Article ID: 1000 - 8152 - (2001)03 - 0363 - 06

The Controller of Global Stabilization for Multivariable Nonlinear Dynamical Systems *

WU Yuqiang
(Institute of Automation, Qufu Normal University · Shangdong Qufu, 273165, P.R. China)
YU Xinghuo
(Faculty of Information and Communication, Central Queensland University · Rockhampton, 4702, Australia)
FENG Chunbo
(Research Institute of Automation, Southeast University · Nanjing, 210096, P.R. China)

Abstract: The controller of global stabilization for multivariable nonlinear dynamical systems which can be transformed into the Byrnes-Isidori normal form is given using only state variables of the linear composite part. The concept of the finite time sliding mode is introduced in which the advantage is that the linear dynamics tend to zero in finite time. The global stability is guaranteed under the developed controller when the nonlinear system is minimum phase.

Key words: nonlinear dynamical systems; global stabilization controller; finite time sliding mode

Document code: A

多变量非线性动态系统的全局稳定化控制器

武玉强
(曲阜师范大学自动化研究所·山东曲阜, 273165)
余星火　　冯纯伯
(澳大利亚中昆士兰大学信息与通讯学院·罗克汉普顿)　(东南大学自动化研究所·南京, 210096)

摘要: 对可化为 Byrnes-Isidori 正规型的多变量非线性系统，仅利用线性组成部分的状态设计了全局稳定化控制器. 引入了有限时间滑动模态的概念，其优点是线性部分的状态在有限时间内趋近于零. 当非线性系统是最小相位时，所设计的控制器保证了系统的全局稳定性

关键词: 非线性动态系统; 全局稳定化控制器; 有限时间滑动模态

1 Introduction

The asymptotic stabilization controller of minimum phase nonlinear systems have been well studied via smooth state feedback control[1-5]. One major methodology makes use of the nonlinear Byrnes-Isidori normal form derived by an appropriate diffeomorphism and a state feedback transformation[6]. Local stabilizability of the Byrnes-Isidori normal form has been well understood using the central manifold theory[7,8]. A counter-example has shown that the global stabilization cannot be guaranteed if the control only keeps the linear composite dynamics exponentially stable[2,9]. To address this problem, extensive research has been focused on exploring special properties of the linear part of the system, e.g., the passivity properties or the positive real condition[5,10,11]. [3] has investigated some special forms for both the nonlinear subsystem and the linear composite system.

In this paper, we deal with the global stabilization problem using the terminal sliding mode (TSM) concept[12]. Because the asymptotic stability makes the state of linear part never reach the equilibrium exactly, the small value of the state during the transient process probably results in the peaking phenomenon for some nonlinear system. The use of TSM is to force the state to reach the equilibrium in a finite time so that the asymptotic ef-

* Foundation item: supported by Foundation for University Key Teacher by the Ministry of Education and Natural Science Foundation of Shandong Province (Q99G04).

Received date: 1999 - 10 - 14; Revised date: 2000 - 09 - 18.

fect of the asymptotic stability on the nonlinear system is removed and hence the peaking phenomenon is avoided. The advantage of the proposed control is that it is independent of the nonlinear part of the system, and only the states of the linear composite dynamics are needed.

2 System description

Consider the following nonlinear system with partially linear composite subsystem[9,11]

$$\begin{cases} \dot{x} = f(x,\xi,t), x \in \mathbb{R}^n, \xi \in \mathbb{R}^l \\ \dot{\xi} = A\xi + Bu, u \in \mathbb{R}^m, \end{cases} \tag{1}$$

where $f(x,\xi,t)$ is a smooth vector function, and A and B are constant matrices. In order to obtain the smooth linear feedback controller to globally stabilize system (1), some special forms are discussed[2,3]. For system (1), the following assumption is made.

H_1: $f(0,0,t) = 0$ for all t. The origin of the zero dynamics

$$\dot{x} = f(x,0,t) \tag{2}$$

is globally asymptotically stable.

H_2: the pair (A,B) is controllable.

