

基于采样输出三角非线性系统的高增益观测器设计

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摘要: 本文研究了一类具有采样输出的三角非线性系统的高增益观测器设计问题。首先, 具有未建模动态的混杂系统被引入, 该系统可以通过增加增益来衰减。然后, 针对信息采样输出设计高增益采样观测器。通过运用 Lyapunov 方法, 误差系统指数稳定性的充分条件被给出。该条件弱于经典的 Lipschitz 条件, 因此, 本文得到的结论适用于更广泛的非线性系统。最后通过数算例的仿真验证了提出方法的有效性。

关键词: 三角非线性系统; 高增益观测器; 未建模动态; 指数稳定; Lipschitz 条件

中图分类号:

Title

High-gain Observer for a class of Triangular Nonlinear Systems with Sampled Outputs

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Abstract:

In this paper, the problem of high-gain observer design for a class of triangular nonlinear systems with sampled output are investigated. Firstly, a class of hybrid system with unmodeled dynamics are introduced, which can be attenuated by increasing the gain. Then, a continuous-discrete observer is designed. By applying Lyapunov functional sufficient conditions are proposed to guarantee the exponential stability of the estimation error dynamics. the condition is weaker than classic Lipschitz condition, therefore, the conclusions obtained in this paper are suitable for a wider nonlinear systems. Finally, a numerical example is presented to illustrate effectiveness.

Key words: triangular nonlinear systems; high-gain observer; unmodeled dynamics; exponential stability; Lipschitz condition

0 引言

【研究意义】非线性的存在使得系统的演化过程极为复杂^[1], 此外, 未建模动态的影响以及在信息测量过程中, 干扰的普遍存在, 可能会导致原系统的状态并不能由观测器准确观测, 从而使系统的状态重构难以实现, 进而无法设计基于观测器的有效控制器。解决此类问题的有效办法之一是设计合适的高增益观测器。【前人研究的进展】高增益观测器已发展成为研究非线性系统输出反馈控制的重要工具^[2]。在早期, Doyle 和 Stein 将高增益观测器应用于线性系统的鲁棒观测器设计^[3]。之后, 基于非线性系统的高增益观测器的研究的也受到了学者们的关注^[4-11]。其中, Gauthier 对全局 Lipschitz 条件下的非线性系统进行了研究^[12], 在非线性函数满足全局 Lipschitz 条件的假设下构造了观测器, 该观测器不仅适用于自治系统, 而且也适用于任何输入都可以观测到的非线性系统。Esfandiari 和 Khalil 已经证明, 在没有全局 Lipschitz 条件的情况下, 会出现峰值现象, 因此, 当观测器的增益足够高时, 高增益观测器可能会破坏闭环系统的稳定性^[13]。近年来, 测量噪声和模型的不确定性问题已成为一个重要的课题^[14-16]。由于建模的不确定性, ^[17]中构造了一个切换增益观测器, 以减少在状态观测过程中干扰

的影响。在^[18]中作者基于一个具有简单结构的对称正定矩阵研究了能够计算观测器增益的算法。在^[19]中考虑了峰值现象提出了能够降低峰值影响的高增益观测器。目前, 高增益观测器已发展成为研究非线性及不确定性系统输出反馈控制的重要工具。而由于现实系统中非线性和不确定性的普遍存在性和多样性, 高增益观测器的持续创新研究和发展, 对完善系统控制建模方法和研究手段具有重要意义。【本文的切入点】基于以上考虑, 本文研究一类不确定的非线性系统的高增益观测器设计问题, 考虑不确定的非线性系统对于非线性项未知的采样数据信息的输出进行测量, 通过增加增益来衰减未建模动态的影响, 未建模动态的名义模型满足较弱的 Lipschitz 条件, 提出了更宽松的稳定性条件。【拟解决的关键问题】首先, 利用未建模动态与名义模型的关系设计增益结构。其次, 建立观测器的采样规则, 系统的状态输出并不能连续获得, 因此观测器不能连续观测系统状态, 只能在离散时间获得采样值。然后, 设计高增益观测器利用状态观测结果, 构建误差系统, 通过构造 Lyapunov 函数分析误差系统的稳定性, 得到误差系统稳定性条件并实现对误差的估计。最后通过数值仿真验证了方法的有效性。

