

Reports of the Institute for Smart System Technologies,
University of Klagenfurt

Series edited by
Prof. Dr.-Ing. Kyandoghere Kyamakya

Baraka Oliver Mushage

**Design and simulation of intelligent
nonlinear controllers for nonlinear
dynamical engineering systems
using MATLAB/SIMULINK**

Application to Selected Engineering systems

Smart System Technologies

Band 7

Baraka Olivier Mushage

**Design and simulation of intelligent nonlinear
controllers for nonlinear dynamical engineering
systems using MATLAB/SIMULINK**

Application to Selected Engineering systems

Shaker Verlag
Düren 2023

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Copyright Shaker Verlag 2023

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-9049-9

ISSN 1866-7791

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: www.shaker.de • e-mail: info@shaker.de

Preface

The design of efficient controllers for nonlinear plants can be problematic because of challenges related to real world applications and limitations imposed by some assumptions or some complicated approaches hard to apply for practitioners. Different approaches are also needed to simultaneously handle several potential issues without any unnecessary additional energy usage and with improved control performances.

This book is a revised and extended version of our PhD thesis realized at the Institute of Smart Systems Technologies of the University of Klagenfurt, in Austria. It presents the design of efficient adaptive nonlinear controllers for some real world engineering applications. The design approaches presented here take into account multiple challenges for increased safety and reliability. Multiple adaptive nonlinear control schemes are presented, which are relatively easy to apply for practitioners and are able to tackle simultaneously and efficiently some and/or all of the following issues : external disturbances, uncertain dynamics, actuation faults, unmeasured states, constrained input, unknown control direction, and singularity in the control law. The book presents the design of multiple control schemes mainly based on Radial Basis Function Neural Networks (RBFNN) or Fuzzy Neural Networks (FNNs). For each design example, the book provides applications and MATLAB codes or SIMULINK models for simulation.

This book, through its eight chapters, intends to disseminate more knowledge about the design processes that can suitably be applied to various control engineering problems. In this book, we want to achieve the following objectives :

- Present simple design approaches for adaptive controllers for a general class of nonlinear SISO or MIMO systems of any order, which can be readily applied by practitioners.
- Present some design approaches for control schemes able to :
 - accommodate simultaneously issues related to uncertain nonlinear dynamics, unavailable full-state measurement, unknown control direction, external disturbances, constrained input, actuator faults (affine or non-affine, linear or nonlinear, constant or time-varying faults especially gain faults or partial loss of effectiveness faults, bias faults, complex faults);
 - guarantee singularity avoidance in the control law, uncertain dynamics approximation errors compensation, and control signal features improvement (low amplitude, low frequency).

- Present how a larger scope of potential applications can be enabled by relaxing assumptions found in most of the published works about the knowledge of the upper and lower bounds of the perturbations (uncertain dynamics, external disturbances, and actuation faults) and the assumption about the positive-definiteness of the control gain function and the knowledge of its bounds and/or its sign.
- Show how the designed control schemes grant the achievement of control objectives with better transient and steady state performances (no peak overshoot, short settling time, small steady state error bounds, small RMSE, and faster restoration of the system performances after the occurrence of an actuator failure) and enable an easy implementation for practical applications (no chattering phenomenon, low energy consumption).

For the sake of an easy exploitation of the book by readers, the contents of each chapter are independent, as all the necessary information needed for its understanding is provided therein.