The control task is to find a control $u(t)$ such that system (1) is asymptotically stable given the assumptions H_1 and H_2. In order to achieve this goal, two important methods for the design of controller were considered. One is that only using the linear composite dynamics ξ to design the linear feedback controller to guarantee the dynamics $\xi(t)$ is exponentially stable so that its action to the nonlinear dynamics $x(t)$ reduces to zero exponentially. This sometimes results in the peaking phenomenon[2]. The second method is to use all system states x and ξ to design a smooth nonlinear feedback controller. In this sense some existing research works require that there exists a known Lyapunov function for the zero dynamics (2). The both aforementioned methods require that function $f(\cdot)$ must satisfy a particular condition for global stability or semiglobal stability[12,13].

In order to illustrate the finite time convergence and TSM of the nonlinear system, let us consider a first order dynamics

$$\dot{x} = -\alpha x - \beta x^{q/p}. \tag{3}$$

We can solve the differential equation (3) analytically. Let $z = x^{1/p}$ and substitute this into (3) leads to

$$pz^{p-1}\dot{z} = -\alpha z^p - \beta x^{q/p}.$$

Its solution is

$$\frac{p-q}{p}(\alpha z^{p-q} + \beta) = c\exp(-\alpha(p-q)t/p). \tag{4}$$

For $x(0) \neq 0$, we have

$$c = \frac{p-q}{p}(\alpha(x(0)^{(p-q)/p} + \beta)).$$

The time to reach zero, t^s, is

$$t^s = \frac{p}{\alpha(p-q)}(\ln(cp) - \ln(\beta(p-q))). \tag{5}$$

Substituting c into (5) gives

$$t^s = \frac{p}{\alpha(p-q)}(\ln(p-q)\alpha(x(0)^{(p-q)/p} + \beta)) - \ln(\beta(p-q))). \tag{6}$$

It should be interesting to see that simply increasing the constant α may result in longer reaching time. There must be a balance of selection of the parameters p, q, α, β. However, if $\alpha = 0$, from (5), large β makes the reaching time t^s very small. To extend the scalar case to MIMO systems, we introduce the following TSM vector

$$s = C_1\xi_1 + C_2\xi_2 + C_3\xi_1(\xi_1^T\xi_1)^{-q_0/p_0}, \tag{7}$$

where $s \in \mathbb{R}^m$, $p_0 > 4q_0$, and C_1, C_2, C_3 are constants $m \times (l-m), m \times m, m \times (l-m)$ matrices, respectively. The constant matrices C_1, C_2, C_3 are to be designed appropriately according to the canonical form of MIMO systems to be adopted. Now let us look at the term $\xi_1(\xi_1^T\xi_1)^{-q_0/p_0}$ in (7). It meets

$$\| \xi_1(\xi_1^T\xi_1)^{-q_0/p_0} \| = \| \xi_1^T\xi_1 \|^{(p_0-2q_0)p_0},$$

which means the powers of the entries of ξ_1 is positive and less than one if $p_0 - 2q_0 > 0$. This means that in (7) as $\| \xi_1 \|$ is sufficiently small, s does not escape to infinite and s is smooth in ξ. This property will be used in the following section.

3 TSM control design for global stabilization

Without loss of generality, assume that the linear composite part of the nonlinear system (1) is in the following form:

$$\dot{\xi}_1 = A_{11}\xi_1 + A_{12}\xi_2, \tag{8}$$

$$\dot{\xi}_2 = A_{21}\xi_1 + A_{22}\xi_2 + B_2 u, \tag{9}$$

where $\xi_1 \in \mathbb{R}^{l-m}$, $\xi_2 \in \mathbb{R}^m$ are system states, $A_{11}, A_{12}, A_{21}, A_{22}, B_2$ are $(l-m) \times (l-m), (l-m) \times m, m \times (l-m), m \times m, m \times m$ matrices, respectively, the pair (A_{11}, A_{12}) is controllable, and B_2 is nonsingular. We now present the first result on global stabilization.

Theorem 1 For the dynamical system (9), If the control law is designed as

$$u = -(C_2B_2)^{-1}\{[C_1 + C_3(\xi_1^T\xi_1)^{-q_0/p_0} - 2\frac{q_0}{p_0}C_3\xi_1(\xi_1^T\xi_1)^{-1-(q_0/p_0)}\xi_1^T](A_{11}\xi_1 + A_{12}\xi_2) + C_2(A_{21}\xi_1 + A_{22}\xi_2) + s + Ks(s^Ts)^{-q_0/p_0}\}, \tag{10}$$

where K is a positive constant, then the switching manifold s defined in (7) will be reached in finite time and remains at zero forever.

