Robust Adaptive Control for Fractional-Order Systems with Disturbance and Saturation

Mou Chen, Shuyi Shao, and Peng Shi

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To our families, for their love and support

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Preface

This book is devoted to an investigation of some issues of tracking control and synchronization control for fractional-order nonlinear systems in the presence of system uncertainty, external disturbance, and input saturation. On the basis of definitions of the fractional integral and fractional derivatives, lemmas of stability analysis for fractional-order systems, design techniques of disturbance observers, approximation methods of system uncertainty, and handling methods of input saturation, the main research motives of this book are given as follows:

1) In the modeling process, there exist a vast amount of uncertainties caused by modeling error, which may not only degrade the performance of the control system but also even lead to instability of the dynamics system. Therefore, the uncertainty should be considered in the control design to improve the closed-loop system performance of fractional-order systems. Furthermore, neural networks can approximate any continuous uncertain dynamics with an arbitrary accuracy. Many adaptive neural control schemes have been reported for uncertain integer-order nonlinear systems. However, the neural network approximation technique has rarely been considered in uncertain fractional-order nonlinear systems in past decades.
2) A practical system is often subjected to external unknown disturbances. The disturbance may lead to oscillations and even increase the instability of the system. In the field of traditional control, it is well known that feedforward control provides an effective disturbance compensation method which can achieve prompt disturbance attenuation. However, the disturbance has to be measured by sensors for the implementation of traditional feedforward control. Unfortunately, disturbances are usually difficult or even impossible to be measured physically using sensors. Since disturbance observers can estimate external disturbances from known information of the controlled plants, the output of disturbance observers can be used to design the control law. As a result, disturbance rejection is guaranteed to improve the performance and robustness of the closed-loop system. Therefore, disturbance estimation techniques could be used to alleviate the restriction faced by traditional feedforward control and reject the effect of external disturbances. However, disturbance observers have seldom been reported for uncertain fractional-order nonlinear systems subject to external disturbances in the existing literatures. In addition, neural-network-based fractional-order disturbance observers need to be further designed for uncertain fractional-order nonlinear systems.

3) Since the interactive design is rendered more difficult by incorporating the neural network and the disturbance observer, the neural network approximation technique and the disturbance observer have rarely been considered together for integer-order nonlinear systems, although disturbance observers have been widely developed for integer-order nonlinear systems. Conversely, neural-network-based fractional-order disturbance observers have not been designed for uncertain fractional-order nonlinear systems by the interactive design method in the existing literature. For fractional-order systems, the disturbance-observer-based adaptive neural control schemes need to be further developed for uncertain fractional-order nonlinear systems with unknown disturbances.
4) Saturation nonlinearity is a common problem for actuators in a wide range of practical systems. Input saturation can degrade system control performance and even lead to system instability if it is ignored in the control design. Furthermore, control design under consideration of input saturation is a challenging problem for any uncertain nonlinear system. So far, many control design schemes for integer-order nonlinear systems with input saturation have been studied. However, the issues of input saturation and disturbance have rarely been considered together in the control of fractional-order nonlinear systems, although a number of studies have considered input saturation. Therefore, new control schemes need to be further studied for fractional-order nonlinear systems in the presence of system uncertainty, external disturbance, and input saturation.

Based on these research motives, the main contributions of this book are contained in 12 chapters. Chapter 1 introduces some background knowledge. Chapter 2 provides definitions of the fractional integral and fractional derivatives and corresponding lemmas for the stability analysis of fractional-order systems, and introduces some typical fractional-order systems. Chapter 3 gives a fractional-order PID controller and a frequency-domain fractional-order disturbance observer. In Chapter 4, two fractional-order controllers are designed, for integer-order and fractional-order systems, respectively. Chapter 5 develops a disturbance-observer-based sliding-mode control scheme for fractional-order nonlinear systems with external disturbances. In Chapter 6, an adaptive neural control issue is investigated for a fractional-order rotational mechanical system subject to system uncertainties and external disturbance. Chapter 7 considers system uncertainties, external disturbance, and input saturation in the tracking control of fractional-order chaotic systems. In Chapter 8, a stabilization issue is studied for continuous-time fractional-order positive systems based on disturbance observers. Chapter 9 investigates an adaptive sliding-mode synchronization control of fractional-order chaotic systems with disturbances. In Chapter 10, the problem of anti-synchronization control is investigated for fractional-order nonlinear systems based on a disturbance observer and the neural network. In Chapter 11, the input saturation issue is considered for the synchronization of fractional-order systems, while Chapter 12 which considers the synchronization controller design for fractional-order chaotic systems with disturbance and input saturation.

