e}_i^{\mathrm{T}}[(A_i - B_iK_{ci}^{\mathrm{T}})^{\mathrm{T}}P_{1i} + P_{1i}(A_i - B_iK_{ci}^{\mathrm{T}})]\hat{e}_i - \hat{e}_i^{\mathrm{T}}P_{1i}K_{0i}C_ie_i + e_i^{\mathrm{T}}B_iP_{1i}u_{ai} + e_i^{\mathrm{T}}B_iP_{2i}u_{si} + e_i^{\mathrm{T}}B_iP_{2i}w_i' + \frac{1}{2}e_i^{\mathrm{T}}[(A_i - K_{0i}C_i)^{\mathrm{T}}P_{2i} + P_{2i}(A_i - K_{0i}C_i)]e_i + e_i^{\mathrm{T}}P_{2i}B_i\zeta^{\mathrm{T}}(\hat{x})\tilde{\theta}_i + e_i^{\mathrm{T}}P_{2i}B_i\zeta^{\mathrm{T}}(\hat{x})\tilde{\theta}_{ii}u_i + e_i^{\mathrm{T}}P_{2i}B_iw_i' + \frac{1}{\gamma_{1i}}\dot{\tilde{\theta}}_i^{\mathrm{T}}\tilde{\theta}_i + \frac{1}{\gamma_{2i}}\dot{\tilde{\theta}}_{ii}^{\mathrm{T}}\tilde{\theta}_{ii}. \tag{25}$$

由于 $P_{2i}B_i = C_i^{\mathrm{T}}$, 所以 $e_i^{\mathrm{T}}P_{2i}B_i = e_i^{\mathrm{T}}C_i^{\mathrm{T}} = C_ie_i = \tilde{y}_i$, 把参数向量的自适应律(22) 和(23) 代入上式得

$$\dot{V}_i = \frac{1}{2}\hat{e}_i^{\mathrm{T}}[(A_i - B_iK_{ci})^{\mathrm{T}}P_{1i} + P_{1i}(A_i - B_iK_{ci})]\hat{e}_i - \hat{e}_i^{\mathrm{T}}P_{1i}B_iK_{0i}C_ie_i + \hat{e}_i^{\mathrm{T}}P_{i1}B_iu_{si} + e_i^{\mathrm{T}}P_{i2}B_iu_{ai} + \frac{1}{2}e_i^{\mathrm{T}}[(A_i - K_{0i}C_i)^{\mathrm{T}}P_{2i} + P_{2i}(A_i - K_{0i}C_i)]e_i + e_i^{\mathrm{T}}P_{i2}B_iw_i'. \tag{26}$$

把 $u_{si} = K_{0i}P_{1i}\hat{e}_i$, $u_{ai} = -\frac{1}{r}B_i^{\mathrm{T}}P_{2i}e_i$ 代入上式, 并由式(17) 和(18) 得

$$\dot{V}_i \le -\frac{1}{2}\hat{e}_i^{\mathrm{T}}Q_{1i}\hat{e}_i - \frac{1}{2}e_iQ_{2i}e_i - \frac{1}{2\rho^2}e_i^{\mathrm{T}}P_{2i}B_iB_i^{\mathrm{T}}P_{2i}e_i + e_i^{\mathrm{T}}P_{2i}B_iw_i' =$$
$$-\frac{1}{2}\hat{e}_i^{\mathrm{T}}Q_{1i}\hat{e}_i - \frac{1}{2}e_iQ_{2i}e_i + \frac{1}{2}\rho^2w_i'^2 - \frac{1}{2}\left(\frac{1}{\rho}B_i^{\mathrm{T}}P_{2i}e_i - \rho w_i'\right)^{\mathrm{T}}\left(\frac{1}{\rho}B_i^{\mathrm{T}}P_{2i}\tilde{e}_i - \rho w_i'\right) \le$$
$$-\frac{1}{2}\hat{e}_i^{\mathrm{T}}Q_{1i}\hat{e}_i - \frac{1}{2}e_iQ_{2i}e_i + \frac{1}{2}\rho^2w_i'^2. \tag{27}$$

