Global Stabilization via Dynamic Output Feedback for a Class of Uncertain Nonlinear Systems

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Abstract: In this paper, the problem of global stabilization for SISO and MIMO affine nonlinear systems with mismatched uncertainties are investigated. The robust controllers in the form of dynamic output feedback are constructed, which make the controlled uncertain plants be globally asymptotically stable in Lyapunov's sense. A simulated example is given to show the effeciency of the proposed method.

Key words: affine nonlinear system; mismatched condition; dynamic output feedback; global stabilization

一类不确定仿射非线性系统的动态输出反馈全局镇定

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摘要: 本文研究带有非匹配不确定性的 SISO 及 MIMO 仿射非线性系统的动态输出反馈镇定问题,在要求标称系统为双曲极小相位及系统不确定部分满足一定条件下,构造出了输出反馈形式的动态补偿器.该动态补偿器使相应闭环系统在 Lyapunov 意义下全局渐近稳定.数值仿真结果令人满意.

关键词: 仿射非线性; 非匹配条件; 动态输出反馈; 全局镇定

1 Introduction

In recent years, the feedback stabilizing problem for uncertain nonlinear systems gives rise to considerable attention in automation control field because of its importance in both theory and application. Since not all state variables in a system can always be obtained by means of measurement, it is necessary to construct controllers in the form of output feedback for the sake of application. However, at present, the research results concerning output feedback are much fewer than that concerning state feedback because of its difficulty in theory. And, it has become a keen problem in control theory field. One of the characteristics for nonlinear system is that globle stabilization is much more difficult than local stabilization, so that, at present, there are much fewer research results concerning the globle stabilization of nonlinear systems, especially for uncertian nonlinear systems.

In this paper, the main goal is to discuss the problems of global stabilizability via dynamic output feedback for a class of affine nonlinear system with mismatched uncertianties. Under some assumptions easier to verify, the global robust controllers which make the controlled plant be globally asymptotically stable in Lyapunov's sense are constructed. The controllers constructed in this paper possess several remarkable characteristics: they are in the form of dynamic output feedback, not explicitly dependent on Lyapunov function and the constructure of system's uncertainties, and with a simple form so that it is easier to implement. Numerical simulation shows the efficiency of the proposed controllers.

2 Main results

Consider an uncertain affine nonlinear system:

$$\begin{cases} \dot{x} = f(x) + \Delta f + g(x)(\Delta g + u), \\ y = h(x), \end{cases} \tag{1}$$

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where $x \in \mathbb{R}^n, u, y \in \mathbb{R}^m$, represent state variable, control input and measured output of the system respectively; $g(x) = (g_1(x), \cdots, g_m(x)), f(x), g_i(x) \in \mathbb{C}^\infty(\mathbb{R}^n, \mathbb{R}^n)(i = 1,2,\cdots,m)$ and $h(x) \in \mathbb{C}^\infty(\mathbb{R}^n, \mathbb{R}^m)$ with $f(0) = 0, h(0) = 0, g(0) \neq 0_{n\times m}; \Delta f(x)$, $\Delta g(x)$ are the mismatched and matched uncertain parts of the system (1).

The nominal system corresponding to (1) is

$$\begin{cases} \dot{x} = f(x) + g(x)u, \\ y = h(x). \end{cases} \tag{2}$$

In this paper, we will consider stabilization problems for SISO and MIMO systems respectively.

2.1 The SISO case

Consider the problem of output feedback stabilization of system (1) when $m = 1$.

By [1], we know that there exists a local coordinate transformation defined in the neighborhood of 0 if the nominal system (2) has a relative degree r[1], $1 < r < n$,

$$\begin{bmatrix} z \\ w \end{bmatrix} = \begin{bmatrix} \phi_1(x) \\ \phi_2(x) \end{bmatrix} \triangleq \phi(x), \tag{3}$$

satisfying

$$L_g\phi_2(x) = 0,$$

such that (2) is transformed into

$$\begin{cases} \dot{z}_i = z_{i+1}, \quad i = 1,2,\cdots,r-1, \\ \dot{z}_r = a(z,w) + b(z,w)u, \\ \dot{w} = q(z,w), \\ y = z_1, \quad z \in \mathbb{R}^r, \quad w \in \mathbb{R}^{n-r}, \end{cases} \tag{4}$$

where $a(z,w)$ and $b(z,w)$ stand for $L_f^r h(\cdot)$ and $L_gL_f^{r-1}h(\cdot)$ in (z,w) respectively, and $q(z,w)$ represents $L_f\phi_2(\cdot)$ in (z,w).

