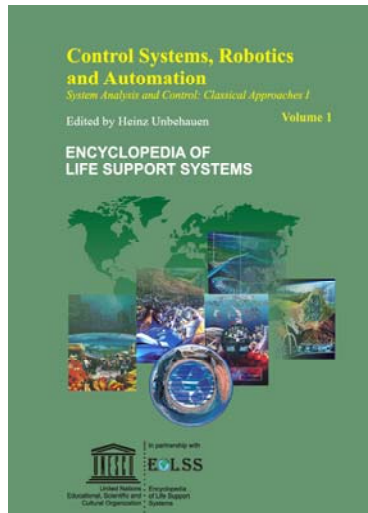


# CONTENTS

## CONTROL SYSTEMS, ROBOTICS, AND AUTOMATION



### **Control Systems, Robotics, and Automation Volume 1**

e-ISBN: 978-1-84826-140-2 (e-Book)

ISBN : 978-1-84826-590-5 (Print)

No. of Pages: 392.

### **Control Systems, Robotics, and Automation Volume 2**

e-ISBN: 978-1-84826-141-9 (e-Book)

ISBN : 978-1-84826-591-2 (Print)

No. of Pages: 416.

### **Control Systems, Robotics, and Automation Volume 3**

e-ISBN: 978-1-84826-142-6 (e-Book)

ISBN : 978-1-84826-592-9 (Print)

No. of Pages: 454.

### **Control Systems, Robotics, and Automation Volume 4**

e-ISBN: 978-1-84826-143-3 (e-Book)

ISBN : 978-1-84826-593-6 (Print)

No. of Pages: 434.

### **Control Systems, Robotics, and Automation Volume 5**

e-ISBN: 978-1-84826-144-0 (e-Book)

ISBN : 978-1-84826-594-3 (Print)

No. of Pages: 558.

### **Control Systems, Robotics, and Automation Volume 6**

e-ISBN: 978-1-84826-145-7 (e-Book)

ISBN : 978-1-84826-595-0 (Print)

No. of Pages: 524.

### **Control Systems, Robotics, and Automation Volume 7**

e-ISBN: 978-1-84826-146-4 (e-Book)

ISBN : 978-1-84826-596-7 (Print)

No. of Pages: 452.

### **Control Systems, Robotics, and Automation Volume 8**

e-ISBN: 978-1-84826-147-1 (e-Book)

ISBN : 978-1-84826-597-4 (Print)

No. of Pages: 458.

### **Control Systems, Robotics, and Automation Volume 9**

e-ISBN: 978-1-84826-148-8 (e-Book)

ISBN : 978-1-84826-598-1 (Print)

No. of Pages: 410.

### **Control Systems, Robotics, and Automation Volume 10**

e-ISBN: 978-1-84826-149-5 (e-Book)

ISBN : 978-1-84826-599-8 (Print)

No. of Pages: 332.

### **Control Systems, Robotics, and Automation Volume 11**

e-ISBN: 978-1-84826-150-1 (e-Book)

ISBN : 978-1-84826-600-1 (Print)

No. of Pages: 406.

**Control Systems, Robotics, and Automation Volume 12**

e-ISBN: 978-1-84826-151-8 (e-Book)

ISBN : 978-1-84826-601-8 (Print)

No. of Pages: 366.

**Control Systems, Robotics, and Automation Volume 13**

e-ISBN: 978-1-84826-152-5 (e-Book)

ISBN : 978-1-84826-602-5 (Print)

No. of Pages: 516.

**Control Systems, Robotics, and Automation Volume 14**

e-ISBN: 978-1-84826-153-2 (e-Book)

ISBN : 978-1-84826-603-2 (Print)

No. of Pages: 394.

**Control Systems, Robotics, and Automation Volume 15**

e-ISBN: 978-1-84826-154-9 (e-Book)

ISBN : 978-1-84826-604-9 (Print)

No. of Pages: 506.

**Control Systems, Robotics, and Automation Volume 16**

e-ISBN: 978-1-84826-155-6 (e-Book)

ISBN : 978-1-84826-605-6 (Print)

No. of Pages:524

**Control Systems, Robotics, and Automation Volume 17**

e-ISBN: 978-1-84826-156-3 (e-Book)

ISBN : 978-1-84826-606-3 (Print)

No. of Pages: 506

**Control Systems, Robotics, and Automation Volume 18**

e-ISBN: 978-1-84826-157-0 (e-Book)

ISBN : 978-1-84826-607-0 (Print)

No. of Pages: 566.

**Control Systems, Robotics, and Automation Volume 19**

e-ISBN: 978-1-84826-158-7 (e-Book)

ISBN : 978-1-84826-608-7 (Print)

No. of Pages: 496.

**Control Systems, Robotics, and Automation Volume 20**

e-ISBN: 978-1-84826-159-4 (e-Book)

ISBN : 978-1-84826-609-4 (Print)

No. of Pages: 320.

**Control Systems, Robotics, and Automation Volume 21**

e-ISBN: 978-1-84826-160-0 (e-Book)

ISBN : 978-1-84826-610-0 (Print)

No. of Pages: 344.

**Control Systems, Robotics, and Automation Volume 22**

e-ISBN: 978-1-84826-161-7 (e-Book)

ISBN : 978-1-84826-611-7 (Print)

No. of Pages: 342.

For more information of e-book and Print Volume(s) order, [please click here](#)  
Or contact : eolssunesco@gmail.com

# CONTENTS

Preface

xcviii

## VOLUME I

<b>Control Systems, Robotics, and Automation</b>	<b>1</b>
<i>Heinz Unbehauen, Control Engineering Division, Department of Electrical Engineering and Information Sciences, Ruhr University Bochum, Germany</i>	

1. Introduction
  - 1.1. What is a Dynamical System?
  - 1.2. Introductory Examples for Simple Closed-Loop Control Systems
  - 1.3. Block Diagram Representation
  - 1.4. Automatic and Manual Control
  - 1.5. Automation and Robotics
  - 1.6. Cybernetics
2. Feedforward and Feedback Control
  - 2.1. Feedforward or Open-Loop Control
  - 2.2. Feedback or Closed-Loop Control
  - 2.3. Some Simple Examples of Feedback Control Systems
  - 2.4. Elements of Feedback Control Systems
  - 2.5. Servomechanism, Regulator, and Process Control
  - 2.6. Continuous and Discontinuous Operation of Automatic Control Systems
3. Analysis and Design of Feedback Control Systems
  - 3.1. Describing the Dynamical Behavior of Systems
  - 3.2. Performance Objectives
  - 3.3. Controller Design
  - 3.4. Non-Standard Types of Control Systems
4. Higher-Level Control Systems
  - 4.1. Adaptive Control Systems
  - 4.2. Large-Scale Systems
  - 4.3. Control of Discrete-Event Systems and Hybrid Systems
  - 4.4. Supervisory Distributed Control Systems
  - 4.5. Fault Diagnosis and Fault-Tolerant Control Systems
5. Applications
  - 5.1. Control of Robot Manipulators
  - 5.2. Other Technical Applications
  - 5.3. Nontechnical Fields of Application
  - 5.4. Computational Tools for Application of Control Systems
6. History
7. Outlook on Some Trends in Future Research and Developments
8. Conclusions

<b>Elements of Control Systems</b>	<b>77</b>
<i>Ganti Prasada Rao, International Centre for Water and Energy Systems, Abu Dhabi, UAE</i>	

1. Introduction
2. System modeling
3. Mathematical models of dynamical systems
  - 3.1. Differential Equation Models for Lumped Parameter Systems in Continuous-time Domain
  - 3.2. State Space Description of Lumped Parameter Systems
  - 3.3. Time-invariant Linear Systems
  - 3.4. Discrete-time Systems or Sampled-Data Systems
  - 3.5. Block Diagram Representation and Simplification

- 3.6. Distributed Parameter Systems
- 3.7. Deterministic and Stochastic Systems
- 3.8. Non-linear Models and Linearization
- 3.9. Causal and Non-causal Systems
- 3.10. Stable and Unstable Systems
- 3.11. Single-Input-Single-Output (SISO) and Multiple-Input-Multiple-Output (MIMO) Systems
- 4. Systems control
  - 4.1. Open-loop Control
  - 4.2. Feedback Control
  - 4.3. Closed-loop Behavior of Control Systems
  - 4.4. Control Strategies

### **Basic Elements of Control Systems**

107

Ganti Prasada Rao, *International Centre for Water and Energy Systems, Abu Dhabi, UAE*

