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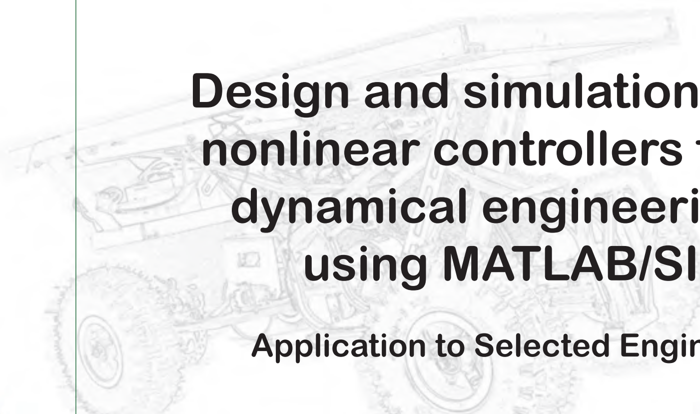

Design and simulation of intelligent nonlinear controllers for nonlinear dynamical engineering systems using MATLAB/SIMULINK

Application to Selected Engineering systems

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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.

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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

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
$\lvert\mathbf{x}\rvert$	modulus of vector $\mathbf{x}$
$\dot{\mathbf{x}}$, $\ddot{\mathbf{x}}$, $\mathbf{x}^{(i)}$	first, second and ith 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
I_n	column vector of n ones
$\mathbb{N}$	set of natural numbers
$\mathsf{sign}(x)$	signum or sign function, $\mathsf{sign}(x)=\begin{cases}+1 \text{ for } x>0\\ -1 \text{ for } x<0\end{cases}$
$\mathsf{sat}(x)$	saturation function, $\mathsf{sat}(x)=\begin{cases}1 & \text{for } x\geq 1\\ x & \text{for } -1<x<1\\ -1 & \text{for } x\leq -1\end{cases}$
∇	vector differential operator, for $\mathbf{x}=[x_1, x_2, \cdots, x_n]^T\in\mathbb{R}^n$, $\nabla=\left[\frac{\partial}{\partial x_1}\ \frac{\partial}{\partial x_2}\ \cdots\ \frac{\partial}{\partial x_n}\right]$
$\mathcal{L}_f h(\mathbf{x})$	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 $\mathsf{ad}_f\mathbf{g}(\mathbf{x})$)
V	Lyapunov candidate function
$\forall$	for all

$\max\limits_{\mathbf{x}\in\Omega} f(\mathbf{x})$	maximum value of $f(\mathbf{x})$ with respect to its argument $\mathbf{x} \in \Omega$
$\arg\min\limits_{\mathbf{x}\in\Omega} f(\mathbf{x})$	value of $\mathbf{x} \in \Omega$ for which $f(\mathbf{x})$ attains it's minimum
$\lvert\lvert\mathbf{x}\rvert\rvert_2$	Euclidean norm or $2-$Norm of vector $\mathbf{x}$ ($\lVert\mathbf{x}\rVert = \sqrt{\mathbf{x}^T\mathbf{x}}$)
$\lVert\mathbf{A}\rVert^2$	norm of matrix $\mathbf{A} \in \mathbb{R}^n$ ($\lVert\mathbf{A}\rVert^2 = tr\left[\mathbf{A}^T\mathbf{A}\right]$)
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
RBFNN	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

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