The zero dynamics of the system (2) is characterized by

$$\dot{w} = q(0,w). \tag{5}$$

The above analysis shows that the normal form (4) and the zero dynamics (5) are locally defined. To discuss the problem of global stabilization, throughout this paper, we assume that the nominal system (2) possesses a globle relative degree r, $1 < r \leqslant n$, and make the following assumptions:

A1) A smooth submanifold

$$L_0 = \{x \mid x \in \mathbb{R}^n : h(x) = L_fh(x) = \cdots = L_f^{r-1}h(x) = 0\}$$

is connected in $\mathbb{R}^n$ and the vector fields

$$\bar{g}(x), ad_{\bar{f}}\bar{g}(x), \cdots, ad_{\bar{f}}^{r-1}\bar{g}(x)$$

are complete, where

$$\bar{g}(x) = \frac{1}{L_gL_f^{r-1}h(x)}g(x),$$

$$\bar{f}(x) = f(x) - \frac{L_f^rh(x)}{L_gL_f^{r-1}h(x)}g(x).$$

A2) The zero dynamics (2) is globally exponentially asymptotically stable.

A3) The function $q(z,w)$ is of Lipschitz uniformly in w, i.e. there exists a positive constant L such that

$$\|q(z,w) - q(0,w)\| \leqslant L\|z\| \quad \text{for all} \quad w \in \mathbb{R}^{n-r}. \tag{6}$$

A4) $L_gL_f^{r-1}h(x) \equiv b(y)$, for all $x \in \mathbb{R}^n$.

Remark 2.1 If A1) holds and (2) has a global relative degree r. Then the coordinate transformation (3) and the zero dynamics (5) are defined globally[2].

Remark 2.2 Under A2), by a converse theorem of Lyapunov, there exist a Lyapunov function $V_0(w)$ and positive constants k_1, k_2, k_3, k_4, such that

$$k_1\|w\|^2 \leqslant V_0(w) \leqslant k_2\|w\|^2,$$

$$\frac{\partial V_0}{\partial w}q(0,\omega) \leqslant -k_3\|w\|^2,$$

$$\left\|\frac{\partial V_0}{\partial w}\right\| \leqslant k_4\|w\|.$$

Remark 2.3 There exist indeed many systems satisfying A4) (e.g., [4~9]), especially, when nominal system (2) is linear, A4) is satisfied automatically.

Under transformation (3), system (1) becomes

$$\begin{cases} \dot{z}_i = z_{i+1} + \delta_1^i(z,w), \quad i = 1,2,\cdots,r-1, \\ \dot{z}_i = a(z,w) + b(y)u + \delta_1^r(z,w) + \delta_2(z,w), \\ \dot{w} = q(z,w) + \psi(z,w), \\ y = z_1, \end{cases} \tag{7}$$

where

$$\psi(z,w) = \frac{\partial\phi_2}{\partial x}\Delta f(x)\Big|_{x=\phi^{-1}(z,w)},$$

$$\delta_1^i(z,w) = L_{\Delta f}L_f^{i-1}h(x)\big|_{\phi^{-1}(z,w)},$$

$$i = 1,2,\cdots,r-1,$$

$$\delta_2(z,w) = L_{g\Delta g}L_f^{r-1}h(x)\big|_{x=\phi^{-1}(z,w)},$$

denote

$$\delta_1(z,w) = \begin{bmatrix} \delta_1^1(z,w) \\ \vdots \\ \delta_1^r(z,w) \end{bmatrix}\Bigg|_{x=\phi^{-1}(z,w)},$$

In order to reduce the effects of uncertainties and achieve robust stabilization by output feedback, we assume:

A5) There exist constants M_1, M_2, M_3, such that:

$\|\delta_1(z,w)\| \leqslant M_1|y|,\quad \|\delta_2(z,w)\| \leqslant M_2|x|,$

$\|\psi(z,w)\| \leqslant M_3|y|.$

Theorem 2.1 If system (1) (m = 1) satisfies A1) ~ A5), and $a(z,w) = a_1(z,w) + a_2(y)$ with $\|a_1(z,w)\| \leqslant N\|(z,w)\|$ for all $(z,w) \in \mathbb{R}^n$. Then there exist a constant $k^* > 0$, and two Hurwitz vectors $l = (l_1,\cdots,l_r)$ and $d = (d_1,\cdots,d_r)$ such that, for all $k \geqslant k^*$, the system (1) can be globally stabilized via following dynamic output feedback:

$$\begin{cases} \dot\theta = A\theta - kBdE_k\theta + k^rE_k^{-1}l^{\mathrm T}(y - C\theta), \\ u(\theta) = -\dfrac{1}{b(y)}kdE_k\theta - a_2(y), \end{cases} \tag{8}$$

where (A,B,C) is Brunovsky form, and $E_k = \mathrm{diag}(k^{r-1},\cdots,k,1)_{r\times r}$.

Remark 2.4 If $L_gL_f^{r-1}h(x) = b(y) = \mathrm{const}$ and $a_2(y) = 0$, then the dynamic feedback control law (8) is linear.

Proof The system (7) and controller (8) yield closed-loop system:

$$\begin{cases} \dot z = Az + \delta_1 + B(a(z,w) + b(y)u + \delta_2), \\ \dot\theta = A\theta - kBdE_k\theta + k^rE_k^{-1}l^{\mathrm T}(y - C\theta), \\ \dot w = q(z,w) + \psi(z,w), \\ u(\theta) = -\dfrac{1}{b(y)}(kdE_k\theta + a_2(y)), \\ y = z_1. \end{cases} \tag{9}$$

Let $e = \theta - z$, system (9) becomes

$$\begin{cases} \dot e = (A - k^rE_k^{-1}l^{\mathrm T}C)e - \delta_1(\theta - e, w) - \\ \qquad B(a_1(\theta - e) + \delta_2(\theta, w)), \\ \dot\theta = (A - kBdE_k)\theta + k^rE_k^{-1}l^{\mathrm T}Ce, \\ \dot w = q(z,w) + \psi(z,w). \end{cases} \tag{10}$$

Take transformation

$$\begin{bmatrix} \bar e \\ \bar\theta \end{bmatrix} = \begin{bmatrix} E_k & \\ & E_k \end{bmatrix}\begin{bmatrix} e \\ \theta \end{bmatrix},$$

system (10) becomes

$$\begin{cases} \dot{\bar e} = k(A - l^{\mathrm T}C)\bar e - E_k\delta_1(z,w) - \\ \qquad Ba_1(\theta - e) - B\delta_2(\cdot), \\ \dot{\bar\theta} = k(A - Bd)\bar\theta + kl^{\mathrm T}C\bar e, \\ \dot w = q(z,w) + \psi(z,w). \end{cases} \tag{11}$$

Select appropriate Hurwitz's vectors l and d such that $\|P_2\|\|l^{\mathrm T}C\| < 1$; where $P_1 > 0$ and $P_2 > 0$ are the solution of Lyapunov equations:

$$P_1(A - l^{\mathrm T}C) + (A - l^{\mathrm T}C)^{\mathrm T}P_1 = -I,$$

$$P_2(A - Bd) + (A - Bd)^{\mathrm T}p_2 = -I$$

respectively.

Consider the Lyapunov candidate

$$V(\bar e,\bar\theta,w) = \bar e^{\mathrm T}P_1\bar e + \bar\theta^{\mathrm T}P_2\bar\theta + V_0(w).$$

Differentiating V along (11) and using A5), we obtain

$$\begin{aligned} &\dot V(\bar e,\bar\theta,w) \leqslant \\ &-k\|\bar e\|^2 + 2\|\bar e\|\|P_1\|\|E_k\|M_1\|CE_k^{-1}(\bar\theta - \bar e)\| + \\ &2\|\bar e\|\|P_1B\|(M_3 + N)(\|\bar e\| + \|\bar\theta\| + \|w\|) - \\ &k\|\bar\theta\|^2 + k\|\bar\theta\|\|P_2\|\|l^{\mathrm T}C\|\|\bar e\| - \\ &k_3\|w\|^2 + k_4\|w\|(L\|\bar e\| + \|\bar\theta\|) + \\ &k_4M_2\|CE_k^{-1}(\bar\theta - \bar e)\| \leqslant \\ &-L_1\|\bar e\|^2 - L_2\|\bar\theta\|^2 - L_3\|w\|^2, \end{aligned} \tag{12}$$