The book is structured as follows:

1. In Chapter 1 of the book, some basic knowledge/tools needed to understand the concepts presented in this book are provided. The reader is introduced to feedback linearizable nonlinear systems. An overview of feedback linearization and the general principle of feedback controllers design are presented as well. As an example, a feedback controller design is presented for a Chua's chaotic circuit synchronization or output tracking.
2. Chapter 2 introduces a series of fundamentals of the traditional Sliding Mode Control (SMC) as a complementary tool for adding the robustness aspect to the feedback controller presented in Chapter 1. This chapter also provides a short description of neuro-fuzzy architectures and some basics about FNNs. An uncertain and disturbed Duffing's system chaos control problem is used to illustrate the design of an adaptive reaching law-based sliding mode controller using a FNN. The simulation of the controlled Duffing's chaotic system is presented with the results.
3. Chapter 3 presents a design approach for adaptive controllers for nonlinear strict-feedback systems subject to both external disturbances and uncertain dynamics issues. This approach is based on a FNN and uses a reaching law-based SMC approach combined with the Input Output Feedback Linearization technique. Two 3D chaotic systems, a one-link robot manipulator with a brush DC motor are simulated with the designed controllers in order to show how they easily tackle the external disturbances, the uncertainty, the FNN approximation errors and the singularity issues efficiently when compared to some intelligent control schemes proposed in the literature for the same class of nonlinear systems.
4. In Chapter 4, the book presents a nonlinear control scheme incorporating a FNN, a state observer, and a Naussbaum type function. The presented scheme cancels the assumption about

the knowledge of the control gain sign and the knowledge of the disturbance, the actuation fault and the FNNs approximation errors' upper bounds considered in many existing works. Application examples are presented for the Boeing 747-100/200 pitch angle control, the inverted pendulum control, and the one-link robot manipulator with a brush DC motor.

5. Chapter 5 presents a particular case of an adaptive nonlinear controller for the Unmanned Surface Vehicle Steering System by using a high-gain state observer and a Radial Basis Function Neural network (RBFNN). The controller is designed such that it is fault-tolerant.
6. Chapter 6 addresses the control problem of a 5-DOF exoskeleton robot with uncertain dynamics, unmeasured states and actuation faults. The simulation results of the control system are presented as well.
7. The design and simulation of an adaptive Neural-Network-based Nonlinear fault-tolerant controller of a disturbed Unmanned Aerial Vehicle (UAV) are presented in Chapter 7.
8. In Chapter 8 we present the design of a nonlinear controller for a 3-axis MEMS Gyroscope with its simulation.

In each chapter, for each design example, we provide the MATLAB code and the SIMULINK model (where needed) giving the presented simulation results. These codes and models are provided by assuming that they can be exploited by readers with at least some basic knowledge about MATLAB and SIMULINK.

Klagenfurt, Austria,

Baraka Olivier Mushage

Abstract

For many decades, the scientific community has devoted a tremendous amount of attention to the design of efficient controllers for nonlinear plants, which can be problematic because of challenges related to real world applications. However, there is still a need for addressing some issues that remain not clearly solved related to limitations imposed by some assumptions or some complicated approaches hard to apply for practitioners. There is also a need for approaches able to handle simultaneously several potential issues without any unnecessary additional energy usage and with improved control performances. Therefore, this book presents the design of efficient adaptive nonlinear controllers for strict-feedback nonlinear systems by taking into account multiple challenges for increased safety and reliability. The considered challenges are external disturbances, uncertain dynamics, actuation faults, unmeasured states, constrained input, unknown control direction, and singularity in the control law. Some adaptive nonlinear control schemes, which are relatively easy to apply for practitioners in order to tackle simultaneously and efficiently some and/or all aforementioned issues are presented. The book presents the design of schemes based on a reaching law-based Sliding Mode Control strategies, combined with the Input-Output Feedback Linearization technique. These schemes use Radial Basis Function Neural Networks (RBFNN) and Fuzzy Neural Networks (FNNs) to approximate the unknown system dynamics. It is illustrated how a model-free high-gain state observer is employed for estimating the unavailable system state variables. For dealing with the unknown control direction, a Nussbaum type function is presented. The schemes presented in this book have a wide scope of potential applications as they overcome important restrictions imposed by some assumptions found in many works, while ensuring very good transient and steady state performances (no peak overshoot, shorter settling time, smaller error bound and Root-Mean-Square-Error) with low leveled continuous control efforts. These canceled restrictions are the requirements about the knowledge of bounds for system dynamics uncertainties, for RBFNN or FNN approximation errors, for actuator's faults and for external disturbances, the knowledge of control direction, the availability of full-state measurement, and the requirement about the positive-definiteness of the control gain function with known lower and upper bounds.