- 1. Dynamical Systems
- 2. Graphical Description of Systems
- 3. Open-loop Control and Closed-loop Control
- 4. Principal Functions of Control
- 5. The Basic Structure of Control Systems
- 6. Some Typical Examples of Control
  - 6.1. Voltage Control of a D.C. Generator
  - 6.2. Course Control of a Ship
  - 6.3. Liquid Level Control
  - 6.4. Control of a Heat Exchanger
- 7. A Brief Overview of the History of Control Systems

### **General Models of Dynamical Systems**

128

Ganti Prasada Rao, *International Centre for Water and Energy Systems, Abu Dhabi, UAE*

- 1. Mathematical Models
- 2. Dynamic and Static Behavior of Systems
- 3. System Properties
  - 3.1. Linear and Non-linear Systems
  - 3.2. Lumped and Distributed Parameter Systems
  - 3.3. Time-varying and Time-invariant Systems
  - 3.4. Systems with Continuous or Intermittent Action
  - 3.5. Systems with Deterministic or Stochastic Properties
  - 3.6. Causal and Non-causal Systems
  - 3.7. Stable and Unstable systems
  - 3.8. SISO and MIMO Systems

### **Description of Continuous Linear Time-Invariant Systems in Time-Domain**

143

Heinz Unbehauen, *Control Engineering Division, Department of Electrical Engineering and Information Sciences, Ruhr University Bochum, Germany*

Ganti Prasada Rao, *International Centre for Water and Energy Systems, Abu Dhabi, UAE*

- 1. Description by differential equations
  - 1.1. Electrical Systems
  - 1.2. Mechanical Systems
  - 1.3. Thermal systems
- 2. System description with reference to special signals
  - 2.1. Step and Impulse Response Functions
  - 2.2. The Convolution Integral
- 3. System description in state space

- 3.1. State Space Description for SISO Systems
- 3.2. State Space Description for MIMO Systems

### **Description of Continuous Linear Time-Invariant Systems in Frequency Domain** **164**

Unbehauen H, *Control Engineering Division, Department of Electrical Engineering and Information Sciences, Ruhr University Bochum, Germany*

1. Laplace Transformation
2. Fourier Transformation
3. Transfer Function of a Dynamical System
  - 3.1. Definition
  - 3.2. Poles and Zeros of  $G(s)$
  - 3.3. Transfer Functions of Interconnected Systems
  - 3.4. Relation between  $G(s)$  and the State-Space Representation
  - 3.5. The Complex G-Plane
4. Frequency-Response of a Dynamical System
  - 4.1. Definition
  - 4.2. Polar Plot Representation
  - 4.3. Bode-Diagram Representation
5. The Most Common Dynamical Systems
  - 5.1. Element with P-Action (Proportional Action or Gain)
  - 5.2. Element with I-Action (Integration)
  - 5.3. Element with D-Action (Differentiation)
  - 5.4. Element with PT1-Action (First-Order Lag Element)
  - 5.5. Element with PT2-action (Second-Order Lag Element)
  - 5.6. Bandwidth of a Dynamic System
  - 5.7. Minimum and Non-minimum Phase Systems

### **Closed-loop Behaviour of Continuous Linear Time-Invariant Systems** **190**

Unbehauen H, *Control Engineering Division, Department of Electrical Engineering and Information Sciences, Ruhr University Bochum, Germany*

1. Dynamic behavior of the closed-loop Control system
2. Sensitivity of feedback control systems to parameter variations
3. Stability
4. Steady-state error
5. ID controller and other standard controller types
6. Behavior of Standard Controllers in Closed-Loop Operation.

### **Stability Concepts** **207**

Alexander B. Kurzhanski, *Faculty of Computational Mathematics and Cybernetics, Moscow State University, Russia*

Irina F. Sivergina, *Institute of Mathematics and Mechanics of Ural Department of Russian Academy of Science, Russia*

1. The Definition of Stability
  - 1.1. Introduction
  - 1.2. The Concept of Liapunov's Stability
  - 1.3. The Second (Direct) Method of Liapunov
  - 1.4. Sylvester's Criterion
  - 1.5. Stability of Linear Systems
  - 1.6. Simplest Types of Stable Equilibrium States
  - 1.7. Stability in the First Approximation
  - 1.8. Stability under Persistent Disturbances
  - 1.9. Further Liapunov-Related Types of Stability

2. Stability Criteria for Linear Time-Invariant Systems
  - 2.1. The Routh Hurwitz Stability Criterion
  - 2.2. The Hermite Stability Criterion
  - 2.3. Kharitonov's Criterion
  - 2.4. Criterion of Leonhard-Mikhailov
  - 2.5. The Nyquist Stability Criterion

**Index** **239**

**About EOLSS** **245**

## VOLUME II

### **Classical Design Methods for Continuous LTI-Systems** **1**

R.T Stefani, *Department of Electrical Engineering, California State University, Long Beach, USA*

1. Introduction

### **Controller Design in Time-Domain** **5**

Unbehauen H, *Control Engineering Division, Department of Electrical Engineering and Information Sciences, Ruhr University Bochum, Germany*

1. Problem formulation
2. Time-domain performance specifications
  - 2.1. Transient Performance
  - 2.2. Integral Criteria
  - 2.3. Calculation of the ISE-Performance Index
3. Optimal controller settings subject to the ISE-criterion
  - 3.1. Example
  - 3.2. Optimal Settings for Combinations of PT<sub>n</sub>-Plants and Standard Controllers of PID Type
4. Empirical procedures
  - 4.1. Tuning Rules for Standard Controllers
    - 4.1.1. Ziegler-Nicols Tuning Rules
    - 4.1.2. Some Other Useful Tuning Rules
  - 4.2. Empirical Design by Computer Simulation
5. Mixed time- and frequency-domain design by standard polynomials
6. Concluding Remarks

### **Design in the Frequency Domain** **34**

Stefani R.T, *Department of Electrical Engineering, California State University Long Beach, USA*

1. Introduction
2. Gain and Phase Margins
  - 2.1. Gain Margin
  - 2.2. Phase Margin
  - 2.3. Examples
  - 2.4. Relationship Between PM and Damping Ratio
3. Types of Compensators
4. Design of PI and Lag Compensators
  - 4.1. Analysis of PI and Lag Compensators
  - 4.2. Design Rules for PI and Lag Compensators
  - 4.3. Example
5. Design of PD Compensators (Realized by Rate Feedback)

- 5.1. Analysis of PD Compensations
- 5.2. Design Rules for PD (Rate Feedback) Compensators
- 5.3. Example
- 6. Design of Lead Compensators
  - 6.1. Analysis of Lead Compensators
  - 6.2. Design Rules for Lead Compensators
  - 6.3. Example
- 7. Design of PID Compensators
  - 7.1. Analysis of PID Compensators
  - 7.2. Design Rules for PID Compensators
  - 7.3. Example
- 8. Design of Lag - Lead Compensators
  - 8.1. Analysis of Lag-Lead Compensators
  - 8.2. Design Rules for Lag-Lead Compensation
  - 8.3. Example

**PID Control****58**Araki M, *Kyoto University, Japan*

- 1. Introduction
- 2. Process Models
- 3. Performance Evaluation of PID Control Systems
- 4. Action Modes of PID Controllers
- 5. Design of PID Control Systems
  - 5.1. Selection of Action Mode
  - 5.2. Identification of Process Model Parameters
  - 5.3. Tuning of PID Parameters
- 6. Advanced Topics
  - 6.1. Windup of the Integral Element and Anti-Windup Mechanism
  - 6.2. Two-Degree-of-Freedom PID Controllers
  - 6.3. Sophisticated Models
  - 6.4. Other Tuning Methods for PID Parameters

**Internal Model Control****80**

Daniel E. Rivera, *Department of Chemical and Materials Engineering, Ira A. Fulton School of Engineering, Arizona State University, Tempe, Arizona 85287-6006, USA*  
 Melvin E. Flores, *Department of Chemical and Materials Engineering, Ira A. Fulton School of Engineering, Arizona State University, Tempe, Arizona 85287-6006, USA*