where

$$\begin{aligned} L_1 &= k(1 - \|P_2\|\|l^{\mathrm T}C\|) - 3\|P_1\|(M_1 + \\ &\quad N + M_3) - \frac{1}{\varepsilon}\|P_1\|(N + M_3) - \\ &\quad \frac{1}{2\varepsilon}k_4L - \frac{1}{2k^{r-1}}M_2L, \\ L_2 &= k(1 - \|P_2\|\|l^{\mathrm T}C\|) - \\ &\quad \|P_1\|(M_1 + N + M_3) - \\ &\quad \frac{1}{2\varepsilon}k_4L - \frac{1}{\varepsilon}Lk_4 - \frac{1}{2k^{r-1}}M_2L, \\ L_3 &= k_3 - \varepsilon\|P_1\|(N + M_3) - \\ &\quad \frac{\varepsilon}{2}k_4L - \frac{1}{2k^{r-1}}M_2L. \end{aligned}$$

Let

$$\varepsilon < \frac{k_3}{4}\Big[\|P_1\|(N + M_3) + \frac{k_4L}{2}\Big],$$

and take

$$\begin{aligned} k^* = \max\Big\{P\frac{1}{l - \|l^{\mathrm T}C\|\|P_2\|}&[3\|P_1\|(M_1 + \\ N + M_3) + &\frac{1}{\varepsilon}\|P_1\|(N + M_3) + \\ &\frac{1}{\varepsilon}k_4L + \frac{M_2L}{2}], \frac{2M_2L}{k_4}, 1\Big\} \end{aligned}$$

it follows that $L_1 > 0, L_2 > 0$ and $L_3 > 0$ for $k > k^*$, which completes the proof.

2.2 The MIMO case

For the MIMO system (1) ($u \in \mathbb{R}^m, y \in \mathbb{R}^m, m > 1$), we take the following assumptions which are multivariable versions of the case of SISO.

A6) The nominal system (2) possesses a global vector relative degree $(r_1, r_2, \cdots, r_m), r_i > 1, \sum_{i=1}^{m} r_i = r \leqslant n$.

A7) There exists a globally defined coordinate transformation

$$\begin{bmatrix} z \\ w \end{bmatrix} = T(x) = \begin{bmatrix} T_1(x) \\ T_2(x) \end{bmatrix}, \tag{13}$$

such that system (2) becomes

$$\begin{cases} \dot{z}_1^i = z_2^i, \\ \vdots \\ \dot{z}_{r_i-1}^i = z_{r_i}^i, \\ \dot{z}_{r_i}^i = a_i(z,w) + \sum_{i=1}^{m} b_{ij}(z,w)u_j, \\ y_i = z_1^i, \\ \dot{w} = q(z,w), \end{cases} \tag{14}$$

with

$$b_{ij}(z,w) = L_{g_i}L_f^{r_i-1}h_i(T^{-1}(z,w)),$$
$$\text{for all } 1 \leqslant i,j \leqslant m,$$
$$a_i(z,w) = L_f^{r_i}h_i(T^{-1}(z,w)),$$
$$\text{for all } 1 \leqslant i \leqslant m,$$

and

$$q(z,w) = dT_2 \cdot f(T^{-1}(z,w)).$$

A8) The zero dynamics of system (2) is globally exponentially stable.

A9) The uncertainties $\Delta f(x) = 0$.

A10) $b_{ij}(z,w) = b_{ij}(y)$ for all $i \leqslant i,j \leqslant m$.

Remark 2.5 A necessary and sufficient condition for existence of global diffeomorphism (13) is given in [2]. Especially, it implies that the distribution $(g_1(x), \cdots, g_m(x))$ is involutive.

