Robust Control for Strict-feedback Form Nonlinear Systems and Its Application

(严格反馈型非线性系统鲁棒控制及应用)

Changyin Sun Yao Yu

Science Press
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内 容 简 介

本书结合作者近年来的研究工作，详细介绍了几类非线性不确定系统的鲁棒控制方法及其在无人飞行器、化学过程、温度控制系统、柔性机械臂系统、智能交通系统等领域的应用。主要内容包括：标准型非线性系统的鲁棒输出反馈控制、分数阶系统容许性的充分必要条件分析、非线性不确定严格反馈型系统的鲁棒反推控制、非线性不确定多输入输出时延系统的鲁棒分散控制等。

本书可供从事控制科学与工程相关工作的科研人员和工程技术人员阅读，也可作为高等院校自动化、应用数学及相关专业的高年级本科生、研究生的参考用书。

图书在版编目（CIP）数据

严格反馈型非线性系统鲁棒控制及应用 = Robust control for strict-feedback form nonlinear systems and its application：英文/孙长银，余瑶著. —北京：科学出版社, 2014.9

ISBN 978-7-03-041866-1

I. ①严… II. ①孙… ②余… III. ①非线性系统(自动化)–鲁棒控制–英文 IV. ①TP273

中国版本图书馆 CIP 数据核字 (2014) 第 204459 号

责任编辑：张海娜 / 责任校对：张怡君
责任印制：肖 兴 / 封面设计：迷底书装

科学出版社 出版
北京东黄城根北街 16 号
邮政编码：100717
http://www.sciencep.com

北京通州皇家印刷厂 印刷
科学出版社发行 各地新华书店经销
*
2014 年 9 月第 一 版 开本：720 × 1000 1/16
2014 年 9 月第一次印刷 印张：11 1/4
字数：291 000

定价：85.00 元

(如有印装质量问题，我社负责调换)

Preface

This book is dedicated to the robust controller design of nonlinear systems. We believe that every effort in this direction will be rewarding in both theoretical and practical results. Systems with nonlinear uncertainties frequently appear in engineering. Typical examples of nonlinear uncertain systems are chemical processes, underwater vehicles, manipulator systems, biosystems and so on. The presence of nonlinear uncertainties makes system analysis and control design very complicated. The stability analysis would become much more complicated when there involves highly complex nonlinear couplings. Due to these difficulties, compared with a mass of results on controller design for SISO nonlinear systems, robust control for MIMO nonlinear systems needs to be further developed. Different kinds of control strategies, such as sliding mode control, robust control, adaptive control, intelligent control, have been developed for both theoretical interests and practical applications. In the last 20 years, backstepping control has become one of the most popular control methods for some special classes of nonlinear systems, since it provides a systematic procedure for designing a controller by a step-by-step recursive algorithm. For better control performance, different control strategies are combined together by taking advantage of their strengths respectively. Combined with backstepping control strategy, many effective methods have been proposed for stability analysis and controller design. However, backstepping control has the drawback of the phenomenon of 'explosion of complexity' in the control law due to repeated differentiations of the virtual control functions.

This book collects work carried out recently by the authors in this field. It covers the whole range of robust control of strict-feedback system: from the description of the mathematic model, controller design to controller implementation; from theoretical developments to practical issues; from flight control, chemical process control, temperature control, flexible manipulator control, to intelligent traffic control. The main aim is to 'make everything as simple as possible'. The phenomenon of 'explosion of complexity' is avoid and a linear robust controller is proposed. This book is intended for graduate students and researchers in control theory and application. It may also be used for self study or reference by engineers and applied mathematicians. We assumed the reader has a basic knowledge of linear systems, nonlinear analysis, design tools, electrical engineering, and mechanical engineering. The mathematical background is the usual level of calculus, matrix theory, and differential equations that any graduate student in mathematics or engineering would have. This book pay much effort to solve complicated problems using simple mathematical tools.