- 1. Introduction
- 2. The Internal Model Control Structure
  - 2.1. Closed-loop Transfer Functions for IMC
  - 2.2. Internal Stability
  - 2.3. Asymptotic closed-loop behavior (System Type)
  - 2.4. Performance Measures
- 3. Internal Model Control Design Procedure
  - 3.1. Requirements for Physical Realizability on the IMC Controller
  - 3.2. Limitations to Perfect Control: the Need for an IMC Design Procedure
  - 3.3. Statement of the IMC Design Procedure
- 4. Application of IMC design to Simple Models
  - 4.1. Example 1a: PI Tuning for A First-Order System
  - 4.2. Example 1b: PI Tuning for a First-Order System with RHP Zero
  - 4.3. Example 1c: PI with Filter Tuning for a First-Order System with LHP Zero
  - 4.4. Example 2: PID Tuning for a Second-Order System with RHP Zero
  - 4.5. Example 3: PID with Filter Tuning for a second-Order Model with RHP Zero
  - 4.6. Example 4: Dead-time Compensation for a First-Order with Delay Plant

- 4.7. IMC-PID Tuning Rules for Plants with Integrator Dynamics
- 5. IMC-PID tuning Rules for First-Order with Delay Plants
- 6. Additional IMC Design Topics

**Smith Predictor and its Modifications****109**Hang C. C, *Department of Electrical Engineering, National University of Singapore, Singapore.*

- 1. Introduction
- 2. Controller design
- 3. Performance comparison
- 4. Modification for high order systems
- 5. Modification for rapid load rejection
- 6. Modifications for open-loop unstable systems

**Digital Control Systems****127**Paraskevopoulos P.N, *National Technical University of Athens, Greece*

- 1. The Basic Structure of Digital Control Systems
- 2. Discrete-Time Systems
  - 2.1. Introduction
  - 2.2. Analysis of Linear Time-Invariant Discrete-Time Systems
- 3. Sampled-Data Systems
  - 3.1. Introduction
  - 3.2. Description and Analysis of Sampled-Data Systems
    - 3.2.1. Example 1
    - 3.2.2. Example 2
  - 3.3. Analysis of Sampled-Data Systems
- 4. Stability
  - 4.1. Definitions and Basic Theorems of Stability
    - 4.1.1. Introduction
    - 4.1.2. Stability of Linear, Time-Invariant, Discrete-Time Systems
    - 4.1.3. Bounded-Input, Bounded-Output Stability
  - 4.2. Stability Criteria
    - 4.2.1. The Routh Criterion using the Mobius Transformation
    - 4.2.2. Example 3
    - 4.2.3. The Jury Criterion
    - 4.2.4. Example 4
    - 4.2.5. Example 5
    - 4.2.6. Example 6
- 5. Controllability
  - 5.1. Example 7
  - 5.2. Example 8
- 6. Observability
  - 6.1. Example 9
- 7. Loss of Controllability and Observability due to Sampling
  - 7.1. Example 10
- 8. Kalman Decomposition

**Discrete-Time, Sampled-Data, Digital Control Systems, and Quantization Effects****152**Paraskevopoulos P.N, *National Technical University of Athens, Greece*

- 1. Discrete-Time Systems
  - 1.1. Introduction
  - 1.2. Properties of Discrete-Time Systems
    - 1.2.1. Linearity



- 1.2.2. Time-Invariant System
- 1.2.3. Causality
- 1.3. Description of Linear, Time-Invariant, Discrete-Time Systems
  - 1.3.1. Difference Equations
  - 1.3.2. Transfer Function
  - 1.3.3. Impulse Response or Weight Function
  - 1.3.4. State-Space Equations
- 1.4. Analysis of Linear, Time-Invariant, Discrete-Time Systems
  - 1.4.1. Analysis Based on the Difference Equation
  - 1.4.2. Analysis Based on the Transfer Function
  - 1.4.3. Analysis Based on the Impulse Response
  - 1.4.4. Analysis Based on the State Equations
- 2. Sampled-Data Systems
  - 2.1. Introduction
  - 2.2. D/A and A/D Converters
  - 2.3. Hold Circuits
  - 2.4. Description and Analysis of Sampled-Data Systems
    - 2.4.1. Analysis Based on the State Equations
    - 2.4.2. Analysis Based on  $H(kT)$
    - 2.4.3. Analysis based on  $H(z)$
- 3. Digital Control Systems
  - 3.1. Introduction
  - 3.2. Comparison between Digital and Continuous-Time Control Systems
- 4. Quantization Effects
  - 4.1. Introduction
  - 4.2. Truncation and Rounding

### **Discrete-Time Equivalents to Continuous-Time Systems**

176

Mohammed S. Santina, *Fellow, The Boeing Company, USA*  
 Allen R. Stubberud, *University of California Irvine, USA*

- 1. Introduction
- 2. Design of Discrete-Time Control Systems for Continuous-Time Plants
  - 2.1. Sampling and A/D Conversion
  - 2.2. Reconstruction and D/A Conversion
- 3. Discrete-Time Equivalents of Continuous-Time Plants
- 4. Discretizing Continuous-Time Controllers
  - 4.1. Numerical Approximation of Differential Equations
    - 4.1.1. Euler's Forward Method (One Sample)
    - 4.1.2. Euler's Backward Method (One Sample)
    - 4.1.3. Trapezoidal Method (Two Sample)
    - 4.1.4. An Example
    - 4.1.5. Mapping Between S and Z Planes Using Euler's and Tustin's Methods
    - 4.1.6. Frequency Response Approximations
    - 4.1.7. Bilinear Transformation with Frequency Prewarping
  - 4.2. Matching Step and Other Responses
  - 4.3. Pole-Zero Matching
- 5. Discretization of Continuous-Time State Variable Models
  - 5.1. Discrete-Time Models of Continuous-Time Systems
  - 5.2. Discrete-Time Approximations of Continuous-Time Systems

### **Design Methods for Digital Controllers, Sample-Rate**

217

Paraskevoudoulos P.N., *National Technical University of Athens, Greece*

- 1. Design Methods for Digital Controllers
  - 1.1. Introduction

- 1.2. Discrete-Time Controller Design Using Indirect Techniques
- 1.3. Direct Digital Controller Design via the Root-Locus Method
- 1.4. Direct Digital Controller Design Based on the Frequency Response
  - 1.4.1. Introduction
  - 1.4.2. Bode Diagrams
  - 1.4.3. Example 1
  - 1.4.4. Nyquist Diagrams
- 1.5. The PID Controller
- 1.6. State-Space Design Methods
- 1.7. Optimal Control
- 2. Sample Rate
  - 2.1. Introduction
  - 2.2. Example 2

**Real-Time Implementation****237**Ulrich Kiffmeier, *dSPACE GmbH, Technologiepark 25, 33100 Paderborn, Germany.*

- 1. Introduction
- 2. A Simple Real-Time System
- 3. Computational Delay and Jitter
- 4. Real-Time Integration of Continuous-Time States
- 5. Implementation on Fixed-Point Processors
- 6. Implementation on Floating-Point Processors
- 7. Real-Time Operating Systems
- 8. Intertask Communication in Multitasking Systems
- 9. Distributed Real-Time Systems
- 10. Time Triggered Systems for Safety Critical Applications
- 11. Development Tools for Real-Time Implementation

**Index****263****About EOLSS****269****VOLUME III****Design of State Space Controllers (Pole Placement) for SISO Systems****1**Lohmann, Boris, *Institut für Automatisierungstechnik, Universität Bremen, Germany*

- 1. Design Objective
- 2. General Remarks on State Space Design
- 3. System Class
- 4. Accompanying Example: Inverted Pendulum on Cart

**Description and Analysis of Dynamic Systems in State Space****14**Boris Lohmann, *Institut für Automatisierungstechnik, Universität Bremen, Germany*

- 1. Extraction of the State Space Representation from the Transfer Function  $G(s)$ 
  - 1.1. Solution 1: Control Canonical Form
  - 1.2. Solution 2: Observer Canonical Form
  - 1.3. Solution 3: Modal Canonical Form (Diagonal and Jordan Canonical Form)
- 2. Transformation to Diagonal Form
- 3. Solution of the State Equations
  - 3.1. Matrix Exponential

- 3.2. Solution of the State Equations by State Transition Matrix
- 3.3. Solution of the Homogeneous State Differential Equation from the Modal Canonical Form
- 4. Stability
- 5. Controllability and Observability
  - 5.1. Definition of Controllability
  - 5.2. Criteria of Controllability
  - 5.3. Definition of Observability
  - 5.4. Observability Criteria
  - 5.5. Interpretation of Controllability and Observability
  - 5.6. Controllability and Observability of eigenvalues
  - 5.7. Pole-Zero Cancellations
  - 5.8. Minimal Realization
- 6. Discrete Time Systems