Proof Choose the Lyapunov function

$$V = \frac{1}{2}s^Ts,$$

The time derivative of V along the system dynamics (9) and (7) is

$$\dot V = s^T\dot s = s^T[C_1\dot\xi_1 + C_2\dot\xi_2 + C_3(\xi_1^T\xi_1)^{-q_0/p_0}\dot\xi_1 - 2\frac{q_0}{p_0}C_3\xi_1(\xi_1^T\xi_1)^{-1-(q_0/p_0)}\xi_1^T\dot\xi_1] = s^T[C_1 + C_3(\xi_1^T\xi_1)^{-q_0/p_0} - 2\frac{q_0}{p_0}C_3\xi_1(\xi_1^T\xi_1)^{-1-(q_0/p_0)}\xi_1^T](A_{11}\xi_1 + A_{12}\xi_2) + s^TC_2(A_{21}\xi_1 + A_{22}\xi_2) + s^TC_2B_2u. \tag{11}$$

Substituting (10) into (11) yields

$$\dot V = -s^Ts - K(s^Ts)(s^Ts)^{-q_0/p_0} = -2V - 2^{(p_0-q_0)/p_0}KV^{(p_0-q_0)/p_0}. \tag{12}$$

According to the analysis given in the above section, $V(t)$ reaches zero in finite time and the finite time t' is able to be determined by the parameters K, p_0, q_0, and the initial value of $V(0)$ which is calculated by $s(0)$ or $\xi_1(0)$ and $\xi_2(0)$. (12) implies that once the trajectory $\varepsilon(t) = (\xi_1(t), \xi_2(t))$ reaches surfaces $s = 0$, it remains in $s = 0$.

We now look at how to choose the constant matrices C_1, C_2, C_3 so that the finite time reachability is achieved. We have the following theorem.

Theorem 2 Define L_1 and L_2 as

$$L_1 = (A_{11} - A_{12}C_2^{-1}C_1), L_2 = A_{12}C_2^{-1}C_3.$$

If the following conditions hold:

1) The matrices C_1 and C_2 are chosen such that

$$\mathrm{Re}\{\lambda(L_1 + L_1^T)\} < 0; \tag{13}$$

2) And the matrices C_2 and C_3 are chosen such that

$$\mathrm{Re}\{\lambda(L_2 + L_2^T)\} > 0, \tag{14}$$

where $\lambda(\cdot)$ represents the eigenvalues, then the equilibrium $\xi_1 = 0$ is globally stable and can be reached in finite time.

Proof Consider the Lyapunov function

$$V = \frac{1}{2}\xi_1^T\xi_1.$$

Differentiating it along the dynamics (8) leads to

$$\dot V = \xi_1^T\dot\xi_1 = \xi_1^T(L_1 + L_1^T)\xi_1 - \xi_1^T(L_2^T + L_2)\xi_1(\xi_1^T\xi_1)^{-q_0/p_0} \leqslant -\min\{|\lambda(L_1^T + L_1)|\}\xi_1^T\xi_1 - \min\{|\lambda(L_2^T + L_2)|\}\xi_1^T\xi_1(\xi_1^T\xi_1)^{-q_0/p_0} \leqslant -2\min\{|\lambda(L_1^T + L_1)|\}V - 2^{-(p_0-q_0)/p_0}\min\{|\lambda(L_2^T + L_2)|\}V^{(p_0-q_0)/p_0}, \tag{15}$$

if the conditions (13) and (14) hold. Then using the same analysis as Theorem 1, $V(t)$ as well as the equilibrium ξ_1 is globally stable and can reach zero in finite time. And since $\dot V < 0$ for $\xi_1 \neq 0$, $V(t)$ and $\xi_1(t)$ will remain zero forever once they reach zero.