This book intends to provide readers with a good understanding of how to achieve tracking control and synchronization control of fractional-order nonlinear systems with system uncertainties, external disturbance, and input saturation. The book can be used as a reference for the academic research on fractional-order nonlinear systems or used in Ph.D. study of control theory and engineering.

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Nanjing, China
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Peng Shi

Series Preface

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Symbols and Acronyms

D^{α}	Caputo fractional derivative
$D_{0,t}^{-\alpha}$	fractional-order integral
${}_{\mathrm{GL}}D_{0,t}^{\alpha}$	Grünwald–Letnikov fractional derivative
${}_{\mathrm{RL}}D_{0,t}^{\alpha}$	Riemann–Liouville fractional derivative
$E_{\alpha,\beta}(z)/\mathscr{E}_{\alpha,\beta}(z)$	Mittag–Leffler function
eig	eigenvalue
$\mathbf{I}$	identity matrix
$\mathscr{L}(\cdot)$	Laplace transform
$\mathfrak{R}$	field of real numbers
R^{r}	r-dimensional real vector space
R^{+}	positive real numbers
sign	signum function
$\lambda_{\max}(\cdot)$	maximum eigenvalue
$\lambda_{\min}(\cdot)$	minimum eigenvalue
$\lvert\cdot\rvert$	absolute value
$\lVert\cdot\rVert$	2-norm
$(\cdot)^{\mathrm{T}}$	transposition
$\forall$	for all
$\in$	belongs to
$\sum$	sum

FOCS	fractional-order chaotic system
FODO	fractional-order disturbance observer
FONS	fractional-order nonlinear system
FOPS	fractional-order positive system
GL	Grünwald–Letnikov definition
MIMO	multi-input and multi-output
ML	Mittag–Leffler
RL	Riemann–Liouville definition
SISO	single-input and single-output
SMDO	sliding-mode disturbance observer
SMFODO	sliding-mode fractional-order disturbance observer
T–S	Takagi–Sugeno

1

Introduction

Over the past decades, fractional calculus has attracted increasing interest from researchers, and has been widely applied in fields in engineering and physics, such as system control [1], electromechanics [2], and signal processing [3]. Since the mathematical model of a real plant can be accurately described via the fractional-order differential method [4, 5], many systems can be expressed as fractional differential equations, for example, fractional-order economic systems [6], fractional-order biological population models [7], fractional-order financial systems [8], and fractional-order chaotic and hyperchaotic systems [9–15]. With the development of fractional calculus, problems of control and synchronization control for fractional-order systems have been extensively investigated. So far, some important control schemes have been reported for fractional-order systems as follows.

Sliding-model control It is well known that sliding-mode control is an effective robust control scheme and has the features of fast global convergence and high robustness to external disturbances [16]. In recent years, sliding-mode control has been investigated for integer-order linear and nonlinear systems [17–25] and many important results have been reported for the control of fractional-order systems using the sliding-mode technique. Dadras and Momeni [6] studied the control for a fractional-order economical system using the sliding-mode method. Chaos control was investigated for a class of fractional-order chaotic systems based on the sliding-mode approach by Chen *et al.* [26]. Yin *et al.* [27] designed a sliding-mode controller for a class of fractional-order chaotic systems. A no-chattering sliding-mode control strategy was proposed for a class of fractional-order chaotic systems by Chen *et al.* [28]. Yin *et al.* [29] realized chaos control for a class of fractional-order chaotic systems via an adaptive sliding-mode controller. Tavazoei and Haeri [30] and Wang *et al.* [31] achieved synchronization for two fractional-order chaotic systems, using the stability theory of fractional-order systems and the active sliding-mode control method. Sliding-mode synchronization control was realized for uncertain fractional-order Duffing–Holmes systems by Hosseinnia *et al.* [32]. Aghababa [33] investigated stabilization and synchronization for a class of chaotic fractional-order systems via a novel fractional-order sliding-mode method. A robust fractional-order sliding-mode scheme was proposed and synchronization was realized for uncertain fractional-order chaotic systems by Zhang and Yan [34]. Li *et al.* [35] presented a new three-dimensional fractional-order chaotic system and studied its adaptive sliding-mode synchronization. Synchronization was studied for a class of fractional-order arbitrary dimensional hyperchaotic systems based on the