1 问题描述

考虑如下非线性系统:

$$\begin{cases} \dot{x}(t) = x_{i+1}(t) + f_i(x_1(t), L, x_i(t)), i=1, L, n-1, \\ \dot{x}_n(t) = \phi(\omega, x) + u(t), \\ y = x_1(t). \end{cases} \quad (1)$$

其中, $x \in \mathbb{R}^n$ 是状态变量, $u(t) \in \mathbb{R}$ 是输入, $y(t)$ 是输出, $f_i(x_1, L, x_i)$ 是具有满足如下条件的非线性函数:

$$|f_i(x_1, L, x_i) - f_i(\hat{x}_1, L, \hat{x}_i)| \leq l_i |x_1 - \hat{x}_1| + L + l_i |x_i - \hat{x}_i|, \quad (2)$$

其中, $l_i, i=1, L, n-1$ 为已知非负常数, $\phi(\omega, x)$ 为包含未建模动态的未知函数, 满足全局 Lipschitz 条件. 为了观测系统的状态, 设计如下形式的观测器:

$$\begin{cases} \dot{\hat{x}}_i(t) = \hat{x}_{i+1}(t) + f_i(\hat{x}_1(t), L, \hat{x}_i(t)) + \frac{\alpha_i}{\varepsilon^i} (y(t_k) - \hat{x}_i(t_k)), i=1, L, n-1, t \in [t_k, t_{k+1}) \\ \dot{\hat{x}}_n(t) = \phi_0(\hat{x}) + \frac{\alpha_n}{\varepsilon^n} (y(t_k) - \hat{x}_n(t_k)) + u(t), \end{cases} \quad (3)$$

其中 $\phi_0(\hat{x})$ 是 $\phi(\omega, x)$ 的名义模型, 设 $\phi_0 = 0$, 因此存在非负常数 L 和 M 有下列不等式成立:

$$\phi(\omega, x) - \phi_0(z) \leq L \|x - z\| + M, \quad (4)$$

其中 $L > 0, M > 0$ 是常数. 时间序列 $\{t_k\}$ 是严格递增的且满足下列条件:

$$t_0 = 0, \bar{h}_{10} \leq t_{k+1} - t_k \leq \bar{h}_1, k \in \mathbb{N}$$

其中 \bar{h}_{10}, \bar{h}_1 是正常数. 为了便于后面分析, 引入如下记号:

$$\rho(t) = t - t_k, \psi(t) = t_{k+1} - t, t \in [t_k, t_{k+1}),$$

$$I_1 = [I_n \ 0_n], I_2 = [0_n \ I_n], I_3 = [I_n \ -I_n]$$

定义误差 $e(t) = x(t) - \hat{x}(t)$, 结合系统(1)与系统(3)得到如下形式的误差系统:

$$\begin{cases} \dot{e}_i(t) = e_{i+1}(t) + f_i(x_1(t), L, x_i(t)) - f_i(\hat{x}_1(t), L, \hat{x}_i(t)) - \frac{\alpha_i}{\varepsilon^i} e_i(t_k) \\ \dot{e}_n(t) = \phi(\omega, x) - \phi_0(\hat{x}) - \frac{\alpha_n}{\varepsilon^n} e_n(t_k) \end{cases} \quad (5)$$

其中 $e_i(t) = x_i(t) - \hat{x}_i(t)$, 为了简化分析做如下变换

$$\gamma_i(t) = \frac{x_i(t) - \hat{x}_i(t)}{\varepsilon^{n-i}}, i=1, L, n, \quad (6)$$

$$\delta_i(t) = \frac{f_i(x_1(t), L, x_i(t)) - f_i(\hat{x}_1(t), L, \hat{x}_i(t))}{\varepsilon^{n-i}}, i=1, L, n-1, \quad (7)$$

$$\delta_n(t) = \phi(\omega, x) - \phi_0(\hat{x})$$

因此, 系统(5)可以写成如下的形式

$$\begin{cases} \varepsilon \dot{\gamma}_i(t) = -\alpha_i \gamma_i(t) + \gamma_{i+1}(t) + \alpha_i (\gamma_i(t) - \gamma_i(t_k)) + \varepsilon \delta_i(t), i=1, L, n-1, \\ \varepsilon \dot{\gamma}_n(t) = -\alpha_n \gamma_n(t) + \alpha_n (\gamma_n(t) - \gamma_n(t_k)) + \varepsilon \delta_n(t) \end{cases} \quad (8)$$