**Controller Design****52**Boris Lohmann, *Institut für Automatisierungstechnik, Universität Bremen, Germany*

- 1. Objectives and Structure of State Feedback Control
- 2. Determination of the pre-compensator  $g$
- 3. Determination of the Controller  $k$ 
  - 3.1. Determination by Matching of Coefficients
  - 3.2. Determination from Control Canonical Form
  - 3.3. Determination by Transform to Control Canonical Form: Ackermann's Formula
  - 3.4. Design Parameters
- 4. Example: Inverted Pendulum
- 5. Discrete-Time State Feedback and Dead-Beat Behavior

**Observer Design****72**Boris Lohmann, *Institut für Automatisierungstechnik, Universität Bremen, Germany*

- 1. Objectives and Structure of the State Observer
- 2. Design of the Observer
  - 2.1. Observer Design by Matching of Coefficients
  - 2.2. Observer Design by State-Feedback Design Procedure
  - 2.3. Design Parameters
- 3. Example: Inverted Pendulum
- 4. The Observer in Closed-Loop Control- The Separation Principle
- 5. Reduced Order Observer
  - 5.1. Example
- 6. Discrete- Time Observers

**Extended Control Structures****90**Boris Lohmann, *Institut für Automatisierungstechnik, Universität Bremen, Germany*

- 1. Steady State Behaviour under realistic assumptions
  - 1.1. External Disturbances
  - 1.2. Model Uncertainty and Parameter Variations
- 2. PI- State Feedback Control
  - 2.1. Structure and Design
  - 2.2. Properties and Further Extensions
- 3. Model-based dynamic pre-compensator
  - 3.1. Structure and Design
  - 3.2. Combination with PI-state-feedback

**Basic Nonlinear Control Systems** 101D. P. Atherton, *University of Sussex, UK*

1. Introduction
2. Forms of nonlinearity
3. Structure and behaviour
4. Stability
5. Aspects of design
6. Conclusions

**Describing Function Method** 109D. P. Atherton, *University of Sussex, UK*

1. Introduction
2. The Sinusoidal Describing Function
3. The Evaluation of some DFs
4. Limit Cycles and Their Stability
5. DF Accuracy
6. Some Examples of DF Usage
  - 6.1. Feedback Loop Containing a Relay with Dead Zone
  - 6.2. Autotuning in Process Control
7. Closed Loop Frequency Response
8. Compensator Design
9. Additional Aspects
10. Conclusions

**Second Order Systems** 129D P Atherton, *University of Sussex, UK*

1. Introduction
2. Basic Principles
3. Analysis Using the Phase Plane
  - 3.1. Example 1
  - 3.2. Example 2
  - 3.3. Example 3
4. Conclusions

**Stability Theory** 142Peter C. Müller, *University of Wuppertal, Germany*

1. Introduction
2. Linearization: Stability in the First Approximation
3. The Direct Method of Lyapunov
  - 3.1. Nonlinear Systems
  - 3.2. Linear Systems

**Popov and Circle Criterion** 154Peter C. Müller, *University of Wuppertal, Germany*

1. Introduction
2. Kalman-Yakubovich-Lemma
3. Criteria for Absolute Stability

**Control by Compensation of Nonlinearities****165**Gang Tao, *Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA 22903, USA*Avinash Taware, *GE Global Research Center, Schenectady, NY 12309, USA*

1. Introduction
2. Plants with Actuator Nonlinearities
3. Parameterized Inverses
4. State Feedback Designs
5. Output Feedback Inverse Control
6. Output Feedback Designs
7. Designs for Unknown Linear Dynamics
8. Designs for Multivariable Systems
9. Designs for Nonlinear Dynamics
10. Neural Network based Adaptive Inverse Compensation
11. An illustrative Example
12. Concluding Remarks

**Estimation and Compensation of Nonlinear Perturbation by Disturbance Observers****217**Peter C. Müller, *University of Wuppertal, Germany*

1. Introduction
2. Problem Statement
3. Theory
  - 3.1. Estimation of Nonlinearities
    - 3.1.1. Comments on The Observability Condition
    - 3.1.2. Choice of Fictitious Model
    - 3.1.3. PI-observer
  - 3.2. Convergence and Estimation Errors
    - 3.2.1. High Gain Proof
    - 3.2.2. Estimation Errors
    - 3.2.3. Lyapunov Approach
  - 3.3. Compensation of Nonlinearities
  - 3.4. Closed-Loop Control System
4. Applications

**Anti Windup and Override Control****228**Adolf Hermann Glattfelder, *Automatic Control Laboratory, ETH Zürich, Switzerland*Walter Schaufelberger, *Automatic Control Laboratory, ETH Zürich, Switzerland*

1. Introduction
  - 1.1. Control Systems with Input Constraints
  - 1.2. Control Systems with Mode Switch
  - 1.3. Control Systems with Output Constraints
  - 1.4. Design Approaches
2. PI-Control with Input Saturations
  - 2.1. Problem Statement and Test Cases
  - 2.2. The Reset Windup Effect
  - 2.3. Anti Windup Structures
  - 2.4. Transient Responses for the Test Cases
  - 2.5. Stability Properties
  - 2.6. Stability Analysis of the Test Cases
  - 2.7. Summary
3. Plants of dominant Second Order
  - 3.1. Problem Statement
  - 3.2. The Plant Windup Effect

- 3.3. Stability Properties
- 3.4. Anti Plant Windup Structures
- 3.5. Extensions
- 3.6. Summary
- 4. Output Constrained Control
  - 4.1. Basic Concepts
  - 4.2. Stability Analysis
  - 4.3. An Example
  - 4.4. Summary
- 5. Conclusion and Outlook

**Gain-Scheduling****273**D.J.Leith, *Hamilton Institute, NUI Maynooth/University of Strathclyde, Ireland*WE.Leithead, *Hamilton Institute, NUI Maynooth/University of Strathclyde, Ireland*

- 1. Introduction
- 2. Linearization Theory
  - 2.1. Series Expansion Linearization about a Single Trajectory or Equilibrium Point
  - 2.2. Series expansion linearization families
  - 2.3. Off-equilibrium linearizations
- 3. Divide and Conquer Gain-Scheduling Design
  - 3.1. Classical gain-scheduling design
  - 3.2. Neural/fuzzy gain-scheduling
  - 3.3. Gain-scheduling using off-equilibrium linearizations
- 4. LPV Gain-Scheduling
  - 4.1. LPV systems
  - 4.2. Small-gain LFT approaches
  - 4.3. Lyapunov-based LPV approaches
    - 4.3.1. Quadratic Lyapunov function approaches
    - 4.3.2. Parameter-dependent Lyapunov function approaches
- 5. Outlook

**Index****301****About EOLSS****307****VOLUME IV****Modeling and Simulation of Dynamic Systems****1**Inge Troch, *Vienna University of Technology, Austria*Felix Breitenacker, *Vienna University of Technology, Austria*

- 1. Introduction
- 2. Systems, Processes and Models
- 3. Simulation
- 4. Classification of Systems and Models
  - 4.1. Properties of Systems and Models
  - 4.2. Properties of Models only
  - 4.3. Some Additional Remarks on the Properties 'Static' and 'Dynamic'
- 5. Modeling
  - 5.1. Some General Considerations
    - 5.1.1. Modeling and Modeler
    - 5.1.2. Modeling and Modeling Goals
    - 5.1.3. Model Structure

- 5.1.4. Model Complexity
- 5.2. Verification and Validation
- 5.3. Numerical Aspects
- 5.4. System Structure and Model Structure
- 5.5. System Descriptions and Relations between Models
- 6. A Short History of Simulation
  - 5.6. Continuous-time Simulation
  - 5.7. Discrete-event Simulation

### **Some Basics in Modeling of Mechatronic Systems**

44

Andreas Kugi, *Chair of System Theory and Automatic Control, Saarland University, Germany*

- 1. Introduction
- 2. System Variables and System Elements
  - 2.1. Energy Storage Elements
    - 2.1.1. Generalized Kinetic Energy
    - 2.1.2. Generalized Potential Energy
    - 2.1.3. The General Case
  - 2.2. Coupling Elements
    - 2.2.1. Electromechanical Example - Solenoid Valve
    - 2.2.2. Hydromechanical Example - Hydraulic Piston Actuator
  - 2.3. Static Elements
    - 2.3.1. Mechanical Example - The Rayleigh Dissipation Function
- 3. Kirchhoff Networks
  - 3.1. Kirchhoff's Laws
  - 3.2. Tellegen's Theorem
  - 3.3. Fundamental Matrices
- 4. Port-Hamiltonian Systems
  - 4.1. Electromechanical Example - Solenoid Valve
  - 4.2. Hydromechanical Example - Hydraulic Piston Actuator