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sliding-mode control method by Liu *et al.* [36]. These works focused on the control of fractional-order systems via the sliding-mode approach.

Adaptive control As is well known, the adaptive control method is a valid control technique for linear and nonlinear systems with parameter uncertainty. So far, integer-order linear and nonlinear systems have been extensively investigated based on the adaptive control method [37–47]. Furthermore, many important results have also been reported for the control of fractional-order systems by using adaptive control strategies. Vinagre *et al.* [48] investigated the use of fractional calculus in conventional model reference adaptive control systems. Odibat [49] proposed an adaptive feedback control scheme for the synchronization of fractional-order chaotic systems with different fractional orders. An adaptive sliding-mode controller was designed for uncertain fractional-order chaotic systems with external disturbance by Yuan *et al.* [50]. Synchronization control was investigated for fractional-order chaotic systems with uncertain parameters by the adaptive function projective control method by Zhou and Ding [51]. Yin *et al.* [52] explored an adaptive fractional-order switching-type control method for three-dimensional fractional-order nonlinear systems. The synchronization of two different uncertain fractional-order time-delay chaotic systems was studied using an adaptive fuzzy sliding-mode control by Lin and Lee [53]. Lin *et al.* [54] studied a chaos synchronization between two different uncertain fractional-order chaotic systems based on adaptive fuzzy sliding-mode control. Adaptive control and synchronization control were investigated for a fractional-order chaotic system by Li and Tong [55]. Lin and Kuo [56] proposed a novel adaptive fuzzy H^∞ control to deal with chaos synchronization between two different uncertain fractional-order chaotic systems. The adaptive control scheme was reported for the control of fractional-order systems in the literature.

Active control Control problems for fractional-order systems using active control schemes have been widely studied. Recently, some important results have been reported. Bhalekar and Daftardar-Gejji [57] realized synchronization between two different fractional-order chaotic systems via active control. Phase and anti-phase synchronization were investigated between two identical and non-identical fractional-order chaotic systems, based on an active control technique, by Taghvafard and Erjaee [58]. Agrawal *et al.* [59] used the active control method to realize the synchronization of two different pairs of fractional-order systems. An active control methodology was presented for controlling the chaotic behavior of a fractional-order version of the Rössler system by Razminia *et al.* [60]. Radwan *et al.* [61] explored control and switching synchronization for fractional-order chaotic systems using an active control technique. A simple integer-order control scheme was proposed for fractional-order systems, based on an active disturbance rejection method, by Li *et al.* [62]. Senejohnny and Delavari [63] developed a novel observer scheme for synchronization of fractional-order chaotic systems. Anti-synchronization was investigated between two identical chaotic fractional-order Qi or Genesio–Tesi systems, as well as between two different fractional-order Genesio–Tesi and Qi systems, using active control method by Srivastava *et al.* [64]. Bhalekar [65] studied synchronization for non-identical fractional-order hyperchaotic systems using active control. An active control scheme was developed for the fractional-order chaotic economic system by Baskonus *et al.*

[66]. These works focused on the control of fractional-order systems using the active control method.