为了简化分析(8), 引入如下符号

$$\begin{aligned} \varepsilon \dot{\gamma}(t) &= A \gamma(t) + \bar{\alpha} (\gamma_1(t) - \gamma_1(t_k)) + \varepsilon \delta(t) \\ &= [\bar{A} \ I] [\eta(t) \ \varepsilon \delta(t)] \end{aligned} \quad (9)$$

$$\text{于是有 } \varepsilon \dot{\gamma}(t) = A_\xi(t) \xi(t), \quad (10)$$

$$\begin{aligned} \text{其中 } \gamma(t) &= [\gamma_1(t) \ \gamma_2(t) \ L \ \gamma_{n-1}(t) \ \gamma_n(t)]^T, \\ \delta(t) &= [\delta_1(t) \ \delta_2(t) \ L \ \delta_{n-1}(t) \ \delta_n(t)]^T \\ \bar{\alpha} &= [\alpha_1 \ \alpha_2 \ L \ \alpha_{n-1} \ \alpha_n]^T, \bar{I}_1 = [1 \ 0 \ L \ 0 \ 0], \bar{A} = [A \ \bar{\alpha} \ \bar{I}_1] \\ A_\xi &= [A \ \bar{\alpha} \ \bar{I}_1 \ I], \gamma(t) = \gamma(t) - \gamma(t_k), \xi(t) = [\gamma(t) \ \delta(t) \ \varepsilon \delta(t)]^T, \\ \eta(t) &= [\gamma(t) \ \delta(t)]^T. \end{aligned}$$

$$A = \begin{bmatrix} -\alpha_1 & 1 & 0 & L & 0 & 0 \\ -\alpha_2 & 0 & 1 & L & 0 & 0 \\ M & M & M & M & M & 0 \\ -\alpha_{n-1} & 0 & 0 & L & 0 & 1 \\ -\alpha_n & 0 & 0 & L & 0 & 0 \end{bmatrix},$$

至此, 误差系统(5)的稳定性问题能够转化为考虑系统(8)的稳定性问题结合(2)-(4)和(6)-(8), 我们有

$$\|\delta(t)\| \leq L \|\gamma(t)\| + M \quad (11)$$

引理1^[6]: 给定任意正定的矩阵 $U \in \mathbb{R}^{n \times n}$, 标量 $a, b > 0$, 若存在向量函数 $\phi: [a, b] \rightarrow \mathbb{R}^n$, 且积分 $\int_a^b \phi^T(s) U \phi(s) ds, \int_a^b \phi(s) ds$ 有意义, 则下列不等式成立:

$$\int_a^b \phi^T(s) U \phi(s) ds \geq \frac{1}{b-a} \int_a^b \phi^T(s) ds U \int_a^b \phi(s) ds$$

引理2^[6]: 给定适合维数的常量矩阵 S_1, S_{12}, S_2 , 其中 $S_1 = S_1^T > 0, S_2 = S_2^T > 0$, 则

$$-S_1 + S_{12} S_2^{-1} S_{12}^T < 0 \text{ 成立等价于如下矩阵不等式成立:}$$

$$\begin{bmatrix} -S_1 & S_{12} \\ S_{12}^T & -S_2 \end{bmatrix} < 0$$

2 主要结果

引入 Lyapunov 函数分析误差系统(8)的稳定性.