Nonlinear controllers are designed for some particular engineering applications like

- the Boeing 747-100/200 pitch angle of attack control, the tracking control of an inverted pendulum
- a 3D chaotic system synchronization
- the tracking control of a one-link manipulator with DC motor
- the control of an Unmanned Surface Vehicle Steering System
- the control of a 5 DOF upper-limb exoskeleton robot for assisted rehabilitation therapy
- the control of a disturbed Unmanned Aerial Vehicle (UAV)
- the control of a 3-axis MEMS Gyroscope

Simulation results for these application examples are provided with the corresponding MATLAB codes/SIMULINK models and compared with those reported in the literature where other adaptive schemes have been applied to the same systems so that the reader can easily see the validation of the control schemes presented in this book.

About the Author

Baraka Olivier Mushage received his civil Engineering degree in Electrical Engineering from the Faculty of Applied Sciences and Technologies of the *Université Libre des Pays des Grands Lacs* (ULPGL), in the Democratic Republic of Congo, in 2010. Then he received his Master and Doctorate degrees in Information Technology from the University of Klagenfurt, in Austria, in 2014 and 2017, respectively. He is currently a Professor in the department of Electrical and Computer Engineering of the Faculty of Applied Sciences and Technologies of ULPGL. His research interests include nonlinear control, fault-tolerant control, intelligent control and robust control.

Acknowledgments

This book is a result of a research stay at the Institute of Smart Systems Technologies of the *Alpen-Adria-Universität Klagenfurt*, in Austria. We would like to thank individuals and organizations who made a contribution to the successful completion of this work.

We would like to thank the *Österreichischer Austauschdienst* (OeAD), for awarding us with the Ernst Mach Grant, Nachbetreuungstipendium/EZA, which made the realization of this work possible in Austria.

We would also like to thank the Institute of Smart Systems Technologies of *Alpen-Adria-Universität Klagenfurt* for hosting us and for giving us access to valuable resources that led to the completion of this work.

We would like to express our gratitude and dedicate this work to the loving memory of our late father, Pierre-Claver Mushage, who has always been our first source of motivation.

We would also like to thank our wife Sarah K. Lutala, our children, friends and family members, for their constant support.

Contents

1	Basics of IOFL	1
1.1	General class of considered systems	2
1.2	Lie Derivative, Lie Bracket and Relative Degree of a Control System	3
1.3	Strict-feedback or Feedback Linearizable Nonlinear Systems	5
1.3.1	State Transformation: Partial Linearization	5
1.3.2	Conditions for Exact Linearization	8
1.4	Design Principle of Input-Output Feedback Linearization (IOFL) Control Systems: Exact Linearization	10
1.4.1	Controller Design	10
1.4.2	Stability Analysis	13
1.5	Illustrative example: Synchronization or output tracking for the Chua's circuit	16
1.6	Some Limitations of the Conventional IOFL	29
1.6.1	The Singularity Issue	29
1.6.2	Robustness Issue	30
1.7	Conclusion	31
2	Fundamentals of Sliding-Mode Control and Fuzzy Neural Networks in Process	
	Control	33
2.1	Problem Statement	34
2.2	Traditional Sliding Mode Control	35
2.2.1	Reaching Laws	36
2.2.2	The Chattering Phenomenon	38
2.2.3	Controller Design Using the Reaching Law-based SMC and IOFL	39
2.2.4	Illustrative example a controller's design using the reaching law-based SMC and IOFL and simulation	43