The book has been divided into four parts: normal form systems, fractional-order singular systems, strict-feedback form systems, and time delay systems. This book is organized as follows. Chapter 1 introduces the research background of robust control for nonlinear systems. Chapter 2 proposes a robust output feedback control of a class of nonlinear systems in normal form. Then, we extend our results to MIMO helicopter systems. Chapter 3 focuses on the sufficient and necessary admissibility condition for fractional-order singular system with order $\alpha \in (0, 1)$. In Chapter 4, it is shown that linear state-feedback may be used in order to make a given system to behave like a given linear one. Chapter 5 deals with the synthesis of robust control law for time-delay systems. The system uncertainties include unknown nonlinear functions, unmodeled dynamic, time delay states, time delay inputs, couplings among control channels, and bounded external disturbances, and noninteracting control method based on signal compensation is presented.

We are grateful to University of Science and Technology Beijing for providing an environment that allowed us to write this book, and to National Nature

Science Foundation of China (61473324), National Outstanding Youth Science Foundation (61125306), National Natural Science Foundation of Major Research Plan (91016004), Specialized Research Fund for the Doctoral Program of Higher Education (20110092110020 and 20130006120027), Beijing Higher Education Young Elite Teacher Project (YETP0378) for supporting our research on robust control for nonlinear systems.

As much as we wish the book to be free of errors, we know this will not be the case. Therefore, reports of errors, sent electronically to us will be greatly appreciated.

Changyin Sun

Yao Yu

June 2014

Acronyms

ABS	anti-lock braking system
PID	proportional-integral-derivative
SISO	single-input single-output
MIMO	multi-input multi-output
BIBS	bounded-input bounded-state
3-DoF	three degrees of freedom
CSTR	continuous stirred-tank reactor
VTOL	vertical take-off and landing

Contents

Chapter 1

Introduction

Abstract In practice there are many cases where the plant involves large property uncertainties. Typical examples for nonlinear systems include power stations, robots, flights, rail trains, ABS for cars etc. The types of nonlinear systems are very abundant, and we focus on several types of nonlinear systems, such as strict-feedback form systems, normal form systems, fractional-order singular systems, and time delay systems. These systems have very wide application background. This chapter will introduce these nonlinear systems from the point of view of the practical application. For such systems, the control problem is very complicated due to the nonlinear uncertainties, couplings, time delays, and fractional-order nonlinearity. Different kinds of control strategies, such as PID control, sliding mode control, robust control, adaptive control, intelligent control, have been developed for both theoretical interests and practical applications. With the help of their efforts, substantial achievements have been made in the field of nonlinear control systems. In this book, we will present tools for the stability analysis and controller design of these nonlinear systems.

1.1 Background

Control problem of nonlinear systems has attracted considerable attention, especially in the last two decades. In practice, typical examples include flights [1], PM synchronous motor [2], automatic guidance of farm vehicles [3], and active suspensions for cars [4] etc. Different kinds of control strategies, such as feedback linearization, robust control, adaptive control, intelligent control, backstepping, have been developed for both theoretical interests and practical applications. The main analysis methods for nonlinear systems are Lyapunov stability theory, input and output analysis theory, passive theory, LaSalle's invariance principle, phase plane analysis and describing function analysis methods. In this book, four kinds of nonlinear systems are discussed: strict-feedback form systems, normal form systems, fractional-order singular systems, and time delay systems.

The strict-feedback systems are described as [5]

$$\Sigma_x \begin{cases} \dot{x}_1 = g_1(\varpi, x_1)x_2 + f_1(\varpi, x_1) \\ \dot{x}_i = g_i(\varpi, x_1, \cdots, x_i)x_{i+1} + f_i(\varpi, x_1, \cdots, x_i) \\ \qquad i = 2, 3, \cdots, n-1 \\ \dot{x}_n = g_n(\varpi, x_1, \cdots, x_n)u + f_n(\varpi, x_1, \cdots, x_n) \end{cases} \tag{1.1}$$

$$\Sigma_\varpi \quad \dot{\varpi} = f(x) + g(\varpi, x)$$

where $\varpi \in \mathbf{R}^\rho$ and x are states. The feature of strict-feedback systems is that for each subsystem, the nonlinear functions f_i and g_i are related to $\varpi, x_1, \cdots, x_i$ and independent of $x_{i+1}, \cdots, x_n$. So this kind of systems is also named lower triangular systems.