Corollary 1 If the matrices C_1, C_2, C_3 are chosen such that

$$A_{11} - A_{12}C_2^{-1}C_1 = -\mathrm{Diag}(\eta_1, \cdots, \eta_{n-m}), (\eta_i > 0), \tag{16}$$

$$A_{12}C_2^{-1}C_3 = -\mathrm{Diag}(\rho_1, \cdots, \rho_{n-m}), (\rho_i > 0), \tag{17}$$

then the equilibrium $\xi_1 = 0$ is globally stable and each entity of ξ_1 can reach in a fixed time specified as

$$t_f(i) = \frac{p}{\eta_i(p-q)}[\ln((p-q)(\eta_i(\xi_i(0)^{(p-q)/p} + \beta)) - \ln(\rho_i(p-q))]. \tag{18}$$

Proof The proof directly follows from the proof of Theorem 2 and Section 2.

There is a problem with $(\xi_1^T\xi_1)^{-q_0/p_0}$. For example, as $\xi_1 \to 0$, a singularity may occur in controller (10) which means $u \to \infty$.

Theorem 3 If

$$p_0 - 4q_0 > 0, \tag{19}$$

then when the dynamics $\xi_1(t)$ and $\xi_2(t)$ reach zero on the surface $s = 0$, the control u defined by (10) will be bounded forever.

Proof Because of controller (10), the terms that would cause the singularity are

$$S_1 = (\xi_1^{\mathrm{T}}\xi_1)^{-q_0/p_0} \times A_{12}\xi_2, \tag{20}$$

and the term

$$S_2 = \xi_1(\xi_1^{\mathrm{T}}\xi_1)^{-1-q_0/p_0}\xi_1^{\mathrm{T}} \times A_{12}\xi_2. \tag{21}$$

When the trajectory moves on the surface $s = 0$, it meets

$$\xi_2 = -C_2^{-1}C_1\xi_1 - C_2^{-1}C_3\xi_1(\xi_1^{\mathrm{T}}\xi_1)^{-q_0/p_0}. \tag{22}$$

Substituting (22) into the above second term, we have

$$\begin{aligned}\| S_2 \| &= \| \xi_1(\xi_1^{\mathrm{T}}\xi_1)^{-1-q_0/p_0}\xi_1^{\mathrm{T}} \times [-C_2^{-1}C_1\xi_1 - \\ &\quad C_2^{-1}C_3\xi_1(\xi_1^{\mathrm{T}}\xi_1)^{-q_0/p_0}] \| \leqslant \\ &\quad M\|\xi_1\|^{1-2q_0/p_0} + N\|\xi_1\|^{1-4q_0/p_0},\end{aligned} \tag{23}$$

where M, N are positive constant numbers. According to the condition $p_0 - 4q_0 > 0$ given in the theorem, S_2 is bounded. The same argument can be used to prove S_1 bounded. Then we know when $\xi_1 \to 0$, the terms S_1 and S_2 tend to zero, the singularity is avoided.

Theorem 3 guarantees that as the trajectories $\xi_1(t)$ and $\xi_2(t)$ reach the switching surface $s = 0$ and move along this surface, the control law $u(t)$ is bounded. If the initial state is not on the surface $s = 0$, it is possible that some of components of $\xi_1(t)$ and $\xi_2(t)$ first reach zero before they reach surface $s = 0$. Under this situation, the control law $u(t)$ is infinite. For example, let $\xi_1 = 0, \xi_2 \neq 0, u(t)$ is unbounded because $(\xi_1^{\mathrm{T}}\xi_1)^{-q_0/p_0}$ is infinite if $\xi_1 = 0$. To overcome this singularity, the two phase control strategy is proposed to deal with the singularity situation[12]. Define the controllability grammian as

$$G_c(0, t_f) \triangleq \int_0^{t_f} \exp(-A\tau)BB^{\mathrm{T}}\exp(-A^{\mathrm{T}}\tau)\mathrm{d}\tau, \tag{24}$$

where A, B are state coefficient matrix and input vector matrix of the linear system (8) and (9), respectively. $G_c(0, t_f)$ is nonsingular for all $t_f > 0$. The solution of (8) and (9) is

$$\xi(t) = \exp(At)\xi(0) + \int_0^t \exp A(t-\tau)Bu(\tau)\mathrm{d}\tau, \tag{25}$$