Theorem 2.2 Let $a(z,w) = (a_1(z,w), \cdots, a_m(z,w))^{\mathrm{T}}$, if $a(z,w) = \bar{a}_1(z,w) + \bar{a}_2(y)$, $\|\bar{a}_1(z,w)\| \leqslant M\|(z,w)\|$, Δf_2 satisfies A5), and MIMO uncertain system (2.1) satisfies A6) ~ A10), then the system (2.1) can be globally stabilized via the following dynamic output feedback:

$$\begin{cases} \dot{\theta} = A\theta - kBDE_k\theta + H(k)\bar{L}^{\mathrm{T}}\bar{E}(y - C\theta), \\ u(\theta) = -\bar{A}^{-1}(y)(kDE_k\theta - \bar{a}_2(y)), \end{cases} \tag{15}$$

where

$$A = \mathrm{blockdiag}(A_{11}, A_{22}, \cdots, A_{mm}),$$
$$B = \mathrm{blockdiag}(b_1, b_2, \cdots, b_m),$$

$$A_{ii} = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 1 & \cdots & 0 & 0 \\ & \vdots & & \cdots & \vdots & \\ 0 & 0 & 0 & \cdots & 0 & 1 \\ 0 & 0 & 0 & \cdots & 0 & 0 \end{pmatrix}_{r_i \times r_i}, \quad b_i = \begin{pmatrix} 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \\ 1 \end{pmatrix}_{r_i \times 1},$$

$$\bar{A}(z,w) = (b_{ij}(y))_{m \times m},$$
$$C = \mathrm{blockdiag}(c_1, c_2, \cdots, c_m),$$
$$c_i = \underbrace{(1,0,\cdots,0)}_{r_i},$$
$$E_k = \mathrm{blockdiag}(E_{k_1}, E_{k_2}, \cdots, E_{k_m}),$$
$$E_{k_i} = \mathrm{diag}(k^{r_i-1}, \cdots, k, 1),$$
$$H(k) = \mathrm{blockdiag}(H_1(k), \cdots, H_m(k)),$$
$$H_i(k) = \mathrm{diag}(k, k^2, \cdots, k^{r_i}),$$
$$\bar{L} = \mathrm{blockdiag}(l_1, \cdots, l_m),$$
$$D = \mathrm{blockdiag}(d_1, \cdots, d_m),$$

and

$$l_i = (l_1^i, l_2^i, \cdots, l_{r_i}^i), \quad d_i = (d_1^i, \cdots, d_{r_i}^i)$$

are Hurwitz vectors to be chosen such that $\|P_2\| \|\bar{L}^{\mathrm{T}}C\| < 1$.

Proof Notice that

$$E_kH(k)\bar{L}^{\mathrm{T}} = \bar{L}^{\mathrm{T}} = \bar{L}^{\mathrm{T}}\begin{pmatrix} k^{r_i} & & \\ & \ddots & \\ & & k^{r_m} \end{pmatrix},$$

$$CE_{\bar{k}}^{-1} = \begin{pmatrix} k^{-(r_1-1)} & & \\ & \ddots & \\ & & k^{-(r_m-1)} \end{pmatrix}C,$$

with the help of the same arguments as in Theorem 2.1, we can prove Theorem 2.2, it is omitted here.

3 Example with simulation

Consider four order system:

$$\begin{cases} \dot{x}_1 = x_3 + \xi_1, \\ \dot{x}_2 = x_3^2 + 2x_3(x_2 - x_3^2) - x_2 + 2x_3u + \xi_2, \\ \dot{x}_3 = x_2 - x_3^2 + u + \xi_3, \\ \dot{x}_4 = x_1 + x_4, \\ y = x_4, \end{cases}$$

where, $\xi_i (i = 1,2,3)$ are system's uncertainties.

This system has a relative degree 3, and zero dynamics

$$\dot{x}_2 = -x_2.$$

Take Hurwitz vectors:

$$d = (1,3,3), \quad l = \left(\frac{3}{5}, \frac{3}{625}, \frac{3}{15528}\right),$$

then, the matrix

$$P = \frac{1}{16}\begin{pmatrix} 37 & 31 & 8 \\ 31 & 52 & 13 \\ 8 & 13 & 7 \end{pmatrix}$$

is the solution of Lyapunov's equation

$$P(A + Bd) + (A + Bd)^{\mathrm{T}}P = -I,$$

which satisfies $\|P\| \leqslant 5, \|Pl^{\mathrm{T}}\| < 1$.