Pinning control As we know, real-world complex networks normally have a large number of nodes. Therefore, it is usually difficult to add controllers to all nodes to control a complex network. To reduce the number of controllers, the method of pinning some of the nodes is employed to control a complex network. Some important results have been proposed for integer-order complex networks [67–73]. With the development of fractional calculus, control problems for fractional-order systems have also been widely investigated. An adaptive pinning synchronization control was studied for fractional-order complex dynamical networks by Chai *et al.* [74]. Sun *et al.* [75] studied multi-group consensus of heterogeneous fractional-order nonlinear agents via pinning control. The pinning control problem of fractional-order weighted complex dynamical networks was investigated by Tang *et al.* [76]. Yu *et al.* [77] explored the leader-following consensus problem of fractional-order multi-agent systems using adaptive pinning control. Adaptive pinning synchronization was developed for fractional-order uncertain complex dynamical networks with delay by Liang *et al.* [78]. Liu *et al.* [79] proposed an adaptive synchronization scheme for a class of fractional-order complex networks via pinning control. Cluster projective synchronization was investigated for complex networks with fractional-order nodes by pinning control by Yang *et al.* [80]. Wang *et al.* [81] developed a pinning impulsive control scheme to study the synchronization of fractional-order complex dynamical networks. The problem of pinning synchronization was explored for fractional-order complex networks with Lipschitz-type nonlinear dynamics by Wang *et al.* [82]. Wang *et al.* [83] studied a projective cluster synchronization scheme for fractional-order coupled-delay complex networks via adaptive pinning control. Synchronization and anti-synchronization were investigated for a new uncertain fractional-order modified unified chaotic systems using a novel active pinning control by Pan *et al.* [84]. In the literature, the pinning control method is effective for the control of fractional-order nonlinear systems.

The aforementioned works focused on control and synchronization control for fractional-order systems via sliding-mode control, adaptive control, and pinning control strategies. In the literature, the issue of adaptive tracking control for fractional-order systems with system uncertainty, unknown disturbance, and input saturation has rarely been considered. Therefore, it is significative to investigate effective robust adaptive control techniques for fractional-order chaotic systems subjected to model uncertainty, unknown disturbance, and input saturation.

Since the uncertain items in nonlinear systems cannot be precisely ascertained, radial basis function neural networks are employed to approximate the uncertainty; neural-network-based control schemes have been proposed to control integer-order uncertain nonlinear systems. Zhang and Ge [85] studied an adaptive neural control scheme for a class of uncertain multi-input and multi-output (MIMO) nonlinear state time-varying delay systems. Robust adaptive neural network control was explored for uncertain MIMO nonlinear systems with input nonlinearities by Chen *et al.* [86]. An adaptive neural output feedback tracking control was investigated for uncertain nonlinear MIMO systems with the discrete-time form by Liu *et al.* [87]. An adaptive neural control scheme was developed for non-strict-feedback stochastic nonlinear systems with unknown backlash-like hysteresis by Wang *et al.* [88]. Liu *et al.* [89]

investigated adaptive output feedback control of uncertain nonlinear single-input and single-output (SISO) systems. An adaptive neural network controller was designed for a class of SISO uncertain nonlinear systems in pure-feedback form by Wang and Huang [90]. Hovakimyan *et al.* [91] developed the adaptive output feedback control scheme for uncertain nonlinear systems via single-hidden-layer neural networks. A robust adaptive neural control scheme was presented for a class of perturbed strict feedback nonlinear systems with both completely unknown virtual control coefficients and unknown nonlinearities by Ge and Wang [92]. Wang and Huang [93] proposed a neural-network-based adaptive dynamic surface control scheme for a class of uncertain nonlinear systems in strict-feedback form. A direct adaptive output feedback control scheme was developed for highly uncertain nonlinear systems using neural networks by Calise *et al.* [94]. Ge *et al.* [95] presented an adaptive neural control scheme for a class of strict-feedback nonlinear systems with unknown time delays. An adaptive neural control scheme was proposed for a class of nonlinear time-delay systems with unknown virtual control coefficients by Ge *et al.* [96]. Yu *et al.* [97] explored neural-network-based adaptive dynamic surface control for permanent magnet synchronous motors. Optimal control was studied for nonlinear discrete time-varying systems based on a new neural network approximation structure by Kiumarsi *et al.* [98]. Chen *et al.* [99] presented an adaptive L_2-gain control scheme for a class of uncertain nonlinear systems with a backstepping method and neural networks. A robust adaptive neural network synchronization controller was designed for a class of chaotic systems with uncertain time delay by Chen and Chen [100]. Chen *et al.* [101] presented a sliding-mode adaptive synchronization controller for two chaotic systems using the radial-basis function neural network. The aforementioned works conclude that the neural network approximation is effective in tackling uncertainties in nonlinear systems. However, the neural network has rarely been considered in the control of uncertain fractional-order chaotic systems (FOCSs); this must be further investigated for uncertain FOCS in the presence of unknown disturbance and input saturation.