### **Modeling and Simulation of Distributed Parameter Systems**

85

A. Vande Wouwer, *Faculté Polytechnique de Mons, Belgium*

- 1. Introduction
- 2. Modeling of distributed parameter systems
  - 2.1. Model Derivation Basic Principles
  - 2.2. More PDEs – Classifications
    - 2.2.1. PDE order
    - 2.2.2. Linearity, Quasilinearity and Nonlinearity
    - 2.2.3. Elliptic, parabolic and hyperbolic PDEs
    - 2.2.4. Convection - Diffusion (Dispersion) - Reaction PDEs
    - 2.2.5. Boundary conditions
  - 2.3. Parameter Estimation
  - 2.4. Model simplification and reduction
- 3. Simulation of distributed parameter systems
  - 3.1. Analytical solution procedures
  - 3.2. Spectral methods and weighted residual approximations
  - 3.3. Spatial discretization
  - 3.4. Time integration
  - 3.5. Early versus Late Lumping

### **Modeling and Simulation of Large-Scale Hybrid Systems**

109

Manuel A. Pereira Remelhe, *Universität Dortmund, Germany.*  
 Sebastian Engell, *Universität Dortmund, Germany.*

1. Introduction
2. General Concepts
3. System Representations and Software Tools
  - 3.1. Representations of Discrete Event and Continuous Systems
  - 3.2. Representations for Hybrid Systems
4. Object-oriented Modeling of Physical Systems
  - 4.1. Hybrid Elements
  - 4.2. Hybrid Systems Arising from Physical Abstractions
  - 4.3. Equation-Based Modeling of Discrete Event Systems
5. Integration of Complex Discrete Event and Object-Oriented Models
  - 5.1. Modeling Aspects
  - 5.2. Numerical Aspects
6. Ongoing Research and Future Challenges

### **Modeling and Simulation of Dynamic Systems using Bond Graphs**

129

Peter C. Breedveld, *University of Twente, Enschede, NL.*

1. Introduction
2. Early history
3. Modeling and simulation of dynamic behavior of physical systems
4. Key aspects of the port-based approach
5. Bond Graph Notation
  - 5.1. Introduction
  - 5.2. Node types
  - 5.3. Constitutive relations
  - 5.4. Relation to other representations
  - 5.5. Systematic conversion of a simple electromechanical system model into a bond graph representation
  - 5.6. Causality
    - 5.6.1. Notation
    - 5.6.2. Causal port properties
    - 5.6.3. Causality assignment
    - 5.6.4. Conversion of a causal bond graph into a block diagram
    - 5.6.5. Causal paths
    - 5.6.6. Generation of a set of mixed algebraic and differential equations
    - 5.6.7. Linear analysis
      - 5.6.7.1. Introduction
      - 5.6.7.2. Impedance analysis using bond graphs
  - 5.7. Hierarchical modeling
    - 5.7.1. Word bond graphs
    - 5.7.2. Multibonds
    - 5.7.3. Multiport generalizations
6. Port-based modeling and simulation of dynamic behavior of physical systems in terms of bond graphs: a simple example
7. Future trends

### **Rapid Prototyping for Model, and Controller Implementation**

175

Peter Schwarz, *Fraunhofer Institute for Integrated Circuits IIS, Design Automation Division EAS Dresden, Germany*

Jörg Uhlig, *Institute of Automation and Computer Control, Ruhr-University Bochum, Germany*

1. Definition of Rapid Prototyping
2. Goals
3. General solution
  - 3.1. Implementation in Software
  - 3.2. Implementation in Hardware



- 3.3. Real-time simulation, Hardware-in-the-loop (HIL)
- 4. Simulation acceleration
- 5. Conclusions

**Modeling Languages for Continuous and Discrete Systems****198**

Peter Schwarz, *Fraunhofer Institute for Integrated Circuits IIS, Design Automation Division EAS Dresden, Germany*

- 1. Aims of Modeling Languages
- 2. Historical background
- 3. A Modeling Approach
  - 3.1. Physical background
  - 3.2. The Multi-Port Approach
- 4. Modeling Languages
  - 4.1. VHDL-AMS
  - 4.2. Modelica
- 5. A comparison of VHDL-AMS and Modelica
- 6. Conclusions

**Simulation Software - Development and Trends****233**

F. Breitenecker, *Vienna University of Technology Vienna, Austria*  
 I. Troch, *Vienna University of Technology Vienna, Austria*

- 1. Introduction
- 2. Continuous Roots of Simulation
- 3. CSSL Structure in Continuous Simulation
  - 3.1. Structure of the Model Frame
  - 3.2. Requirements for the Experimental Frame
- 4. Numerical Algorithms in Simulation Systems
- 5. Simulation Software and CACSD Tools
- 6. Analysis Methods in Simulation Systems
- 7. Implicit Models -Algebraic Loops -Differential-Algebraic Equations
- 8. Discrete Elements in Continuous Modeling and Simulation
- 9. Hybrid modeling and simulation - Combined Modeling and Simulation
- 10. Simulation in Specific Domains
- 11. Developments beyond CSSL
- 12. Discrete Event Simulation
  - 12.1. Statistic Roots and Events
  - 12.2. Modeling Concepts in Discrete Simulation
  - 12.3. Random Number Generators
- 13. Object-oriented Approaches to Modeling and Simulation
- 14. Choice and Comparison of Simulation Software
  - 14.1. Hints for Simulator Choice
  - 14.2. Comparison of Simulation Tools
- 15. Conclusion

**Index****281****About EOLSS****287**

## VOLUME V

### Frequency Domain System Identification 1

J. Schoukens, *Department ELEC, Vrije Universiteit Brussel, Belgium*

R. Pintelon, *Department ELEC, Vrije Universiteit Brussel, Belgium*

1. Introduction
2. A brief introduction to identification
  - 2.1. Basic Steps in the Identification Process
    - 2.1.1. Collect Information about the System
    - 2.1.2. Select a Model Structure to represent the System
    - 2.1.3. Match the selected Model to the Measurements
    - 2.1.4. Validate the selected Model
    - 2.1.5. Conclusion
  - 2.2. Description of the Stochastic Behavior of Estimators: What can be expected from a good Estimator?
    - 2.2.1. Location Properties: Unbiased and Consistent Estimates
    - 2.2.2. Dispersion Properties: Efficient Estimators
  - 2.3. A Statistical Approach to the Estimation Problem
    - 2.3.1. Least Squares Estimation
    - 2.3.2. Weighted Least Squares Estimation
    - 2.3.3. The Maximum Likelihood Estimator
3. System Identification: problem statement
  - 3.1. Experiment Setup
    - 3.1.1. Choice of the Setup: ZOH <math>\llcorner</math> BL
    - 3.1.2. Choice of the Excitation Signals
  - 3.2. Choice of a model structure
    - 3.2.1. Plant Model
    - 3.2.2. Noise Models
  - 3.3. Match the Model to the Data
    - 3.3.1. The Errors-in-variables Formulation
    - 3.3.2. Differences and Similarities with the ‘Classical’ Time Domain Identification Framework
  - 3.4. Model Selection and Validation
4. Time and frequency domain identification
  - 4.1. Time and Frequency Domain Identification: Equivalencies
    - 4.1.1. Initial Conditions: Transient versus Leakage Errors
    - 4.1.2. Windowing in the Frequency Domain, (non causal) Filtering in Time Domain
  - 4.2. Time and Frequency Domain Identification: Differences
    - 4.2.1. Choice of the Model
    - 4.2.2. Unstable Plants
    - 4.2.3. Noise Models: Parametric or Non-parametric Noise Models
    - 4.2.4. Extended Frequency Range: Combination of Different Experiments
    - 4.2.5. The Errors-in-variables Problem
5. Selection of an identification scheme
  - 5.1. Questions
    - 5.1.1. Application?
    - 5.1.2. Domain?
    - 5.1.3. Excitation?
    - 5.1.4. Noise?
  - 5.2. Advices