定理1 考虑误差系统(8), 假设条件(2)和(4)成立, 对于给定的常数 $\alpha_1 > 0$ 如果存在 $n \times n$ 矩阵 $P > 0, R > 0, 2n \times n$ 矩阵 $M_1, n \times n$ 矩阵 $X_1 = X_1^T, X_2 > 0$, 标量 $\beta_1, \beta_0, L_1 > 0$ 使得下列线性矩阵不等式成立

$$\begin{bmatrix} \Pi(t) + \Phi(t) & \Omega(t) & \bar{h}_1 \bar{A}^T R \\ * & -\beta_0 I & \bar{h}_1 I^T R \\ * & * & -\bar{h}_1 R \end{bmatrix} < 0 \quad (12)$$

$$\begin{bmatrix} \Pi(t) + \Phi(t) & \Omega(t) & \bar{h}_1 \bar{A}^T R & \bar{h}_1 M_1 e^{\alpha_1 \bar{h}_1} \\ * & -\beta_0 I & \bar{h}_1 I^T R & 0 \\ * & * & -\bar{h}_1 R & 0 \\ * & * & * & -\bar{h}_1 R \end{bmatrix} < 0 \quad (13)$$

$$\begin{aligned} \text{其中 } \Phi(t) &= 2\varepsilon \alpha_1 I_1^T P I_1 + (2\varepsilon \alpha_1 \bar{h}_1 - \varepsilon) I_2^T X_1 I_2 \\ &+ (4\varepsilon \alpha_1 \bar{h}_1 - 2\varepsilon) I_3^T X_2 I_2 + \varepsilon^2 L^2 (1 + \beta_1) \beta_0 I_1^T I_1 \\ &+ 2\bar{h}_1 I_2^T X_1 \bar{A} + 4\bar{h}_1 L_3^T X_2 \bar{A} \end{aligned}$$

$$\Pi(t) = I_1^T P \bar{A} + \bar{A}^T P I_1 + \varepsilon M_1 I_2 + \varepsilon I_2^T M_1^T$$

$$\Omega(t) = I_1^T P + h_1 I_2^T X_1 + 2h_1 I_3^T X_2$$

对于闭环系统(8), 存在正常数 a, b, c 和 ε , 以及 $\varepsilon = 1$ 使得从 γ_0 出发的解 $\gamma(t)$ 满足如下估计

$$\|\gamma(t)\| \leq a \|\gamma(t_0)\| e^{-bt} + \varepsilon M c \quad (14)$$

证明 构造如下形式的 Lyapunov 函数对系统(8)进行稳定性分析:

$$V(t) = \varepsilon \gamma^T(t) P \gamma(t) + \psi(t) \varepsilon^2 \int_{t-\rho(t)}^t e^{2\alpha_1(s-t)} \mathcal{X}(s) R \mathcal{X}(s) ds + \psi(t) \varepsilon (\mathcal{P}(t) X_1 \mathcal{P}(t) + 2(\gamma(t) - \mathcal{P}(t))^T X_2 \mathcal{P}(t)) \quad (15)$$

沿着轨线(8)对 $V(t)$ 求导, 有

$$\begin{aligned} \dot{V}(t) &= 2\gamma^T(t) P \varepsilon \mathcal{X}(t) \\ &- \varepsilon^2 \int_{t-\rho(t)}^t e^{2\alpha_1(s-t)} \mathcal{X}(s) R \mathcal{X}(s) ds \\ &+ \varepsilon^2 \psi(t) \mathcal{X}(t) R \mathcal{X}(t) \\ &- 2\alpha_1 \psi(t) \varepsilon^2 \int_{t-\rho(t)}^t e^{2\alpha_1(s-t)} \mathcal{X}(s) R \mathcal{X}(s) ds \\ &- \varepsilon [\mathcal{P}(t) X_1 \mathcal{P}(t) + 2(\gamma(t) - \mathcal{P}(t))^T X_2 \mathcal{P}(t)] \\ &+ 2\psi(t) \mathcal{P}(t) X_1 \varepsilon \mathcal{X}(t) \\ &+ 4\psi(t) (\gamma(t) - \mathcal{P}(t))^T X_2 \varepsilon \mathcal{X}(t) \end{aligned} \quad (16)$$