2.3	Higher-Order Sliding Mode Control (HOSMC)	50
2.3.1	Second Order Sliding Mode Control	52
2.3.2	Illustrative example a controller's design using the reaching law-based SOSMC and simulation	58
2.4	Fundamentals of Fuzzy Neural Networks	64
2.4.1	Some preliminaries	65
2.4.2	Integration of Fuzzy Logic and Neural Networks: Neuro-Fuzzy Architectures	66
2.5	FNN-based Adaptive Controller for Strict-Feedback Systems	69
2.5.1	Overview of Some Methods for Tuning FNN for Performance Optimization ..	70
2.5.2	Illustrative example of a FNN-based Adaptive Sliding Mode Controller design and simulation for the Duffing's chaotic system	71
2.6	Conclusion	82
3	Design of a FNN-based Adaptive SMC of Uncertain Nonlinear Systems	85
3.1	Introduction	85
3.2	Problem Statement and Preliminaries	89
3.3	Configuration of the Fuzzy Neural Network	93
3.4	Design of the FNN Adaptive Sliding Mode Controller (FNNASMC)	96
3.5	Application Examples and Discussions	100
3.5.1	Example 1: Control of a Theoretical Disturbed Strict-feedback Nonlinear System	101
3.5.2	Example 2: Synchronization of two 3D Chaotic Systems	117
3.5.3	Example 3: Control of a One-link Robot Manipulator with a Brush DC Motor	128
3.6	Conclusion	135
4	Observer-based Fuzzy Adaptive Fault-Tolerant Nonlinear Controller Design for Uncertain Nonlinear Systems with Unknown Control Direction	137
4.1	Introduction	138
4.2	Problem Statement and Preliminaries	141
4.2.1	Problem Statement	141
4.2.2	Nussbaum Function Properties	146
4.3	Main Results	147
4.3.1	The High-Gain Observer	147
4.3.2	Design of the Intelligent FNN and Observer-based Fault-Tolerant Controller ..	150
4.4	Application Examples and Discussions	159
4.4.1	Example 1: Boeing 747-100/200 Pitch Angle Control	159

4.4.2	Example 2: Control of a One-Link Robot Manipulator with a Brush DC Motor	172
4.5	Conclusion	181
5	Observer and Neural Network Based Fault-Tolerant Nonlinear Controller Design for Unmanned Surface Vehicle Steering System	183
5.1	Introduction	183
5.2	Problem Statement and Preliminaries	185
5.2.1	Presentation of the USV model	185
5.2.2	The High-Gain State Observer	187
5.2.3	The Radial Basis Function Neural Network (RBFNN)	189
5.3	Fault-tolerant nonlinear controller design	190
5.4	Simulation results and discussions	194
5.5	Conclusion	206
6	FNN and Observer-based Fault-Tolerant Adaptive Nonlinear Controller Design for an Uncertain 5-DOF Upper-Limb Exoskeleton Robot	207
6.1	Introduction	208
6.2	Preliminaries and Problem Statement	210
6.2.1	Exoskeleton Control Problem	211
6.2.2	Controller Design: Ideal Case With Available States and System Dynamics	214
6.3	Main Results	217
6.3.1	High-Gain State Observer Design	217
6.3.2	FNN and Observer-based Nonlinear Controller Design	219
6.4	Simulation and Discussion	224
6.5	Conclusion	244
7	Design of an Intelligent Nonlinear Fault-Tolerant Controller of a Quadrotor with Parametric Uncertainty and External Disturbances	245
7.1	Introduction	245
7.2	Quadrotor model presentation	248
7.3	Problem statement	250
7.4	Design of the adaptive RBFNN-based fault-tolerant controller	252
7.4.1	Controller design for the altitude subsystem	252
7.4.2	Controller design for the roll, pitch and yaw subsystem	255
7.4.3	Virtual controller design for the x and y positions subsystem	256
7.4.4	General form of the control law	257