### Measurements of Frequency Response Functions 45

J. Schoukens, *Department ELEC, Vrije Universiteit Brussel, Belgium*

R. Pintelon, *Department ELEC, Vrije Universiteit Brussel, Belgium*

1. Introduction
2. An introduction to the discrete Fourier transform
  - 2.1. The Sampling Process
  - 2.2. The Discrete Fourier Transform (DFT-FFT)
    - 2.2.1. Discretization in Time
    - 2.2.2. Windowing
    - 2.2.3. Discretization in Frequency
    - 2.2.4. The DFT-expressions
  - 2.3. DFT-properties of Periodic Signals
    - 2.3.1. Integer Number of Periods Measured
    - 2.3.2. No Integer Number of Periods Measured
  - 2.4. DFT of Burst Signals
  - 2.5. Conclusion
3. Spectral representation of periodic signals
4. Analysis of FRF measurements using periodic excitations
  - 4.1. Measurement Setup
  - 4.2. Error Analysis
    - 4.2.1. Bias Error on the FRF
    - 4.2.2. Variance Analysis of the FRF
5. Reducing FRF measurement errors for periodic excitations
  - 5.1. Basic Principles
  - 5.2. Processing Repeated Measurements
  - 5.3. Improved Averaging Methods for Non-synchronized Measurements
  - 5.4. Coherence
6. FRF measurements using random excitations
  - 6.1. Basic Principles
  - 6.2. Reducing the Noise Influence
    - 6.2.1. Systematic Errors
    - 6.2.2. Variance
  - 6.3. Leakage Errors
7. FRF measurements of multiple input multiple output systems
8. Guidelines for FRF measurements
  - 8.1. Advice 1: Use periodic excitations
  - 8.2. Advice 2: Select the best FRF estimator
    - 8.2.1. Periodic Excitations
    - 8.2.2. Random Excitations
  - 8.3. Advice 3: Pretreatment of data
9. Conclusions

### Estimation with Unknown Noise Model

79

R. Pintelon, *Department ELEC, Vrije Universiteit Brussel, Belgium*  
 J. Schoukens, *Department ELEC, Vrije Universiteit Brussel, Belgium*

1. Introduction
  - 1.1. Frequency Domain Data
  - 1.2. Plant Model
  - 1.3. Noise Model
2. Estimation Algorithms – General
  - 2.1. General Form of Cost Functions
  - 2.2. Minimization of Cost Functions
  - 2.3. Quick Tools to Analyze Estimators
  - 2.4. Asymptotic Properties
3. Estimation Algorithms – Specific
  - 3.1. Linear Least Squares
  - 3.2. Nonlinear Least Squares
  - 3.3. Total Least Squares Algorithms
    - 3.3.1. Introduction - Practical Implementation

- 3.3.2. Total Least Squares
- 3.3.3. Generalized Total Least Squares
- 3.4. Maximum Likelihood
- 3.5. Approximate Maximum Likelihood
  - 3.5.1. Introduction
  - 3.5.2. Iterative Quadratic Maximum Likelihood
  - 3.5.3. Bootstrapped Total Least Squares
- 3.6. Subspace Algorithms
- 4. Illustration and Overview of the Properties
  - 4.1. Real Measurement Example
  - 4.2. Overview of the Properties
- 5. Extensions
  - 5.1. Systems with Time Delay
  - 5.2. Identification in Feedback
  - 5.3. High Order Systems
- 6. Model Selection - Model Validation
  - 6.1. Detection of Undermodeling
  - 6.2. Detection of Overmodeling
  - 6.3. Whiteness Test on Residuals
  - 6.4. Model Validation
  - 6.5. Conclusion - Illustration

#### Frequency Domain Subspace Algorithms

115

R. Pintelon, *Department ELEC, Vrije Universiteit Brussel, Belgium*  
 J. Schoukens, *Department ELEC, Vrije Universiteit Brussel, Belgium*

- 1. Introduction
- 2. Model equations
  - 2.1. Plant Model
  - 2.2. Noise Model
- 3. Subspace algorithms
  - 3.1. Algorithm for Discrete-time Systems
  - 3.2. Algorithm for Continuous-time Systems
  - 3.3. Asymptotic Properties
- 4. Practical remarks
- 5. Simulation examples
  - 5.1. Continuous-time System
  - 5.2. Discrete-time System
- 6. Real measurement example

#### Estimation with Unknown Noise Model

134

R. Pintelon, *Department ELEC, Vrije Universiteit Brussel, Belgium*  
 J. Schoukens, *Department ELEC, Vrije Universiteit Brussel, Belgium*

- 1. Introduction
  - 1.1. Problem Statement
  - 1.2. Noise Model
- 2. Estimation algorithms
  - 2.1. Maximum Likelihood
  - 2.2. Generalized Total Least Squares
  - 2.3. Bootstrapped Total Least Squares
  - 2.4. Subspace Algorithms
  - 2.5. Instrumental Variables
- 3. Overview and Illustration of the properties
  - 3.1. Overview of the Properties
  - 3.2. Simulation Example

- 3.3. Real Measurement Example
4. Identification of parametric noise models
5. Identification in feedback
6. Model selection

**Modal Analysis****157**

Patrick Guillaume, *Department of Mechanical Engineering, Acoustics & Vibration Research Group, Vrije Universiteit Brussel, Belgium.*

1. Introduction
2. The “Modal” Model
  - 2.1. Single Degree of Freedom
  - 2.2. Multiple Degrees of Freedom
    - 2.2.1. Mode Shapes and Operating Deflection Shapes
    - 2.2.2. Observability and Controllability of Modes
3. Frequency-Domain Identification of Modes
  - 3.1. Least Squares Estimation
    - 3.1.1. Common-Denominator Model
    - 3.1.2. Linearity in the Parameters
    - 3.1.3. Reduced Normal Equations
    - 3.1.4. Fast Implementation of the Reduced Normal Equations
    - 3.1.5. Solving the Reduced Normal Equations
    - 3.1.6. Stabilization chart
  - 3.2. Maximum Likelihood Estimation
    - 3.2.1. Gauss-Newton Optimization
    - 3.2.2. Confidence Intervals
4. Application
5. Conclusion

**Identification of Linear Systems in Time Domain****176**

Torsten Söderström, *Uppsala University, Sweden*

1. What Is System Identification?
  - 1.1. The Need of Mathematical Models
  - 1.2. Classification of Models
  - 1.3. Mathematical Modeling
  - 1.4. Applying System Identification
2. The Setup
  - 2.1. Some Basic Concepts
  - 2.2. Identifiability
3. Identification Methods
  - 3.1. Least Squares Method
  - 3.2. Instrumental Variable Methods
    - 3.2.1. The Basic Case
    - 3.2.2. Extended IV Methods
    - 3.2.3. Consistency Analysis
    - 3.2.4. Asymptotic Distribution
  - 3.3. Prediction Error Methods
    - 3.3.1. Description
    - 3.3.2. Properties
  - 3.4. Subspace Identification Methods
4. Recursive Identification Algorithms
  - 4.1. Real-Time Algorithms
5. Identification for Control
6. Continuous-Time Identification

**Least Squares and Instrumental Variable Methods****206**Tomas McKelvey, *Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

1. Introduction
2. Models as predictors
  - 2.1. Linearly Parameterized Predictors
3. Estimating the model parameters
  - 3.1. Solving the Least Squares Problem
4. Stochastic analysis
  - 4.1. Preliminaries
  - 4.2. Deterministic Regressors
  - 4.3. Stochastic Regressors
5. Instrumental variable method
6. Computing the estimate
7. Multivariable systems
8. Optimal weighted LS estimator

**Prediction Error Methods****230**Torsten Söderström, *Department of Systems and Control, Information Technology, Uppsala University, Uppsala, Sweden*

1. Description
  - 1.1. Introduction
  - 1.2. General Linear Dynamic Models
    - 1.2.1. Introduction
    - 1.2.2. ARMAX Models
    - 1.2.3. State Space Models
  - 1.3. Optimal Prediction
  - 1.4. Interpretations
  - 1.5. Implementation Aspects
    - 1.5.1. Optimization
    - 1.5.2. Evaluation of Gradients
  - 1.6. Extensions
    - 1.6.1. Prefiltering of Data
    - 1.6.2. Modified Criterion Function
    - 1.6.3. Using Multistep Prediction Errors
2. Properties
  - 2.1. Identifiability
  - 2.2. Convergence and Consistency
  - 2.3. Asymptotic Accuracy and Distribution
  - 2.4. Model Approximation

**Subspace Identification Methods****253**Katrien De Cock, *K.U. Leuven, Department of Electrical Engineering (ESAT-SCD), Belgium*  
Bart De Moor, *K.U. Leuven, Department of Electrical Engineering (ESAT-SCD), Belgium*

