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Fuzzy Sliding Mode Control and Observation of Complex Dynamic Systems and Applications

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Preface

In the complex real world, it is difficult, challenging, or even impossible, to exactly describe a plant quantitatively, which is in terms of mathematical models predominantly because the facts of many elements in the plant subject to nonlinearities and uncertainties in structure, and perturbations in parameters and external disturbances. In engineering practice, the stability, accuracy and robustness of a control system are crucial. Accordingly, implementation-oriented control engineers have been seeking the controllers which can provide high accuracy as well as insensitivity to structural uncertainties, parameter perturbations and environmental disturbances.

In the design of a control system with structural uncertainties, parameter perturbations and environmental disturbances, designers normally try to minimise the use of a detailed mathematical model whose ambiguities can never be modelled accurately. One suitable approach for this kind of nonlinear controller designs, avoiding the use of complicated models, is to employ variable structure system theory, which has been successfully applied to a wide variety of systems having uncertainties in the representative system model. In meeting the specifications of the closed loop system, those conventional controller design strategies usually fail to achieve the desired characteristics. In order to upgrade the performance of the controller and facilitate the design procedure, one should integrate artificial intelligence, most likely from expert linguistic knowledge, with conventional control algorithms.

Since V. Utkin published his distinguished survey paper in 1977, research interest on variable structure systems with sliding mode manifolds has been significantly generated in scientific and commercial communities in the control area. The research work in this book attempts to strengthen the interest and widen the applications in this area.

The research work of this book was firstly motivated by the increasing demands of high precision and high performance control for complex systems with uncertainties which include unmodelled dynamics, unknown parameters and functions, and external disturbances. The pure sliding mode control strategy, though providing feasible and robust solutions for many kinds of complex systems, suffers from some unavoidable disadvantages; the first one is chattering, which deteriorates system performance and sometimes causes serious troubles; and another one is that, sometimes, in order to guarantee the global stability of the system, overestimates of the system functions and/or parameters should be applied which conflict with the requirements of high performance of the control system. Fuzzy logic enhanced conventional sliding mode control will be an effective and efficient candidate to overcome the problems listed above, but fuzzy logic related control systems are normally criticised for a lack of systematic design, mathematical rigor and stability analysis. This book attempts to develop high performance control strategies integrating fuzzy logic with conventional sliding mode control, which are chatter free, more robust, with no strict constraints and whose stability is guaranteed in the sense of conventional control theory.

And secondly, the research work of this book was motivated by the demand from practical applications. Because of the complexity of practical applications, different control schemes should be applied for dynamic systems with different characteristics. Normally, it is difficult to employ a generalised design procedure to deal with the control of a complex dynamic system. It is the authors' belief that taking the advantages of the known properties of a dynamic system and injecting human experience with conventional control theory in the controller design will produce more desirable results.

This book contains nine chapters. The main body of the book can be classified into two parts: the first part includes **Chapters 1-5**, concentrating on the theoretical studies of the sliding mode theory for system control and observation; the second part includes **Chapters 6-9**, dealing with the applications of the sliding mode techniques in complex dynamic systems; for bench tests, some case studies are investigated for helicopter hovering control, robotic manipulation and control of a few of more commonly encountered plants/processes (vehicle suspension systems, a two-level water tank, and a hydraulic cylinder respectively). The outline of the book is listed as follows:

Chapter 1. The literature survey covers the integration of artificial intelligence and the conventional control theory to tackle the problems of the control of nonlinear complex systems.

Chapter 2. The fundamental knowledge and preliminary methodologies related to the research work in this book are set out, and some concepts and definitions are

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clarified.

Chapter 3. Adaptive fuzzy sliding mode control algorithms are developed for SISO and MIMO nonlinear complex systems, and the stability of the control systems is proved in the sense of Lyapunov's stability theory.

Chapter 4. A novel adaptive sliding mode observer is developed to reconstruct the system states for nonlinear stochastic systems with structure uncertainty, parameter perturbation and external disturbance which is presented in the Itô differential equations.

Chapter 5. An adaptive observer based controller is designed to enhance the design of nonlinear stochastic system control with sliding mode schemes. First of all, an adaptive sliding mode observer is developed to reconstruct the system states with the system output, and then a sliding mode control law is synthesized based on the estimated states. The convergence of the observer and the asymptotic stability in probability of the controller based on sliding mode schemes are theoretically analysed and the effectiveness of the proposed control strategy is verified with numerical simulation studies.

Chapter 6. The mathematical model of a hover beam simulator is established under the analysis of the aerodynamics of the system; a fuzzy sliding mode controller is effectively employed to control the unstable and uncertain system with external disturbances.