In the interval $[0, t_f]$, the control input

$$u(t) = B^{\mathrm{T}}\exp(-A^{\mathrm{T}}t)G_c^{-1}(0, t_f)[\exp(At_f)\xi(t_f) - \xi(0)] \tag{26}$$

can transfer any initial state $\xi(0)$ to any preset final state $\xi(t_f)$. Substituting (26) into (25) we obtain now the final state $\xi(t_f)$ is selected on the surface $s = 0$ which means it satisfies

$$C_1\xi_1(t_f) + C_2\xi_2(t_f) + C_3\xi_1(t_f)(\xi_1^{\mathrm{T}}(t_f)\xi(t_f))^{-q_0/p_0} = 0. \tag{27}$$

Combining control (26) with the TSM control (10), we will obtain a nonsingular control strategy stated as follows:

1) Define properly the parameters C_1, C_2, C_3, K, and let q_0, p_0 satisfy the condition in Theorem 3.

2) Define switching function s and in the surface $s = 0$, choose an arbitrary point ξ_f.

3) For (8), (9) and $\xi(0)$, first choose a proper time t_f such that the state $\xi_f = \xi(t_f)$ is reached by using control (26).

4) Once $\xi(t_f) = \xi_f$ is reached, the control is immediately switched to the TSM control law (10). Since $\xi_f \in \{\xi : s = 0\}$ Theorem 1 guarantees that $\xi(t)$ will be confined on this surface forever. Upon the action of the TSM control law (10), $\xi(t)$ reaches zero in finite time along the surface $s = 0$.

Now for the original nonlinear system (1), we have the following results:

Theorem 4 For system (1), if for any input $\xi(t)$ which satisfies $\xi(t)^{\mathrm{T}}\xi(t) \leqslant |y(t)|$ where $y(t)$ is certain solution of system

$$\dot{y} = -\alpha y - \beta y^{q/p}, \tag{28}$$

where $\alpha > 0$ and $\beta > 0$ are certain positive constants and q and p are positive odd constants ($q < p$ and $2q - p > 0$), the solution $x(t)$ of the nonlinear dynamical system

$$\dot{x} = f(x, \xi, t),$$

with arbitrary initial value can be extended to $[0, \infty)$, which means $x(t)$ cannot escape to infinite in finite time, the conditions of Theorem 2 and Theorem 3 hold, and the controllers are chosen in (10) and (26), then system (1) is globally asymptotically stable.

Proof For any given initial state (x_0, ξ_0), (26) only acts in time interval $[0, t_f]$ and the time t_f can be chosen arbitrarily. We can always select a small t_f, α, β, and p and q such that in $[0, t_f]$, the solution $\xi(t)$ with initial $\xi(0)$ meets $\xi^{\mathrm{T}}(t)\xi(t) \leqslant |y(t)|$. Therefore, $x(t)$ and $\xi(t)$ with initial $x(0)$ and $\xi(0)$ are bounded in time interval $[0, t_f]$. Once the controller is switched to the TSM control (10), the trajectory $(x(t), \xi(t))$ will move along the surface $s = 0$ and $\xi(t)$ reaches zero in finite time. As aforementioned in Theorem 2 and Theorem 3, $\|\xi(t)\|^2 = V$ and V meets

$$\dot{V} \leqslant -2V - 2^{(p_0-q_0)/p_0} K V^{(p_0-q_0)/p_0}.$$

According to the condition of this theorem, the solution $x(t)$ can be extended to interval $[0, \infty)$, that is, the following equation

$$\dot{x}(t) = f(x(t), \xi(t), t)$$

is defined in the interval $[0, \infty)$. After a finite time t_f, TSM control law drives $\xi(t)$ to zero, then $x(t)$ meets

$$\dot{x}(t) = f(x(t), 0, t), t > t_f + t'.$$

Assumption H_1 guarantees that $x(t)$ then tends to zero.

Corollary 2 If for any input $\xi(t)$ which belongs to the set

$$\Omega = \{M e^{-Nt} : N > 0, M > 0\},$$

the solution of the first equation of system (1) can be extended to interval $[0, \infty)$, and other conditions required in Theorem 4 hold, then TSM controller(10) together with (26) globally asymptotically stabilizes system (1).