1. Introduction
  - 1.1. State Space Models
  - 1.2. The Basic Idea behind Subspace Identification Algorithms
2. Notation
  - 2.1. Block Hankel Matrices and State Sequences
  - 2.2. Model Matrices
3. Geometric Tools
  - 3.1. Orthogonal Projections
  - 3.2. Oblique Projections

4. Deterministic subspace identification
  - 4.1. Calculation of a State Sequence
  - 4.2. Computing the System Matrices
5. Stochastic subspace identification
  - 5.1. Calculation of a State Sequence
  - 5.2. Computing the System Matrices
6. Combined deterministic-stochastic subspace identification algorithm
  - 6.1. Calculation of a State Sequence
  - 6.2. Computing the System Matrices
  - 6.3. Variants
7. Comments and perspectives
8. Software

**Recursive Algorithms****285**

Han-Fu Chen, *Institute of Systems Science, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, P. R. China.*

1. Introduction
2. Recursive Algorithm for Constant Coefficients
  - 2.1. Least Squares (LS)
  - 2.2. Extended Least Squares (ELS)
  - 2.3. RLS with Forgetting Factors
  - 2.4. Instrumental Variables Estimate
  - 2.5. Stochastic Approximation Estimate
  - 2.6. Stochastic Gradient Algorithm
  - 2.7. Recursive Algorithms Derived From Off-Line Identification
3. Convergence of Estimates
4. Time-Varying Systems
5. Concluding Remarks

**Identification for Control****302**

Paul M.J. Van den Hof, *Delft University of Technology, The Netherlands.*  
 Raymond A. de Callafon, *University of California, San Diego, USA.*

1. Introduction
  - 1.1. Relation between modeling and control
  - 1.2. When is a model good for feedback control?
2. Identification of approximate models
  - 2.1. Prediction error identification
  - 2.2. Closed-loop process-model mismatch
  - 2.3. Identification of control-relevant approximate models
3. Identification from closed-loop data
4. Iterative Identification and Control
5. Extensions
6. Conclusions

**Continuous-Time Identification****319**

Rolf Johansson, *Department of Automatic Control, Lund Institute of Technology, Lund University, Sweden*

1. Introduction
2. A model transformation
  - 2.1. Parameter Transformations
3. Noise Modeling
4. Parameter Estimation
  - 4.1. Numerical Iterative Optimization

5. Statistical Consistency and Convergence
  - 5.1. Orthogonalization and Numerical Aspects
6. Discussion and Conclusions

### **Identifiability of Linear Closed-Loop Systems**

340

G. Bretthauer, *Institute for Applied Computer Science, Karlsruhe Research Center, Germany*

M. Kaufmann, *Institute for Applied Computer Science/Automatic Control, University of Karlsruhe (TH), Germany*

1. Introduction
2. Identifiability Concepts
  - 2.1. Deterministic Identifiability
  - 2.2. Stochastic Identifiability
  - 2.3. Structural Identifiability
  - 2.4. System Identifiability
  - 2.5. Strong System Identifiability
  - 2.6. Parameter Identifiability
3. Identifiability Conditions for Closed-Loop Systems -A Short Overview
  - 3.1. SISO Systems
  - 3.2. MIMO systems
4. Complete and Partial I/O-Identifiability of Multivariable Closed-Loop Systems
  - 4.1. Motivation
  - 4.2. Definition of complete and partial I/O-identifiability
  - 4.3. Results
5. Conclusions

### **Relations between Time Domain and Frequency Domain Prediction Error Methods**

366

Tomas McKelvey, *Signal Processing, Dept. of Signals and Systems, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

1. Introduction
  - 1.1. Problem Formulation
  - 1.2. Frequency Domain System Relations
2. Prediction error methods
  - 2.1. Time Domain
  - 2.2. Frequency Domain
    - 2.2.1. Asymptotic Properties
  - 2.3. A Comparison
  - 2.4. Closed Loop
  - 2.5. Frequency Domain ARX Case
    - 2.5.1. ARX Example
3. Discussion
4. Numerical example
5. Conclusions

### **Identification of Time Varying Systems**

384

Peter Young, *Centre for Research on Environmental Systems and Statistics, Lancaster University, U.K., and Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia*

1. Introduction
2. Simple Limited Memory Algorithms
3. Modeling the Parameter Variations: The Dynamic Transfer Function (DTF) Model
  - 3.1. Optimization of the Hyperparameters
4. Illustrative Examples
  - 4.1. A Simulation Example



- 4.2. A Real Data Example
- 5. Conclusions

**Index** **405**

**About EOLSS** **411**

## VOLUME VI

**Identification of Nonlinear Systems** **1**

H. Unbehauen, *Ruhr University Bochum, Germany*

1. Introduction
2. Parametric Models
  - 2.1. Regression Models
    - 2.1.1. Kolmogorov-Gabor (KG-) Polynomial Model
    - 2.1.2. Basis Function Network Models
      - 2.1.2.1. The Basic Idea
      - 2.1.2.2. Nonlinear Network Model Structures
  - 2.2. Input-Output Models Based on Nonlinear Differential Equations
  - 2.3. Nonlinear State-Space Models
    - 2.3.1. State-Space Modeling by Filtering
    - 2.3.2. Sliding Mode System Reference Adaptive Model (SRAM)
    - 2.3.3. Subspace Models
3. Nonparametric Models
  - 3.1. The Volterra Series Model
  - 3.2. The Wiener Kernel Model
  - 3.3. Generalized Frequency Response Models
  - 3.4. Other Types of Nonparametric Models
    - 3.4.1. Step Response Model
    - 3.4.2. Phase Plane Model
    - 3.4.3. Non-parametric State Dependent Parameter Model
4. Semi-Parametric Models
  - 4.1. Fuzzy Models
    - 4.1.1. Mamdani-Model
    - 4.1.2. Takagi-Sugeno-Model
  - 4.2. Neuro-Fuzzy (NF-) Models
5. Specific Nonlinear Models
  - 5.1. Block-oriented Models
    - 5.1.1. Hammerstein Model
    - 5.1.2. Wiener Model
    - 5.1.3. Other Block-oriented Models
  - 5.2. The Bilinear Model
6. Signal Dependent Parameter Models
7. Identification Methods
  - 7.1. Estimation of Model Parameters
    - 7.1.1. Parameter Estimation for LIP-Type Models
    - 7.1.2. Parameter Estimation for Non-LIP-Type Models
      - 7.1.2.1. Prediction Error Methods
      - 7.1.2.2. Numerical Search Methods
  - 7.2. Estimation of Model Structure
  - 7.3. Model Validation
8. Critical Valuation of Some Most Important Nonlinear Models
9. Conclusions

**Nonparametric System Identification****70**H. Kashiwagi, *Kumamoto University, Japan*

1. Introduction
2. Representation of Nonlinear Systems
3. Identification of Wiener Kernels
  - 3.1. Wiener's Orthogonal Expansion Method
  - 3.2. Lee - Schetzen's Method
4. Identification of Volterra Kernels
  - 4.1. HooperGyftopoulos Method
  - 4.2. Watanabe - Stark's Method
  - 4.3. Kashiwagi - Sun's Method
5. Frequency Domain Approach

**Identification of Block-Oriented Models****87**Ronald K. Pearson, *ProSanos Corporation, Harrisburg, PA, USA*

1. Introduction
2. The building blocks
  - 2.1. Linear Dynamic Subsystems
  - 2.2. Static Nonlinearities
3. Hammerstein models
4. Wiener models
5. Other feedforward structures
  - 5.1. More Complex Series-connected Structures
  - 5.2. Parallel-connected Model Structures
6. Qualitative behavior of feedforward structures.
7. Feedback block-oriented structures
8. Practical issues in model building
9. Concluding Remarks

**Identification of NARMAX and Related Models****110**Stephen A. Billings, *Department of Automatic Control and Systems Engineering, University of Sheffield, UK*Daniel Coca, *Department of Automatic Control and Systems Engineering, University of Sheffield, UK*

1. Introduction
2. System Identification
3. Nonlinear Models vs. Linear Models
4. The NARMAX model
5. Practical Implementations of the NARMAX model
  - 5.1. Polynomials and Rational Implementations
  - 5.2. Neural Network Representations
    - 5.2.1. Multilayer Perceptron Networks
    - 5.2.2. Radial Basis Function Networks
  - 5.3. Wavelet Implementations
    - 5.3.1. The Wavelet Network
    - 5.3.2. Wavelet Multiresolution Models
6. The NARMAX Method
  - 6.1. Structure Determination and Parameter Estimation
    - 6.1.1. Nonlinear in the Parameter Models
    - 6.1.2. Linear in the Parameters Models
  - 6.2. Model Validation
7. Mapping the NARMAX Model in the Frequency Domain
8. A Practical Example
9. Conclusions