由(15)可得

$$\begin{aligned} &- 2\alpha_1 \psi(t) \varepsilon^2 \int_{t-\rho(t)}^t e^{2\alpha_1(s-t)} \mathcal{X}(s) R \mathcal{X}(s) ds \\ &= -2\alpha_1 V(t) + 2\alpha_1 \varepsilon \gamma^T(t) P \gamma(t) \\ &+ 2\alpha_1 \varepsilon \psi(t) (\mathcal{P}(t) X_1 \mathcal{P}(t) + 2(\gamma(t) - \mathcal{P}(t))^T X_2 \mathcal{P}(t)) \end{aligned}$$

由 $\mathcal{P}(t) = \int_{t-\rho(t)}^t \mathcal{X}(s) ds$, 可得下式成立

$$\begin{aligned} 0 &= 2\eta^T(t) \varepsilon M_1 (\mathcal{P}(t) - \int_{t-\rho(t)}^t \mathcal{X}(s) ds) \\ &\leq \eta^T(t) (\varepsilon M_1 I_2 + \varepsilon I_2^T M_1^T) \eta(t) \\ &+ (t - t_k) \eta^T(t) M_1 R^{-1} e^{2\alpha_1 h} M_1^T \eta(t) \\ &+ \varepsilon^2 \int_{t-\rho(t)}^t \mathcal{X}(s) R e^{2\alpha_1(s-t)} \mathcal{X}(s) ds \end{aligned} \quad (17)$$

由(11), 可得

$$0 \leq \varepsilon^2 (L^2 (1 + \beta_1) \gamma^T(t) \gamma(t) + M^2 (1 + \frac{1}{\beta_1}) - \|\delta(t)\|^2) \beta_0 \quad (18)$$

其中, $\beta_1 > 0, \beta_0 > 0, t \in [t_k, t_{k+1})$, 结合(16),(17)和(18)能够导出

$$\dot{V}(t) \leq -2\alpha_1 V(t) + \varepsilon^2 \beta_0 M^2 (1 + \frac{1}{\beta_1}),$$

进一步的可以得到

$$\|\gamma(t)\| \leq \sqrt{\frac{\lambda_2}{\lambda_1}} e^{-\alpha_1 t} \|\gamma(t_0)\| + \sqrt{\frac{1}{\lambda_1} \frac{1}{2\alpha_1} (1 + \frac{1}{\beta_1})} \varepsilon M \quad (19)$$

其中 $\lambda_1 = \lambda_{\min}(P), \lambda_2 = \lambda_{\max}(P)$, 因此(14)成立, 其中 $\varepsilon > 0, \varepsilon = 1$. 证毕.

注 1 因 $\gamma_i(t) = e_i(t) / \varepsilon^{n-i}$, 所以 $\|\gamma(t)\|$ 能够被估计, 就表明 $\|e(t)\|$ 也能够被估计

$$\begin{aligned} \|\gamma(t)\| &= \frac{1}{\varepsilon^{n-1}} \sqrt{e_1^2(t) + \varepsilon^2 e t + L + \varepsilon^{n-1} e_n^2(t)} \\ &\leq \frac{1}{\varepsilon^{n-1}} \|e(t)\| \end{aligned}$$

$$\|\gamma(t)\| \leq a \|\gamma(t_0)\| e^{-bt} + \varepsilon M c \leq \frac{1}{\varepsilon^{n-1}} a e^{-bt} \|e(0)\| + \varepsilon M c$$

因此下式成立

$$\|e_i(t)\| \leq \frac{1}{\varepsilon^{i-1}} a e^{-bt} \|e(0)\| + \varepsilon^{n-(i-1)} M c \quad (20)$$

对于所有的 $t \geq 0$, 有 $\|e_i(t)\|$ 是指数衰减并有界的。

3 数值例子

本节对下列数值例子构造高增益观测器, 设计其增益结构, 并通过仿真来对本文所提出的高增益观测器设计方法的有效性进行验证与说明, 考虑如下形式的系统:

$$\begin{cases} \dot{x}_1 = x_2(t) \\ \dot{x}_2 = x_3(t) - \frac{F_2(t)}{J_2} x_2(t) - \frac{K}{J_2} x_1(t) \\ \quad - \frac{mgd}{J_2} (\cos(x_1(t)) - 1) \\ \dot{x}_3(t) = x_4(t) \\ \dot{x}_4 = \frac{K^2}{J_1 J_2 N^2} x_1(t) - \frac{K}{J_2 N} x_3(t) - \frac{F_1(t)}{J_1} x_4(t) \\ \quad + \frac{1}{10} (|\hat{x}_3(t) + 1| - |\hat{x}_3(t) - 1|) + u(t) \\ y(t_k) = x_1(t_k) \end{cases} \quad (21)$$