Chapter 7. The adaptive fuzzy control strategy developed in **Chapter 3** is applied to the control of simulated robotic manipulators with no strict constraints or prior knowledge of the controlled plant.

Chapter 8. The dynamics of vehicle suspension systems is analysed using singular perturbation theory, and the control strategies based on fuzzy sliding mode schemes are exploited to improve the ride comfort and drive safety.

Chapter 9. The models of an AC servo motor, a two-container water tank and a position control system of a hydraulic cylinder are derived. Then the fuzzy PID control strategy and the SMC strategy are adopted to analyze the three kinds of dynamic systems.

The book is primarily intended for the researchers and students in background of control theory and control engineering who wish to extend their knowledge in developing new algorithms and applications. It is useful for the scientists in the field of artificial intelligence, complex dynamic systems, emerging/innovative modelling and control. This book will be helpful for practising engineers for achieving requested specifications in industrial modelling and control in a user-friendly prototype.

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Abbreviations

Abbreviation	Description
A	Attribute
ABC	Active Body Control
AFSMC	Adaptive Fuzzy Sliding Mode Control
ASMO	Adaptive Sliding Mode Observer
AVSS	Active Vehicle Suspension System
BSMC	Boundary Layer Sliding Mode Control
C	Condition
CVRSS	Continuously Variable Road Sensing Suspension
D	Definition
DOF	Degree of Freedom
DSMC	Discrete-time Sliding Mode Control
DVSC	Discrete-time Variable Structure Control
DVSS	Discrete-time Variable Structure System
EC	Evolutionary Computation
ECU	Electronic Control Unit
F	Feature
FBF	Fuzzy Basis Function
FL	Fuzzy Logic
FLC	Fuzzy Logic Control
FLS	Fuzzy Logic System
FSMC	Fuzzy Sliding Mode Control
FUA	Fuzzy Universal Approximation
GA	Genetic Algorithm
IQSM	Ideal Quasi Sliding Mode
L	Lemma
LQR	Linear Quadratic Regulator

Abbreviation	Description
M	Merit
ML	Machine Learning
MIMO	Multi-Input and Multi-Output
MISO	Multi-Input and Single-Output
NB	Negative Big
NC	Neural Computing
NFSMC	Neural-Fuzzy Sliding Mode Control
NN	Neural Network
NS	Negative Small
P	Property
PB	Positive Big
PID	Proportional, Integral and Derivative
PISMC	Proportional Integral Sliding Mode Controller
PR	Probabilistic Reasoning
PS	Positive Small
PVSS	Passive Vehicle Suspension System
QSM	Quasi Sliding Mode
QSMB	Quasi Sliding Mode Band
R	Remark
RM	Reaching Mode
SC	Soft Computing
SISO	Single-Input and Single-Output
SM	Sliding Mode
SMC	Sliding Mode Control
SS	Steady State
T-S	Takagi-Sugeno
TSFSMC	Takagi-Sugeno Fuzzy Sliding Mode Control
VSC	Variable Structure Control
VSS	Variable Structure System
VTOL	Vertical Take Off and Landing
ZE	ZEro
ZOH	Zero-Order Hold

Symbols

1. General

Symbol	Definition
c_i	Hurwitzian coefficient (or λ_i)
$\boldsymbol{c}$	Coefficient vector of Hurwitzian polynomial
$\boldsymbol{C}$	Coefficient matrix of Hurwitzian polynomial
$d(t)$	External disturbance
$e(t)$	Error between the reference and the feedback of the output of a system
$\boldsymbol{e}(t)$	Error vector between the reference and the feedback of the output of a system
$\boldsymbol{f}(\boldsymbol{x})$	System function
$\boldsymbol{F}(\boldsymbol{x})$	System function vector
$\boldsymbol{g}(\boldsymbol{x})$	System control gain (or $\boldsymbol{b}(\boldsymbol{x})$)
$\boldsymbol{G}(\boldsymbol{x})$	System control gain matrix
k	Discrete time instant
p	Laplace operator
$s(t)$	Sliding mode function (switching function)
$\boldsymbol{S}(t)$	Sliding mode vector $\boldsymbol{S}(t)=[s_1(t),\cdots,s_P(t)]^{\mathrm{T}}$
S	Sliding mode surface $S=\{\boldsymbol{x} \mid s(\boldsymbol{x})=0\}$
t	Time variable
Δt	Sampling time step (or T)
T_s	Simulation period
$u(t)$	System control input
$u_{eq}(t)$	Equivalent control
$u_s(t)$	Switching control
x	System state