令 $P_i = \mathrm{diag}[P_{1i}, P_{2i}]$, $Q_i = \mathrm{diag}[Q_{1i}, Q_{2i}]$, $E_i^{\mathrm{T}} = [\hat{e}_i^{\mathrm{T}}, e_i^{\mathrm{T}}]$, 则上式可变为

$$\dot{V}_i \le -\frac{1}{2}E_i^{\mathrm{T}}Q_iE_i + \frac{1}{2}\rho^2w_i'^2. \tag{28}$$

因为 $w_i' \in L_2$, 与文献[1]的证明相同, 可得 $\hat{e}_i, e_i, u \in L_\infty$, $\lim_{t\to\infty}\hat{e}_i = 0$, $\lim_{t\to\infty}e_i = 0$.

对式(28) 积分得

$$V_i(T) - V_i(0) \le$$

$$-\frac{1}{2}\int_0^T E_i^{\mathrm{T}} Q_i E_i \mathrm{d}t + \frac{1}{2}\rho^2\int_0^T w_i^2 \mathrm{d}t \qquad (29)$$

因为 $V_i(T) \geq 0$, 因此上式变为

$$\frac{1}{2}\int_0^T E_i^{\mathrm{T}} Q_i E_i \mathrm{d}t \leq$$
$$\frac{1}{2}E_i^{\mathrm{T}}(0)P_iE_i(0) + \frac{1}{2\gamma_{1i}}\tilde{\theta}_i^{\mathrm{T}}(0)\tilde{\theta}_i(0) +$$
$$\frac{1}{2\gamma_{2i}}\tilde{\theta}_{ii}^{\mathrm{T}}(0)\tilde{\theta}_{ii}(0) + \frac{1}{2}\rho^2\int_0^T w_i^2 \mathrm{d}t \qquad (30)$$

即模糊自适应输出反馈控制获得 H^{∞} 跟踪性能指标 □

4 仿 真

考虑如下双输入双输出非线性系统[3,6]:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix} x_2 \\ x_1 + x_2^2 + x_3 \\ x_1 + 2x_2 + 3x_3x_1\end{bmatrix} +$$
$$\begin{bmatrix} 0 \\ 3u_1 + u_2 \\ u_1 + 2(2 + 0.5\sin x_1)u_1\end{bmatrix}, \qquad (31)$$
$$y_1 = x_1, y_2 = x_3.$$

由(31) 可解得

$$\begin{bmatrix}\ddot{y}_1\\ \dot{y}_2\end{bmatrix} = \begin{bmatrix} x_1 + x_2^2 + x_3 \\ x_1 + 2x_2 + 3x_3x_1\end{bmatrix} +$$
$$\begin{bmatrix} 3 & 1 \\ 1 & 4 + \sin x_1\end{bmatrix}\begin{bmatrix}u_1\\ u_2\end{bmatrix}. \qquad (32)$$

即系统的相对阶向量为 $[r_1 \quad r_2] = [2 \quad 1]$. 给定参考信号为

$$y_{m1} = \pi/30 \sin t, \; y_{m2} = \pi/30 \cos t$$

对变量 x_1, x_2, x_3 定义区间 $[-1, 1]$ 上的模糊集, 选择隶属函数为

$$\mu_{F_i^1}(x_i) = \frac{1}{1 + \exp(5(x_i + 0.6))},$$
$$\mu_{F_i^2}(x_i) = \exp(-(x_i + 0.4)^2),$$
$$\mu_{F_i^3}(x_i) = \exp(-(x_i + 0.2)^2),$$
$$\mu_{F_i^4}(x_i) = \exp(-x_i^2),$$
$$\mu_{F_i^5}(x_i) = \exp(-(x_i - 0.2)^2),$$
$$\mu_{F_i^6}(x_i) = \exp(-(x_i - 0.4)^2),$$
$$\mu_{F_i^7}(x_i) = \frac{1}{1 + \exp(-5(x_i - 0.6))}.$$