If the nonlinear functions $f_i = 0 (i = 1, 2, \cdots, n-1)$ and $g_i = 1 (i = 1, 2, \cdots, n-1)$, the strict-feedback systems are simplified to Byrnes-Isidori normal form systems [6]

$$\Sigma_x \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_i = x_{i+1}, \quad i = 2, 3, \cdots, n-1 \\ \dot{x}_n = \beta(x, \varpi)u + \alpha(x, \varpi) \\ y = x_1 \end{cases} \tag{1.2}$$

$$\Sigma_\varpi \quad \dot{\varpi} = \phi(x, \varpi)$$

Fractional-order systems are also considered in this book. Based on the definition of fractional-order integral, the well known definition of Caputo fractional-order derivative operator is defined as [7]

$$ {}_0^C\mathrm{D}_t^\alpha f(t) := \mathrm{D}^\alpha f(t) = \frac{1}{\Gamma(n-\alpha)} \int_0^t (t-\tau)^{n-\alpha-1} f^{(n)}(\tau)\mathrm{d}\tau \tag{1.3} $$

where $n-1<\alpha<n$.

Delay may occur in the feedback loop of a plant, either in the states, inputs or outputs, where propagation and transmission of information or material are involved. The presence of delays makes system analysis and control design much more complex. A class of uncertain MIMO nonlinear systems with time delays in block-triangular form can be described by

$$ \begin{aligned} \dot{x}_{ij}(t) &= g_{ij}(x,u,d,t)\, x_{i(j+1)}(t) + \phi_{ij}(x,u,d,t) \\ &\quad + h_{ij}(x(t-\tau_{ij}(t)), u(t-\tau_{ij}(t)), d) \\ \dot{x}_{i\rho_i}(t) &= g_{i\rho_i}(x,u,d,t)u_i(t) + \phi_{i\rho_i}(x,u,d,t) \\ &\quad + h_{i\rho_i}(x(t-\tau_{i\rho_i}(t)), u(t-\tau_{i\rho_i}(t)), d) \\ y_i &= x_{i1} \\ &\quad i=1,2,\cdots,m;\ j=1,2,\cdots,\rho_i-1 \end{aligned} \tag{1.4} $$

with states $x_{ij}(j=1,2,\cdots,\rho_i; i=1,2,\cdots,m)$, inputs $u_i(t)$ and outputs $y_i(t)(i=1,2,\cdots,m)$, and $x(t-\tau_{ij}(t))$ is the delayed state vector, $u(t-\tau_{i\rho_i}(t))$ is the delayed input vector, $\tau_{ij}(t)$ are unknown time-varying delays, $d(t)$ is an external disturbance vector, $g_{ij}(x,u,d,t)$ are unknown virtual control coefficients, $\phi_{ij}(x,u,d,t)$ and $h_{ij}(x(t-\tau_{ij}(t)),d)$ are nonlinear time-varying uncertainties. ρ_i is the order of the i-th subsystem.

In reality, many systems are nonlinear.

Example 1.1 The first example is the motor speed control system. The permanent magnet synchronous motor has advantages of simple structure, high air gap flux density, big power density, high torque current ratio and large torque to inertia ratio, so it is widely used in small power servo systems. The permanent magnet synchronous motor model in d,q coordinates is as follows:

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} -\dfrac{R}{L}x_1 + n_p x_2 x_3 \\ n_p \dfrac{\phi_a}{J}x_3 - \dfrac{B}{J}x_2 \\ -n_p x_1 x_2 - \dfrac{R}{L}x_3 - n_p \dfrac{\phi_a}{L}x_2 \end{bmatrix}$$

$$+ \begin{bmatrix} \dfrac{1}{L} & 0 \\ 0 & 0 \\ 0 & \dfrac{1}{L} \end{bmatrix} u + \begin{bmatrix} 0 \\ -\dfrac{1}{J} \\ 0 \end{bmatrix} T_l$$

where

$$u = [u_d \quad u_q]^{\mathrm{T}}, \quad x = [i_d \quad \omega \quad i_q]^{\mathrm{T}}, \quad y = [i_d \quad \omega]^{\mathrm{T}}$$

i_d, i_q, ω are d-axis current, q-axis current, and mechanical angular velocity, respectively. R is stator resistance, L is direct axis inductance. n_p is number of pole-pairs. B is damping coefficient. ϕ_a is rotor flux linkage, T_l is load torque. Choosing i_d and ω as outputs, the permanent magnet synchronous motor system is a nonlinear strict-feedback form system [8].