It is well known that the control performance of nonlinear plants is characterized by time-varying external unknown disturbances. Meanwhile, external disturbances in nonlinear systems cannot be efficiently handled using the neural network approximation. To compensate for the influence of unknown disturbances, nonlinear disturbance observers have been designed to estimate the unknown external disturbance, and disturbance-observer-based control schemes have been widely proposed by Li *et al.* [102]. Chen *et al.* [103] studied a nonlinear disturbance observer for robot manipulators. A control method based on a disturbance observer was proposed for a nonlinear system with disturbance by Chen [104]. Chen *et al.* [105] explored an adaptive fuzzy tracking control scheme using a disturbance observer for MIMO nonlinear systems. An overview of disturbance-observer-based control and related methods is given by Chen *et al.* [106]. Yang *et al.* [107] introduced a sliding-mode control method for systems with mismatched uncertainties based on a nonlinear disturbance observer. On the basis of the designed disturbance observer, an adaptive dynamic surface control scheme was investigated for near-space vehicles by Chen and Yu [108]. Chen and Yu [109] developed a disturbance-observer-based adaptive sliding-mode control scheme for near-space vehicles. A robust control scheme was proposed for a class of systems with uncertainty and time delay based on the disturbance-observer technique by Chen and Chen [110]. Chen *et al.* [111] proposed a robust adaptive tracking control for an underwater robot in the presence of parametric uncertainties and unknown external disturbances. A robust synchronization control scheme was investigated for chaotic systems subjected to system uncertainties and unknown external disturbances by Chen *et al.* [112]. Chen and Ge [113] proposed an adaptive neural output feedback control scheme for uncertain nonlinear systems in the presence of unknown hysteresis, external disturbances, and unmeasured states. A robust attitude control scheme based on the backstepping technique was developed for near-space vehicles with time-varying disturbances by Chen and Jiang [114]. Chen and Chen [115] proposed a sliding-mode control scheme for a class of nonlinear systems based on disturbance observers. The sliding-mode control scheme was developed for near-space vehicles with strong nonlinearity, high coupling, parameter uncertainty, and unknown time-varying disturbance, based on radial basis function neural networks and the nonlinear disturbance observer, by Zhou and Chen [116]. Chen [117] proposed a nonlinear disturbance-observer-enhanced dynamic inversion control scheme for missiles. Robust control of nonlinear systems with disturbances and uncertainties was studied using a disturbance-observer-based control technique by Yang *et al.* [118]. Yang *et al.* [119] presented a nonlinear disturbance-observer-based control scheme for MIMO nonlinear systems subjected to a mismatch condition. According to these discussions, the anti-disturbance ability of control systems can be improved by employing a disturbance observer in the robust control design for the uncertain nonlinear system with external disturbance. However, fractional-order disturbance observers (FODOs) have rarely been reported for the control of uncertain fractional-order systems with unknown disturbance and input saturation. Therefore, the development of the disturbance-observer-based neural control scheme is significant for the control of uncertain fractional-order systems.