7.5	Simulation results and discussions	262
7.6	Conclusion	294
8	Observer and Fuzzy Neural Network based 3-Axis MEMS Gyroscope Nonlinear Controller Design	295
8.1	Introduction	295
8.2	Problem Statement	297
8.3	Observer and FNN Nonlinear Controller Design	299
8.3.1	High-gain State Observer Design	299
8.3.2	Controller design	301
8.4	Simulation results and discussions	305
8.5	Conclusion	318
	Bibliography	319
	References	319

Glossary

Throughout this book, lowercase letters represent scalars, bold lowercase letters represent vectors, and bold uppercase letters represent matrices.

x	a scalar
\mathbf{x}	a vector
$x(\cdot)$	a scalar function
$\mathbf{x}(\cdot)$	a vector function
$ \mathbf{x} $	modulus of vector \mathbf{x}
$\dot{\mathbf{x}}, \ddot{\mathbf{x}}, \mathbf{x}^{(i)}$	first, second and i th time derivative of \mathbf{x} : $\frac{d\mathbf{x}}{dt}, \frac{d^2\mathbf{x}}{dt^2}, \frac{d^i\mathbf{x}}{dt^i}$
\mathbb{R}	set of real numbers
\mathbb{R}^+	set of positive real numbers
\mathbb{R}^n	n -dimensional real vector space
$\mathbf{1}_n$	column vector of n ones
\mathbb{N}	set of natural numbers
$\text{sign}(x)$	signum or sign function, $\text{sign}(x) = \begin{cases} +1 & \text{for } x > 0 \\ -1 & \text{for } x < 0 \end{cases}$
$\text{sat}(x)$	saturation function, $\text{sat}(x) = \begin{cases} 1 & \text{for } x \geq 1 \\ x & \text{for } -1 < x < 1 \\ -1 & \text{for } x \leq -1 \end{cases}$
∇	vector differential operator, for $\mathbf{x} = [x_1, x_2, \dots, x_n]^T \in \mathbb{R}^n$, $\nabla = \left[\frac{\partial}{\partial x_1} \quad \frac{\partial}{\partial x_2} \quad \dots \quad \frac{\partial}{\partial x_n} \right]$
$\mathcal{L}_f h(\mathbf{x})$	Lie derivative of $h(\mathbf{x})$ with respect to f , $\mathcal{L}_f h(\mathbf{x}) = \nabla h(\mathbf{x}) \cdot f$
$[\mathbf{f}(\mathbf{x}), \mathbf{g}(\mathbf{x})]$	Lie bracket of $\mathbf{f}(\mathbf{x})$ and $\mathbf{g}(\mathbf{x})$ (other notation $\text{ad}_f \mathbf{g}(\mathbf{x})$)
V	Lyapunov candidate function
\forall	for all

$\max_{\mathbf{x} \in \Omega} f(\mathbf{x})$	maximum value of $f(\mathbf{x})$ with respect to its argument $\mathbf{x} \in \Omega$
$\arg \min_{\mathbf{x} \in \Omega} f(\mathbf{x})$	value of $\mathbf{x} \in \Omega$ for which $f(\mathbf{x})$ attains its minimum
$\ \mathbf{x}\ _2$	Euclidean norm or 2-Norm of vector \mathbf{x} ($\ \mathbf{x}\ = \sqrt{\mathbf{x}^T \mathbf{x}}$)
$\ \mathbf{A}\ ^2$	norm of matrix $\mathbf{A} \in \mathbb{R}^n$ ($\ \mathbf{A}\ ^2 = \text{tr} [\mathbf{A}^T \mathbf{A}]$)
$\text{span}\{\cdot\}$	span of vectors
CA	Center Average
COA	Center of Area
DAC	Direct Adaptive Control
DC	Direct Current
DCOG	Discrete center of gravity
DOF	Degree Of Freedom
DSP	Digital Signal Processor
FDD	Fault Detection and Diagnosis
FLS	Fuzzy Logic System
FNN	Fuzzy Neural Network
FNNASMC	Fuzzy Neural Network Adaptive Sliding Mode Controller
FOSMC	First Order Sliding Mode Control
FPGA	Field Programmable Gate Arrays
FT	Fault-Tolerant
FTC	Fault Tolerant Control
HVDC	High Voltage Direct Current
IAC	Indirect Adaptive Control
IOFL	Input-Output Feedback Linearization
MEMS	Micro-Electro-Mechanical System
MIMO	Multiple-Input-Multiple-Output
MISO	Multiple-Input-Single-Output
NEFCON	Neural Fuzzy Controller
NN	Neural Network
ODE	Ordinary Differential Equation
QANFTC	Quadrotor Adaptive Nonlinear FTC
RBFINN	Radial Basis Function Neural Network
RMSE	Root-Mean-Square-Error
RQ	Research question
SAFNC	Self-organizing Adaptive Fuzzy Neural Control