Example 1.2 The second example is the continuous stirring reactor (CSTR) control system. CSTR is a chemical reactor widely used in the process of fermentation, chemical industry, oil production, Biological pharmaceutical industry. Its temperature, pressure, concentration control quality directly affects the production efficiency and quality[9-12].

Fig. 1.1 is a two-continuous-stirred-tank reactor control system. F_0, T_0, C_{A0} are feeding velocity, temperature and concentration of the first reactor, respectively. F_1, T_1, C_{A1} are discharging velocity, temperature and concentration of the first reactor, respectively. F_2, T_2, C_{A2} are discharging velocity, temperature and concentration of the second reactor, respectively. F_{j1}, T_{j10}, F_{j2}, T_{j20} are the water flow rate and temperature of the first and the second insulating layer water circulation cooling systems, respectively. The two-continuous-stirred-tank reactor control system can be described as [11,10]

$$\dot{C}_{A2}=\frac{F+F_R}{V}C_{A1}-\frac{F+F_R}{V}C_{A2}-\alpha C_{A2}\mathrm{e}^{-E/R}$$

$$\dot{C}_{A1}=\frac{F_0}{V}C_{A0}-\frac{F+F_R}{V}C_{A1}+\frac{F_R}{V}C_{A2}-\alpha C_{A1}\mathrm{e}^{-E/R}$$

$$\dot{T}_1=\frac{F_0}{V}T_0-\frac{F+F_R}{V}T_1-\frac{F_R}{V}T_2-\frac{\alpha\lambda}{\rho c_p}C_{A1}\mathrm{e}^{-E/R}-\frac{UA}{\rho c_p V}(T_1-T_{j1})$$

$$\dot{T}_{j1}=\frac{F_{j1}}{V_j}(T_{j10}-T_{j1})+\frac{UA}{\rho_j c_j V_j}(T_1-T_{j1})$$

$$\dot{T}_2=\frac{F+F_R}{V}T_1-\frac{F+F_R}{V}T_2-\frac{\alpha\lambda}{\rho c_p}C_{A2}\mathrm{e}^{-E/R}-\frac{UA}{\rho c_p V}(T_2-T_{j2})$$

$$\dot{T}_{j2}=\frac{F_{j2}}{V_j}(T_{j20}-T_{j2})+\frac{UA}{\rho_j c_j V_j}(T_2-T_{j2})$$

$$u=[C_{A0}\quad T_{j10}\quad T_{j20}],\quad y=[C_{A1}\quad T_1\quad T_2]$$

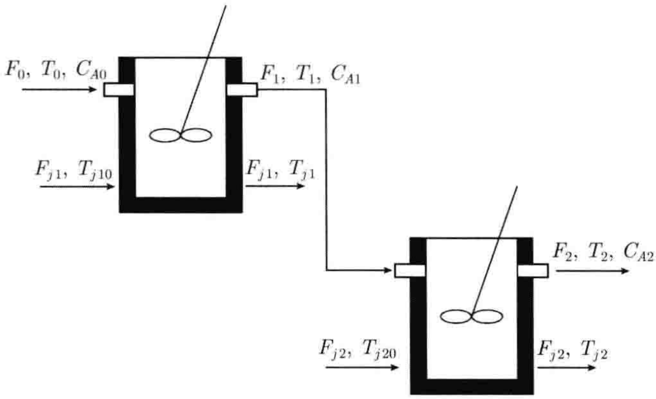

Fig. 1.1 The two-continuous-stirred-tank reactor control system

where α, E, λ are the reaction rate constant, activation energy, and heat generation rate, respectively. ρ and ρ_j are the liquid density of the reactor and thermal insulation layer, respectively. c_p and c_j are thermal capacity. T_{j10}, T_{j20} and C_{A0} are control inputs. T_1, C_{A1} and T_2 are outputs. The two-continuous-stirred-tank reactor control system is strict-feedback form system.