其中 J_1, J_2, K, N, m, g , 和 d 是已知的参数, $F_1(t), F_2(t)$ 是不确定的函数, 且是有界的, 上界为一个未知的常数 $C > 0$, 因此高增益观测器被设计为如下的形式。

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2(t) + \frac{\alpha_1}{\varepsilon} (y(t_k) - \hat{x}_1(t_k)) \\ \dot{\hat{x}}_2 = \hat{x}_3(t) - \frac{F_2(t)}{J_2} \hat{x}_2(t) - \frac{K}{J_2} \hat{x}_1(t) \\ \quad - \frac{mgd}{J_2} (\cos(\hat{x}_1(t)) - 1) + \frac{\alpha_2}{\varepsilon^2} (y(t_k) - \hat{x}_1(t_k)) \\ \dot{\hat{x}}_3(t) = \hat{x}_4(t) + \frac{\alpha_3}{\varepsilon^3} (y(t_k) - \hat{x}_1(t_k)) \\ \dot{\hat{x}}_4 = \frac{K^2}{J_1 J_2 N^2} \hat{x}_1(t) - \frac{K}{J_2 N} \hat{x}_3(t) - \frac{F_1(t)}{J_1} \hat{x}_4(t) \\ \quad + \frac{1}{10} (|\hat{x}_3(t) + 1| - |\hat{x}_3(t) - 1|) + u(t) + \frac{\alpha_4}{\varepsilon^4} (y(t_k) - \hat{x}_1(t_k)) \end{cases} \quad (22)$$

系统参数

$$K / J_2 = 5, mgd / J_2 = 4, K^2 / (J_1 J_2 N^2)$$

$$2, K / (J_2 N) = 3, F_1(t) / J_1 = 10, F_2 / J_2 = 10,$$

观测器增益 $\alpha_1 = 4, \alpha_2 = 6, \alpha_3 = 4, \alpha_4 = 1$, 初始条件

$$(x_1(0), x_2(0), x_3(0), x_4(0)) = (-5, -1, 4, 20)$$

, $(\hat{x}_1(0), \hat{x}_2(0), \hat{x}_3(0), \hat{x}_4(0)) = (5, 3, -1, -4), \varepsilon = 0.46$, 假设

$\{t_k\}$ 随机获得, 通过求解 LMI(13), $\bar{h}_1=0.016$, 数值结果如图所示

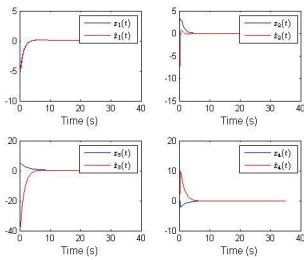


图1 $x(t)$ 和 $\hat{x}(t)$ 的仿真结果

Fig.1 The simulation results : $x(t)$ and its estimate $\hat{x}(t)$

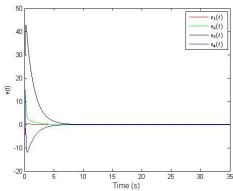


图2 误差 $e(t)$ 的仿真结果

Fig.2 The simulation results of $e(t)$

4 结论

本文首先针对一类具有未建模动态的三角非线性系统构造了高增益观测器, 通过增大增益来降低未建模动态对观测的影响。然后对系统进行变换, 针对变换后的误差系统, 引入 Lyapunov 方法分析其稳定性, 运用线性矩阵不等式 (LMI) 理论, 得到了离散时刻信息采样条件下的误差系统稳定性的充分条件。最后数值算例的仿真验证了所提出的高增益观测器设计方法的有效性。

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