Conversely, system control performance can be degraded under input saturation, which can even lead to closed-loop system instability [120, 121]. In recent years, some schemes have been proposed for the control of nonlinear systems with input saturation. Adaptive fuzzy output feedback control was investigated for uncertain nonlinear systems subjected to input saturation by Li *et al.* [122, 123]. Cao *et al.* [124] analyzed the stability of linear systems with state delay and input saturation. Adaptive control was studied for single-input uncertain nonlinear systems in the presence of input saturation and unknown external disturbance by Wen *et al.* [125]. Lan and Huang [126] investigated semiglobal stabilization and output regulation problems of singular linear systems subjected to input saturation. A neural network tracking control scheme was proposed for ocean surface vessels with input saturation by Chen *et al.* [127]. Chen *et al.* [128] proposed an adaptive tracking control for a class of uncertain MIMO nonlinear systems with asymmetric input constraints. An adaptive sliding-mode control scheme was presented for Lorenz chaos in the presence of input saturation by Yau and Chen [129]. Choi [130] studied the stabilization problem for linear discrete time systems subjected to input saturation. The stabilization problem was investigated for a linear system with distributed input delay and input saturation by Zhou *et al.* [131]. Li *et al.* [132] presented a novel decentralized adaptive neural control scheme for a class of interconnected large-scale uncertain nonlinear time-delay systems in the presence of input saturation. The problem of global tracking and stabilization control was studied for internally damped mobile robots with unknown parameters, and subjected to input torque saturation and external disturbances by Huang *et al.* [133]. Yang *et al.* [134]

proposed a decentralized adaptive neural output feedback control scheme for a class of large-scale time-delay systems with saturating inputs. Sector-condition-based results were proposed for adaptive control and synchronization of chaotic systems with input saturation by Iqbal *et al.* [135]. In the literature, input saturation, unknown disturbance, and uncertainty in the robust tracking control design for fractional-order systems have rarely been considered, although a number of studies have considered input saturation. The asymptotic stabilization method was studied for linear fractional-order systems with input saturation by Lim *et al.* [136]. Luo [137] derived a sufficient condition for the asymptotic stability of nonlinear fractional-order systems subjected to the effects of input saturation. Therefore, the development of a disturbance-observer-based neural control scheme is significant for the control of uncertain fractional-order systems in the presence of input saturation and unknown disturbance.

Many physical systems, called positive systems, have the peculiarity of having only non-negative states, such as absolute temperature, population level, the height of the human body, or concentration of a substance in a chemical process [138, 139]. In the past decade, positive system control has received much attention and many important results have been proposed. On the basis of Gersgorin's theorem, a stabilization method was proposed for positive linear continuous-time and discrete-time systems by Kaczorek [140]. Gao *et al.* [141] presented a sufficient and necessary linear matrix inequality condition for the stabilization of positive linear systems. A static feedback controller was designed to stabilize positive linear continuous-time systems by Wang and Huang [142]. Benzaouia *et al.* [143] reported on the sufficient conditions of asymptotic stability for positive Takagi–Sugeno (T–S) fuzzy systems based on multiple Lyapunov functions. The problem of ℓ_1-induced controller design was investigated for discrete-time positive systems with the use of linear Lyapunov functions by Chen *et al.* [144]. Chen *et al.* [145] studied the stabilization problem for continuous-time positive systems with interval uncertainties based on a designed ℓ_1-induced output-feedback controller. An ℓ_1-induced sparse controller was designed for continuous-time positive systems with interval uncertainties by Chen *et al.* [146]. Chen and colleagues [147, 148] explored positive filtering problems for positive continuous-time systems and positive T–S fuzzy systems based on the ℓ_1-induced performance. The ℓ_∞-gain analysis problem was studied for positive linear systems with unbounded delays by Shen and Lam [149]. Furthermore, the stabilization problems of switched positive linear systems were investigated by Liu and colleagues [150–153]. The aforementioned works focus on investigations of stabilization problems for positive linear continuous-time systems, discrete-time positive systems, switched positive linear systems, and positive T–S fuzzy systems. In addition, many results have been reported for the control of fractional-order positive systems (FOPSs).

On the basis of the definitions of fractional derivatives [154], many significant conclusions have been proposed for FOPSs [155]. Kaczorek [156] introduced a new class of continuous-time FOPSs and gave sufficient conditions for the reachability of FOPS. Stability and stabilization problems were studied for the linear FOPS via a state feedback method by Kaczorek [157]. Hmamed *et al.* [158] presented necessary and sufficient conditions for the boundedness of continuous-time FOPSs. A minimum-energy control problem was investigated for continuous-time FOPSs with bounded inputs by Kaczorek [159]. Mesquine *et al.* [160] explored the robust stabilization problem for continuous-time FOPSs with bounded control. The stabilization problem was studied