By Theorem 2.1, constructing observer

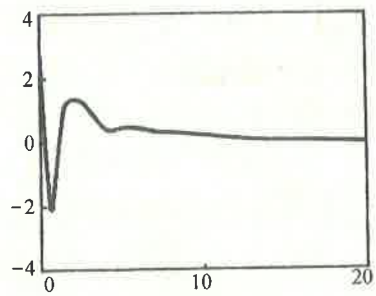
$$\begin{cases} \dot{\theta}_1 = \theta_2 + \dfrac{3}{25}k(x_4 - \theta_1), \\ \dot{\theta}_2 = \theta_3 + \dfrac{3}{625}k^2(x_4 - \theta_1), \\ \dot{\theta}_3 = -k^3\theta_1 - 3k^2\theta_2 - 3k\theta_3 + \dfrac{3}{15528}(x_4 - \theta_1), \\ u = -k^3\theta_1 - 3k^2\theta_2 - 3k\theta_3. \end{cases}$$

Take:

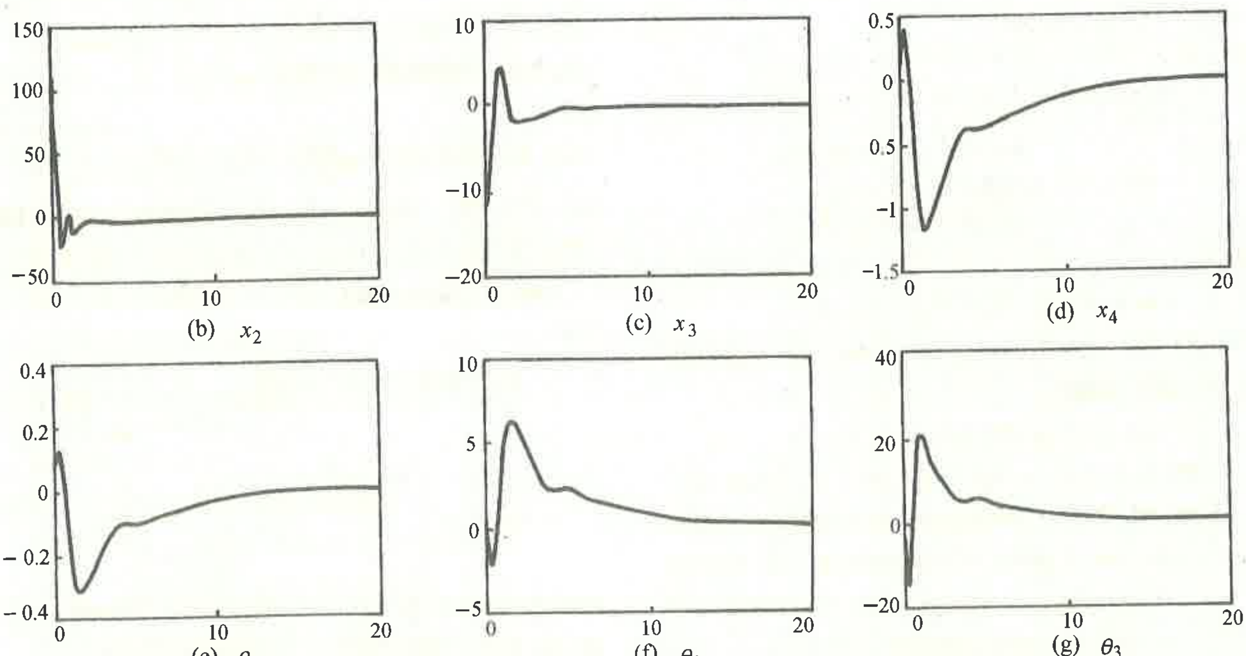
$$k = 60, \quad \xi_1 = ax_4\sin x_4,$$
$$\xi_2 = 2bx_3,$$
$$\xi_3 = c(1 - \cos x_3),$$
$$x(0) = (2, -10, 5, 0),$$
$$\theta(0) = (0, 0, -2),$$
$$a = 2, \quad b = 4, \quad c = 3.$$

The simulation result is shown in Fig. 1.

From the result, it can be seen that the system has been stabilized globally.



(a) x_1



(b) x_2 (c) x_3 (d) x_4

(e) θ_1 (f) θ_2 (g) θ_3

Fig. 1 system's and dynamic compensator's state trajectories

4 Conclusion

In this paper, we discussed the problem of global stabilization for a class of affine nonlinear systems with both matched and mismatched uncertainties. The constructed controllers are in the form of dynamic output feedback, which are more practical in system's design. The simulated result shows the efficiency of the proposed method.

The assumptions A4) and A10) play an important role in the proof of our theorem. These assumptions actually mean that the control channels of the system can only depend on system's output, which confines the application scope of the controllers in this paper.

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