Example 1.3 The third example is vehicle active suspension control system. At present, the common models of suspension systems are: four degrees of freedom model, six degrees of freedom model. The parallel structure of four degrees of freedom for the active suspension model is as follow [13, 14]:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -\frac{1}{M_1}\left[K_a(x_1 - x_3) + C_a(x_2 - x_4) - u_a\right]$$

$$\dot{x}_3 = x_4$$

$$\dot{x}_4 = -\frac{1}{M_2}\left[K_a(x_1 - x_3) + C_a(x_2 - x_4) - K_t(x_3 - r) - u_b\right]$$

where x_1 is the height of the car. x_2 is car velocity along the direction of gravity. x_3 is the hight of tyre center. x_4 is tyre velocity along the direction of gravity. u_a, u_b are active suspension control input of hydro-pneumatic spring. M_1 is weight of the car. M_2 is weight of the tyre. K_a is elasticity coefficient. C_a is damping coefficient of shock absorber. r is disturbance from the road. Suspension system of four degrees of freedom model of active suspension can be described as a normal form system with two inputs and two outputs.

Example 1.4 The fourth example is flexible joint manipulator control system. The dynamics model of flexible joint manipulator with a rotating mechanical arm can be described as[15-18]

$$\dot{x}_1(t) = x_2(t)$$

$$\dot{x}_2(t) = -\frac{1}{H_1(x_1)}\left\{C(x_1, x_2)x_2 + g(q_1) + K[x_1(t) - x_3(t)]\right\}$$

$$\dot{x}_3(t) = x_4(t)$$

$$\dot{x}_4(t) = \frac{1}{H_2}\left\{u(t) - Bx_4 + K[x_1(t) - x_3(t)]\right\}$$

where $x_1(t)$ and $x_3(t)$ are displacements of connecting rod and rotor, respectively. $x_2(t)$ and $x_4(t)$ are velocities of connecting rod and rotor, respectively. $H_1(x_1)$ is the inertia of connecting rod. $C(x_1, x_2)$ is centripetal force related items. $g(x_1)$ is gravity related items. K is the flexible rotor. H_2 is the inertia of motor rotor.

B is viscous friction. Due to the particularity of flexible structure, the movement of the mechanical arm involves deformation and vibration. This makes the flexible manipulator control system become a complex nonlinear normal form system.

Example 1.5 The fifth example is the four rotor aircraft motion control system. The four rotor aircraft is a 6-DoF underactuated rotor helicopter with highly coupling dynamic, as shown in Fig. 1.2, The Lagrange dynamics equation of the four rotor aircraft are described as[19-21]

$$\begin{aligned}
\ddot{x} &= [(C_\phi C_\psi S_\theta + S_\phi S_\psi)\,u_1 - K_{dtx}\dot{x}]\,/m \\
\ddot{y} &= [(C_\phi S_\psi S_\theta - S_\phi C_\psi)\,u_1 - K_{dty}\dot{y}]\,/m \\
\ddot{z} &= [C_\phi C_\theta u_1 - K_{dtz}\dot{z} - mg]\,/m \\
\ddot{\phi} &= \left[du_2 - K_{afx}\dot{\phi} - (I_z - I_y)\dot{\theta}\dot{\psi}\right]/I_x \\
\ddot{\theta} &= \left[du_3 - K_{afy}\dot{\theta} - (I_x - I_z)\dot{\phi}\dot{\psi}\right]/I_y \\
\ddot{\psi} &= \left[u_4 - K_{afz}\dot{\psi} - (I_y - I_x)\dot{\theta}\dot{\phi}\right]/I_z
\end{aligned}$$

where x, y, z are displacements in the earth coordinates. ϕ, θ, ψ are the roll angle, pitching angle and yaw angle in the earth coordinates, respectively. Choosing roll angle, pitching angle, yaw angle and hight as the system outputs, the four rotor flight control system is a four-input four-output normal form system with nonlinear couplings.

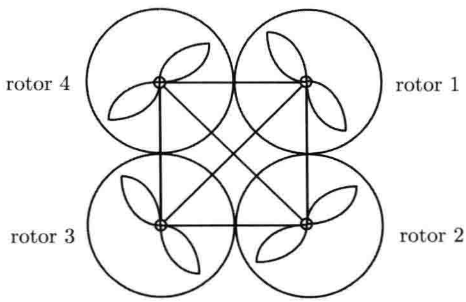

Fig. 1.2 The four rotor aircraft