Theorem 5 For system(1), if the assumptions H_1 and H_2 are satisfied and the conditions of Theorem 2 and Theorem 3 hold, then for any fixed constants R, we can always use controller(26) and TSM controller (10) with appropriate parameters setting such that for any initial value $\xi(0)$ and $x(0)$ which meet $\|x(0)\| \leqslant R$ and $\|\xi(0)\| \leqslant R$, the trajectory $x(t)$ tends to zero asymptotically and $\xi(t)$ reaches zero in finite time.

Proof Define M as

$$M = \max\{\|f(x, \xi, t)\| : \|x\| \leqslant 2R, \|\xi\| \leqslant 2R, t \in [0, R]\}.$$

Since $f(x, \xi, t)$ is a continuous function in x, ξ, t, M is a finite constant. From the first equation of (1), we have

$$x(t) = x(0) + \int_0^t f(x(\tau), \xi(\tau), \tau) \mathrm{d}\tau. \quad (29)$$

Further, when t is very small it can be obtained that

$$\|x(t)\| \leqslant \|x(0)\| + \int_0^t \|f(x(\tau), \xi(\tau), \tau)\| \mathrm{d}\tau \leqslant R + Mt. \quad (30)$$

In addition, $\xi(t)$ is solved as

$$\xi(t) = \exp(At)\xi(0) + \exp(At) G_c(0, t) \cdot G_c^{-1}(0, t_f)[\exp(At_f)\xi(t_f) - \xi(0)]. \quad (31)$$

It can be seen that as t_f as well as $\|\xi(t_f)\|$ is very small and $t < t_f, \xi(t) \leqslant 2R$. If let

$$t \in [0, \min\{t_f, R/M\}],$$

then we obtain from (30)

$$\|x(t)\| \leqslant R + R = 2R.$$

This implies that in $t \in [0, R/M]$, (30) is still valid which means in this time interval $x(t)$ is bounded.

In (26), we choose $t_f = R/(2M)$, and let $\xi(t_f)$ meet $\|\xi(t_f)\| \leqslant 1$ and $s(\xi(t_f)) = 0$. According to the definition of the TSM control and Theorem 2, the terminal sliding mode time t' on surface $s = 0$ should satisfy

$$t' \leqslant \frac{p_0 - q_0}{\beta q_0^{2(p_0-q_0)/p_0} \min\{|\lambda(L_2^{\mathrm{T}} + L_2)|\}} V(t_f)^{(p_0-q_0)/p_0} \leqslant \frac{p_0 - q_0}{\beta q_0^{2(p_0-q_0)/p_0} \min\{|\lambda(L_2^{\mathrm{T}} + L_2)|\}}. \quad (32)$$

If we choose β properly large such that $t' \leqslant R/(2M)$, then after $t > R/M$, $\xi(t)$ is zero. Consequently, after $t > R/M$, $x(t)$ meets

$$\dot{x}(t) = f(x(t), 0, t).$$

This implies that $x(t)$ will tend to zero asymptotically since assumption H_1 holds.

Theorem 6 For system (1), if there exists a constant T such that in the interval $[0, T]$, for any bounded input $\xi(t)$ the solution $x(t)$ of the nonlinear dynamics

$$\dot{x} = f(x, \xi(t), t) \quad (33)$$

with arbitrary initial value can not escape to infinite, then the dynamical system (1) can be globally asymptotically stabilised by (26) and TSM controller (10).

Proof Let $t_f = T/2$, and choose $\|\xi(t_f)\| \leqslant 1$ which meets $s(\xi(t_f)) = 0$. From the definition of (26), $\xi(t)$ with any initial value is bounded in time interval $[0, t_f]$. And according to the condition given in this theorem, in time interval $[0, t_f]$ $x(t)$ can not escape to infinite. In addition, in time instant $t_f, \xi(t)$ is controlled to $\xi(t_f)$, and then will move on surface $s = 0$. As long as we properly design the parameters of the TSM control law (10), the sliding time t' can be made to less than $T/2$ since $\xi(t_f)$ is confined into a known bounded region. That is $t' \leqslant T/2$. After $t > T$, $\xi(t)$ becomes zero and will not act on the dynamic system (33) so that (33) becomes

$$\dot{x} = f(x,0,t),\ t > T.$$

Hence, $x(t)$ will tend to zero since Assumption H_1 hold.