Symbol	Definition
$\boldsymbol{x}$	System state vector
$\boldsymbol{X}_i$	Universe of discourse
y	System output
$\boldsymbol{y}$	System output vector
$y_d(t)$	Desired reference signal (or $x_d(t)$, $y_r(t)$)
$\boldsymbol{y}_d(t)$	Desired reference signal vector (or $\boldsymbol{y}_r(t)$)
γ	Adaptive rate
γ_x	Adaptive rate for a special parameter x
$\boldsymbol{\Gamma}$	Discrete time control gain, $\boldsymbol{\Gamma} \in R^{n\times m}$
η	Positive constant of sliding condition
$\mu(\boldsymbol{x})$	Fuzzy membership function of crisp variable $\boldsymbol{x}$
$\boldsymbol{\Phi}$	Discrete time transfer function, $\boldsymbol{\Phi} \in R^{n\times n}$

2. Helicopter aerodynamics

Symbol	Definition
A	Rotor disk area
C_P	Power coefficient of a rotor
C_Q	Shaft torque coefficient of a rotor
C_T	Thrust coefficient of a rotor
R	Rotor blade radius
T_h	Rotor thrust
v_c	Climb velocity
v_i	Induced inflow velocity
v_{tip}	Blade tip speed of a rotor
w	Weight of the helicopter
ϑ	Blade/rotor azimuth angle
λ_i	Induced inflow ratio
ρ	Density of fluid
ω	Rotation speed of a rotor

3. Robot manipulation

Symbol	Definition
a_i	Length of arm i
$\boldsymbol{C}^i$	Velocity coupling matrix for joint i
$f_c(\dot{\boldsymbol{q}})$	Coulomb friction

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Symbol	Definition
$\boldsymbol{h}$	Gravity loading vector
m_i	Mass of arm *i*
$\boldsymbol{M}(\boldsymbol{q})$	Inertia matrix
$M_{ii}(\boldsymbol{q})$	Moment of inertia at joint *i* axis
$M_{ij}(\boldsymbol{q})$	Effect of the acceleration of joint *i* on joint *j*
$N(\boldsymbol{q},\dot{\boldsymbol{q}})$	Vector of centripetal and Coriolis forces
$\boldsymbol{q}(t)$	Actual joint position vector
$\dot{\boldsymbol{q}}(t)$	Actual joint velocity vector
$\ddot{\boldsymbol{q}}(t)$	Actual joint acceleration vector
$\boldsymbol{q}_r(t)$	Reference joint position vector
$\dot{\boldsymbol{q}}_r(t)$	Reference joint velocity vector
$\ddot{\boldsymbol{q}}_r(t)$	Reference joint acceleration vector
$\boldsymbol{\tau}$	Arm torque vector

4. Vehicle suspension systems

Symbol	Definition
b_s	Damping coefficient
f_d	Damping force
f_s	Sprung spring force
f_t	Tyre force between unsprung mass and road
F_a	Hydraulic force of the actuator
F_f	Friction force
k_s	Spring stiffness for sprung mass
k_t	Spring stiffness for unsprung mass
m_s	Sprung mass
m_u	Unsprung mass
s_f	Sliding function for fast dynamic model
s_s	Sliding function for slow dynamic model
u_f	Fast control law
u_{feq}	Equivalent control law for fast dynamic model
u_s	Slow control law
u_{seq}	Equivalent control law for slow dynamic model
x_1	Suspension travel
x_2	Vehicle body velocity
x_3	Wheel deflection

Symbol	Definition
x_4	Wheel velocity
z_r	Road disturbance input
z_s	Displacement of car body
z_u	Displacement of wheel

5. Related mathematical symbols and operations

Symbol	Definition
R^+	Set of non-negative real numbers
$\boldsymbol{x} \in R^n$	n-vector
$\boldsymbol{A} \in R^{n \times m}$	$n \times m$ matrix
$(\bullet)^{\mathrm{T}}$	Transposition
$\overline{\lambda}(\boldsymbol{A})$	Maximum eigenvalue of a symmetric matrix $\boldsymbol{A}$
$\underline{\lambda}(\boldsymbol{A})$	Minimum eigenvalue of a symmetric matrix $\boldsymbol{A}$
$\lVert \boldsymbol{x} \rVert$	Length of a vector $\boldsymbol{x}$ or Euclidean norm, also called L^2 distance or L^2 norm
$\lVert \boldsymbol{x} \rVert_1$	Sum of absolute values of the vector or 1-norm of a vector
exp	Exponential function
C_0	Continuous function
C_1	Differentiable function
$\boldsymbol{I}_m$	Identity matrix with $m \times m$ dimension
Ω	Sample space
$\mathscr{F}$	σ-algebra of the subsets of the sample space
$\mathscr{P}$	Probability measure
$\mathscr{E}\{\bullet\}$	Expectation operator

Table of Contents

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