给定正定矩阵 $Q_i = \mathrm{diag}[10 \quad 10], Q_2 = 0, K_{c1}^{\mathrm{T}} = [144, 24], K_{c2} = 120, K_{01}^{\mathrm{T}} = [60, 900], K_{02} = 50, \gamma_{11} = \gamma_{12} = 0.1, \gamma_{21} = \gamma_{22} = 0.01, r = 20.$ 初始条件为 $\hat{x}_1(0) = \hat{x}_2(0) = \hat{x}_3(0) = 0, x_1(0) = x_2(0) = x_3(0) = 0.1, \theta_{1i}(0) = 0, \theta_{2i}(0) = 1$, 积分步长为 0.001, 采用MATLAB 进行仿真, 仿真结果如图 1 ～ 图 3 所示

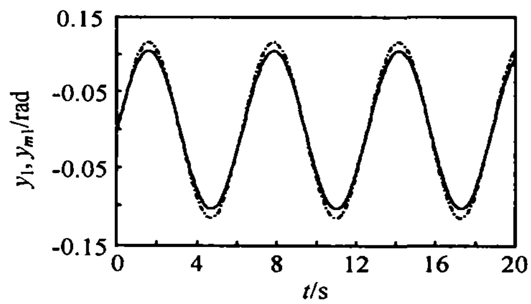


图 1 输出 y_1 和参考信号 y_{m1}

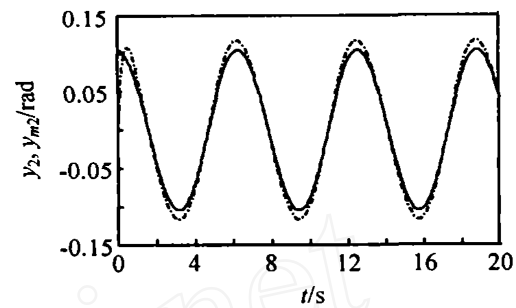
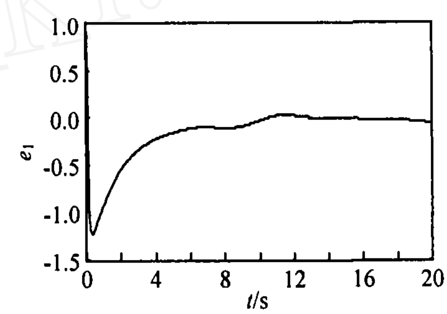
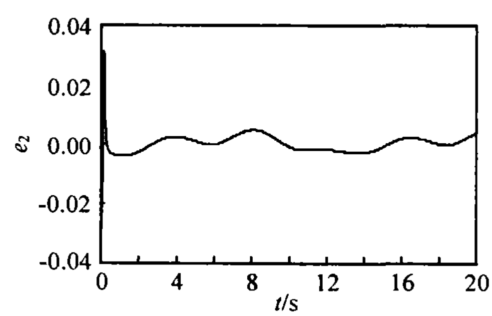


图 2 输出 y_2 和参考信号 y_{m2}



(a) 估计误差 e_1



(b) 估计误差 e_2

图 3 估计误差曲线

5 结 语

本文提出了一种基于观测器的自适应模糊控制方法 该控制方法不需要系统的状态变量可测的条件, 而是通过设计观测器获得它的估计值, 并利用“主导输入”的思想很好地解决了系统中的耦合对于跟踪误差的影响问题 本文提出的整个控制方案保证了闭环系统的稳定性

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6 结　　语

受滚动约束的轮移式机器人的运动规划问题是机器人技术中的一个关键, 它是不可能用离线全局算法完成的. 本文把优化方法与RRT 算法机制结合起来, 在寻找避障路径的同时, 满足运动方程的约束条件. 而对于动态环境, 利用滚动规划的思想, 连接多个滚动约束的RRT 的规划轨迹就可到达全局目标状态. 对于多自由度的机器人, 这种含随机性的算法可以降低算法复杂度, 提高实时性. 这种算法还可以扩展到同时受运动学与动力学约束的非完整机器人系统.

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