SISO	Single-Input-Single-Output
SMC	Sliding Mode Control
SOSMC	Second Order Sliding Mode Control
STA	Super Twisting Algorithm
TA	Twisting Algorithm
T-S	Takagi-Sugeno
TV	Total Variation
UAV	Unmanned Aerial Vehicle
USV	Unmanned Surface Vehicle
VSC	Voltage Source Converter

List of Figures

1.1	Chaotic behavior of the Chua's circuit: x_1 - x_2 phase plane	17
1.2	Synchronization of Chua's circuit: system's states tracking the reference trajectory (dashed line)	25
1.3	Synchronization of Chua's circuit: (a) tracking error dynamics; (b) feedback control signal	25
1.4	Tracking error on the variables x_1 , x_2 and x_3 when a disturbance $d(t) = \sin(t)$ is applied to the Chua's system	31
2.1	(a) Phase portrait of a 2-dimensional system: example of an ideal sliding mode; (b) real sliding mode (the chattering phenomenon)	36
2.2	(a) Signum function $\text{sign}(s)$; (b) saturation function $\text{sat}(s)$	39
2.3	Simulation result for example 3.1: (a) The output y tracking the reference y_d ; (b) tracking error; (c) control signal with $\text{sign}(s)$ (signal with chattering phenomenon); (d) control signal with $\text{sat}(s)$ (chattering-free signal)	50
2.4	Second order sliding mode trajectory [28]	52
2.5	Twisting controller trajectory in the phase plane	53
2.6	Simulation results: System's output y tracking the reference y_d (a) when the FOSMC is applied; (b) when the SOSMC is applied; tracking error e (c) when the FOSMC is applied; (d) when the SOSMC is applied.	62
2.7	Simulation results: Control signal (a) with the signum function in Eq. (2.62); (b) with the saturation function in Eq.(2.62)	63
2.8	System response (a) with $\eta = 1.2$ in Eqs. (2.56) and (2.62) and (b) with $\eta = 2$ in Eqs. (2.56) and (2.62); Twisting trajectory in phase plane $s - \dot{s}$ (c) with $\eta = 1.2$ in Eqs. (2.56) and (2.62) and (d) with $\eta = 2$ in Eqs. (2.56) and (2.62).	64
2.9	Neuro-fuzzy architecture of a system based on the Mamdani approach	67