4 Conclusion

The global stabilization of nonlinear systems with partially linear composite dynamics has been discussed in this paper using the terminal sliding modes. The proposed control strategy enables the equilibrium of the linear subsystems to be reached in finite time, resulting in the effect of asymptotic convergence on the nonlinear system being removed. Under some light conditions for nonlinear function $f(\cdot)$, the globally asymptotic stabilization is realized and the assumption of weak minimum phase for the linear composite system is not needed as long as the system dynamics firstly is suppressed into an arbitrary bounded region by an appropriate control. The results achieved have also shown that the TSM controller which globally asymptotically stabilise system (1) is not related to the nonlinear dynamics x. The resulting control is not chattering.

References

[1] Byrnes C I and Isidori A. Asymptotic stabilization of minimum phase nonlinear systems [J]. IEEE Transactions on Automatic Control, 1991, 36(10):1122 – 1137

[2] Sussmann H J and Kokotovic P V. The peaking phenomenon and the global stabilization of nonlinear systems [J]. IEEE Transactions on Automatic Control, 1991, 36(4):424 – 439

[3] Saberi A, Kokotovic P V and Sussmann H J. Global stabilization of partially linear composite systems. SIAM Journal of Control and Optimization, 1990, 28(6):1491 – 1503

[4] Teel A and Praly L. Tools for semiglobal stabilization by partial state and output feedback [J]. SIAM Journal of Control and Optimization, 1995, 33(5): 1443 – 1488

[5] Ortega R. Passivity properties for stabilization of cascaded nonlinear systems [J]. Automatica, 1991, 27(2):423 – 424

[6] Isidori A. Nonlinear Control Systems [M]. New York: Springer-Verlag, 1989

[7] Aeyels D. Stabilization of a class of nonlinear systems by a smooth feedback [J]. Systems and Control Letters, 1985, 5(2):181 – 191

[8] Carr J. Application of Centre Manifold Theory [M]. New York: Springer-Verlag, 1981

[9] Sussmann H J. Limitations on the stabilizability of globally minimum phase systems [J]. IEEE Transactions on Automatic Control, 1990, 35(1):117 – 119

[10] Kokotovic P V and Sussmann H J. A positive real condition for global stabilization of nonlinear systems [J]. Systems and Control Letters, 1989, 12(2):125 – 134

[11] Lozano R, Brogliato B and Landau I D. Passivity and global stabilization of cascaded nonlinear systems [J]. IEEE Transactions on Automatic Control, 1992, 37(9):1386 – 1388

[12] Wu Y, Yu X and Man Z. Terminal sliding mode control design for uncertain dynamic systems [J]. Systems and Control Letters, 1998, 34 (5):281 – 288

[13] Byrnes C I and Isidori A. Local stabilization of minimum phase nonlinear systems [J]. Systems and Control Letters, 1988, 11(1): 7 – 9

本文作者介绍

武玉强 1962年生.1988年曲阜师范大学硕士研究生毕业,获硕士学位.1988年留曲阜师范大学自动化研究所工作.1994年东南大学自动控制理论及应用专业博士研究生毕业,获工学博士学位.现为曲阜师范大学自动化研究所教授.主要研究方向有自适应控制与变结构控制.

余星火 1960年生.1982年、1984年获中国科技大学自动控制专业学士、硕士学位.1987年获东南大学自动控制理论及应用博士学位.1987年12月至1989年4月在中科院自动化所工作.1989年4月至1990年12月在澳大利亚阿德莱德大学作博士后研究,现为澳大利亚中昆士兰大学教授,信息与通讯学院副院长.研究领域:变结构控制,自适应控制,智能控制,人工智能.在国际刊物及会议上发表论文百余篇.1995年获中昆士兰大学校长研究奖.

冯纯伯 1928年生.1950年毕业于浙江大学电机系.1953年毕业于哈尔滨工业大学研究生班.1958年获前苏联技术科学副博士学位.现任东南大学教授、中国自动化学会常务理事、俄罗斯联邦自然科学院外籍院士、中国科学院院士.目前主要从事系统建模,自适应、鲁棒及智能化控制理论及应用,机器人控制等方面的研究.