2.10 Phase plane of the uncontrolled Duffing's circuit: (a) chaotic behavior for $q = 1.95$; (b) limit cycle for $q = 7$	72
2.11 FNN designed for adaptive control of the Duffing's circuit	74
2.12 Duffing's circuit chaos suppression from $t = 5$: (a) State variable x_1 with the periodic reference x_{1d} ; (b) State variable x_2 with \dot{x}_{1d} ; (c) the tracking error $e(t)$; (d) Control signal u_a ; (e) 3 Membership functions for each input x_j ; (f) the exact nonlinear function $f(x)$ (dashed line) and its FNN approximation $\hat{f}(x)$	77
3.1 Synthetic representation of the FNN where x_{ej} ($j = 1, 2, \dots, k$) are the inputs, and $\hat{\alpha}(x_e \hat{\theta}_\alpha)$ and $\hat{\beta}(x_e \hat{\theta}_\beta)$ are the outputs	93
3.2 The block diagram of the FNN Adaptive Sliding Mode Control system	100
3.3 Membership functions for example 1 (obtained using Eq. (3.56))	102
3.4 Results for case 1 with Eq. (3.58) applied; On the top : System's output $y(t)$ (dashed line) tracking the desired trajectory $y_d(t)$ (continuous line); On the bottom : the chattering-free control signal $u_a(t)$	104
3.5 Results for case 2 with the controller from [105]; On the top : System output $y(t)$ (dashed line) tracking the desired trajectory $y_d(t)$ (continuous line); On the bottom : the control signal $u_a(t)$	110
3.6 Phase portrait revealing the transient chaos exhibited by the system (3.60) with the parameters $a = 1.8$, $b = 5$, $c = 1.5$, $d = 10$ and initial conditions $(0.1, 0.8, 1.2)$: (a) Represents the 3D view of the state variables; (b) represents the $x_1 - x_2$ phase portrait; (c) represents the $x_2 - x_3$ phase portrait and (d) represents the $x_1 - x_3$ phase portrait	117
3.7 Membership functions for Example 2	119
3.8 Numerical simulation results of system (3.60) before and after activation of the controller at $t = 10$: (a) state x_1 and its reference x_{1d} ; (b) state x_2 and its reference x_{2d} ; (c) state x_3 and its reference x_{3d} ; (d) tracking error of x_1 ; (e) tracking error of x_2 ; (f) tracking error of x_3	120
3.9 The control signal introduced at simulation $t = 10$	121
3.10 System's response when the controller from [105] is used	127
3.11 Membership functions for Example 3	129
3.12 Link angular position x_1 and reference trajectory y_d (dashed line): (a) when Eq. (3.66) is applied; (b) results from [150]	130
3.13 Control input u_a : (a) when Eq. (3.66) is applied; (b) results from [150]	130
4.1 Block diagram of the FTC scheme	159

4.2	(a) Results with the presented scheme, before and after the 50% loss of effectiveness fault and 20% dynamic uncertainty occurrence (at $t = 25$); (b) with the adaptive controller from [8] (available full-state & disturbance-free): on top pitch angle $x_1(t)$ and reference signal x_{1d} or θ_d ; at the bottom the deflection of elevator $u_a(t)$	162
4.3	(a) Observed states (example 1): On top: $x_1(t)$ and its estimation $\hat{x}_1(t)$ (dashed line); on bottom: $x_2(t)$ and its estimation $\hat{x}_2(t)$ (dashed line); (b) On top: the Nussbaum function $N(\zeta)$; at the bottom the variable $\zeta(t)$	162
4.4	Tracking error for the state x_1	163
4.5	Link angular position x_1 (solid line) and reference trajectory y_d (dashed line): (a) before and after the fault and the parameter change (at $t = 10$) (example 3) when Eq. (4.87) is applied; (b) results from [150] (no actuation failure and available full-state)	174
4.6	Control input u_a : (a) when Eq. (4.87) is applied; (b) when the scheme from [150] is applied	174
4.7	Observed states (example 3): (a) represents the swing angle $x_1(t)$ and its estimation $\hat{x}_1(t)$ (dashed line); (b) represents the swing angle rate $x_2(t)$ and its estimation $\hat{x}_2(t)$ (dashed line)	175
5.1	The motion model of the USV	185
5.2	(a) Desired yaw angle $\psi_d(t)$ compared with the output obtained using the traditional SMC and the proposed controller. (b) Tracking error of the yaw angle obtained with each controller	195
5.3	(a)(a) Desired yaw rate $r_d(t)$ compared with the yaw rate obtained using the traditional SMC and the proposed controller. (b) Tracking error of the yaw rate obtained with each controller	195
5.4	Control actions $u(t) = \delta(t)$ obtained with the proposed controller and with the SMC.	196
5.5	SIMULINK model of the USV controlled by the presented controller	196
5.6	SIMULINK model of the USV controlled by the Sliding Mode Controller	197
6.1	Links' positions q_1, q_2 and q_3 for $K_1 = K_2 = K_3 = 5$ (dashed line) and for $K_1 = K_2 = K_3 = 2$ (dashdot line) tracking the references q_{d1}, q_{d2} and q_{d3} with the nonlinear fault tolerant controller from [210] (see (a), (c) and (e)), and with our nonlinear controller (see (b), (d) and (f))	226

6.2	Links' positions q_4 and q_5 for $K_4 = K_5 = 5$ (dashed line) and for $K_4 = K_5 = 2$ (dashdotted line) tracking the references q_{d4} and q_{d5} with the nonlinear fault tolerant controller from [210] (see (a) and (c)), and with our nonlinear controller (see (b) and (d))	227
6.3	Actual velocity \dot{q}_2 (dashed line) with its estimated value $\hat{\dot{q}}_2$ for the 2nd link	228
6.4	The five links actuation torques τ_1, \dots, τ_5 obtained: (a) with nonlinear FT controller from [210]; (b) with the control approach proposed in this chapter	228
6.5	SIMULINK simulation model for the 5-DOF upper-limb exoskeleton robot	229
7.1	Quadrotor	248
7.2	x, y and z positions with the proposed QANFTC and with the robust SOSMC from [263] (without perturbation).	265
7.3	Euler angles ϕ, θ and ψ with the proposed QANFTC and with the robust SOSMC from [263] (without perturbation).	265
7.4	3D trajectory (a) with the robust SOSMC from [263] and (b) with the proposed QANFTC (without perturbation).	266
7.5	Control signals u_1, u_2, u_3 and u_4 with the proposed QANFTC and with the robust SOSMC from [263] (without perturbation).	266
7.6	x, y and z positions with the proposed QANFTC and with the robust SOSMC from [263] (with multiple perturbations).	268
7.7	3D trajectory (a) with the proposed QANFTC (with multiple perturbations) and (b) with the robust SOSMC from [263].	268
7.8	Control signals u_1, u_2, u_3 and u_4 with the proposed QANFTC and with the robust SOSMC from [263] (with multiple perturbations).	269
7.9	SIMULINK simulation model for quadrotor with the QANFTC	270
7.10	SIMULINK simulation model for quadrotor with the SOSMC	270
8.1	Position tracking on the x, y and z axis	306
8.2	State estimation by the high-gain state observer	307
8.3	Control signal on the three axis	307
8.4	SIMULINK model of the USV controlled by the presented controller	308

List of Tables

3.1	Some works addressing the adaptive control of uncertain and/or disturbed strict-feedback systems	86
3.2	Steady state and transient phase performances specifications for the two controllers applied on system (3.54)	105
3.3	Steady state and transient phase performance specifications when the control law (3.61) is applied for synchronization of system (3.60)	122
3.4	Steady state and transient phase performances specifications for the two controllers applied on system (3.63)	131
4.1	Some works addressing the adaptive nonlinear control of perturbed strict-feedback systems	140
4.2	Steady state and transient phase performances specifications for the two controllers applied to system (4.81)	171
4.3	Steady state and transient phase performances specifications for the two controllers applied on system (4.84)	175
6.1	5-DOF upper-limb exoskeleton robot parameters [209,210]	213
6.2	Some performance specifications on the five links using the control law Eq. (6.59) and the FT adaptive nonlinear controller from [210]	227
7.1	Parameters of the simulated quadrotor	263
7.2	QANFTC and RBFNN parameters	263
7.3	Desired positions and angles	264
7.4	Performance specifications for the two controllers applied to the UAV without perturbations	264
7.5	Aerodynamics forces and torques	267

7.6 Performance specifications for the two controllers applied on the UAV with multiple perturbations 269