**System Identification Using Neural Networks****140**Abid Ali, *Fakultät für Elektrotechnik und Informationstechnik, Ruhr-Universität Bochum, Germany*Christian Schmid, *Institute of Automation and Computer Control, Ruhr-Universität Bochum, Germany*

1. Introduction
2. Artificial Neural Networks
  - 2.1. Static Neural Networks
    - 2.1.1. Multi-Layer Perceptron Networks
    - 2.1.2. Radial-Basis Function Networks
    - 2.1.3. Local Model Networks
  - 2.2. Dynamic Neural Networks
    - 2.2.1. Dynamic Multi-Layer Perceptron Networks
    - 2.2.2. Recurrent Networks
3. System Identification using Artificial Neural Networks
  - 3.1. Identification of Discrete-Time Systems
  - 3.2. Identification of Continuous-Time Systems
  - 3.3. Miscellaneous Issues

**System Identification Using Fuzzy Models****159**Robert Babuška, *Delft University of Technology, Faculty of Information Technology and Systems, The Netherlands*

1. Introduction
2. Nonlinear Dynamic Models for System Identification
3. Fuzzy Models
  - 3.1. Mamdani Model
  - 3.2. Takagi-Sugeno model
  - 3.3. Fuzzy Logic Operators
  - 3.4. Dynamic Fuzzy Models
4. Identification of Fuzzy Models
  - 4.1. Structure and Parameters
  - 4.2. Estimation of Consequent Parameters
  - 4.3. Construction of Antecedent Membership Functions
  - 4.4. Model Validation
5. Illustrative Example
6. Conclusions

**System Identification Using Wavelets****185**Daniel Coca, *Department of Electrical Engineering and Electronics, University of Liverpool, UK*Stephen A. Billings, *Department of Automatic Control and Systems Engineering, University of Sheffield, UK*

1. Introduction
2. Wavelets - A Brief Overview
  - 2.1. The Continuous Wavelet Transform
  - 2.2. Wavelet Series
    - 2.2.1. Dyadic Wavelets
    - 2.2.2. Wavelet Multiresolution Approximations
3. System Identification
4. System Identification using Wavelets
  - 4.1. System Identification Using Wavelet Networks
    - 4.1.1. The Wavelet Network Model
    - 4.1.2. Structure Selection and Parameter Estimation for Wavelet Network Models
  - 4.2. Wavelet Multiresolution Models
    - 4.2.1. The B-spline Wavelet Multiresolution Model Structure
    - 4.2.2. Model Sequencing and Structure Selection

## 5. Conclusions

**Parameter Estimation for Differential Equations** **208**  
 Amit Patra, *Department of Electrical Engineering, Indian Institute of Technology, Kharagpur-721302, India*

1. Introduction
2. The Hartley Transformation
  - 2.1. The Continuous Hartley Transform (CHT)
  - 2.2. Properties of CHT
    - 2.2.1. Scaling of Variable
    - 2.2.2. Convolution in Time-domain
    - 2.2.3. Multiplication in the Time-Domain
    - 2.2.4. Differentiation
  - 2.3. The Discrete Hartley Transform (DHT)
3. The Hartley Modulating Functions
  - 3.1. Definition
  - 3.2. Properties of HMF
    - 3.2.1. Spectra for Derivatives of Signals
    - 3.2.2. Spectra for the Product of a Measured Signal and the Derivative of Another
4. Formulation of the parameter estimation equation
  - 4.1. Linear Systems
  - 4.2. Integrable Nonlinear Systems
  - 4.3. Modulatable Nonlinear Systems
5. Computational Issues
  - 5.1. Computation of CHT using DHT
  - 5.2. Computation of HMF Spectra
  - 5.3. Computing the Estimates
  - 5.4. Frequency-weighted Estimation
6. Illustrative Examples
7. Application to an Inverted Pendulum Model
  - 7.1. Derivation of System Equations
  - 7.2. Data Generation
  - 7.3. Formulating the Parameter Estimation Equations
8. Conclusions

**Parameter Estimation for NonLinear Continuous-Time State-Space Models from Sampled Data** **242**  
 C. Bohn, *Continental AG, Strategic Technology Department, Hanover, Germany*

1. Introduction and Overview
2. Mathematical Preliminaries
3. The Prediction-Error Approach to Parameter Estimation
4. State-Space Models and State Estimation
5. Parameter Estimation for State-Space Models
  - 5.1. State Augmentation
  - 5.2. Prediction-Error Approach
  - 5.3. Remarks
6. Conclusion

**Identification in the Frequency Domain** **267**  
 Julius S. Bendat, *J.S. Bendat Company, Los Angeles, CA, USA*

1. Introduction
2. Linear System Identification

- 2.1. SI/SO Linear Models
- 2.2. MI/SO Linear Models
3. Nonlinear System Identification
  - 3.1. Volterra Nonlinear Models
  - 3.2. Hammerstein and Wiener Nonlinear Models
  - 3.3. SI/SO Nonlinear Models
  - 3.4. Models With Nonlinear Feedback
4. Conclusions for Nonlinear System Identification

**Parametric Identification using Sliding Modes****281**Fabienne Floret-Pontet, *Laboratoire des signaux et systèmes, CNRS, Supélec, FRANCE*Francoise Lamnabhi-Lagarrigue, *Laboratoire des signaux et systèmes, CNRS, Supélec, FRANCE*

1. Introduction
2. State Identification
3. Parameter Identification
4. State and parameter identification
5. Simulations results
  - 5.1. Noiseless Context
  - 5.2. Robustness Study
6. Conclusion

**Bound-based Identification****296**Eric Walter, *CNRS-Supélec-Université Paris-Sud, France.*

1. Introduction
2. Bounded-error estimation
3. Characterization of the feasible set for the parameters
  - 3.1. The Error is Affine in the Parameters
  - 3.2. The Error is not Affine in the Parameters

**Linear-Model Case****306**Norton, John, *Department of Electronic, Electrical and Computer Engineering, School of Engineering, University of Birmingham, UK*

1. Bounding a linear model: the simplest case
2. Computation of the exact feasible set
3. Approximate parameter bounding
  - 3.1. Limited-complexity polytopes
  - 3.2. Ellipsoidal bounding
  - 3.3. Box bounding
  - 3.4. Parallelotope bounding
  - 3.5. Hybrid algorithms
4. Parameter bounding with unknown output-error bound
5. Parameter bounding with uncertain explanatory-variables vector
6. Clashes and outliers
7. Parameter bounds for time-varying linear systems
  - 7.1. Heuristic recursive bounding of time-varying parameters using ellipsoids
  - 7.2. Bounding of time-varying parameters treated as state variables
8. Conclusions

**Nonlinear-Model Case****328**Keesman, Karel J. *Systems and Control Group, Wageningen University, The Netherlands*

1. Introduction
2. Definitions and notation
3. Classification of non-linear parameter bounding algorithms
  - 3.1. Intersection
  - 3.2. Encapsulation
  - 3.3. Discrete approximation
  - 3.4. Projection
  - 3.5. Special model classes
4. Example
5. Concluding Remarks

**Practical Issues of System Identification****345**Lennart Ljung, *Linköping University, Sweden.*

1. The Framework
  - 1.1. Starting Point
  - 1.2. Some Typical Model Structures
  - 1.3. Estimating the Parameters
2. The User and the System Identification Problem
  - 2.1. The Tool: Interactive Software
3. Choice of Input Signals
  - 3.1. Common Input Signals
  - 3.2. Periodic Inputs
4. Preprocessing Data
  - 4.1. Drifts and Detrending
  - 4.2. Prefiltering
5. Selecting Model Structures
6. Some Applications

**Index****369****About EOLSS****377****VOLUME VII****Control of Linear Multivariable Systems****1**Katsuhisa Furuta, *Tokyo Denki University, School of Science and Engineering, Ishizaka, Hatoyama, Saitama, Japan*

1. Linear Multivariable Systems
  - 1.1. Emergence of State Space Approach
  - 1.2. Discrete-time Control
  - 1.3. Riccati Equation and Stabilization for Continuous-time Systems
  - 1.4. Design Procedure
  - 1.5. Static Output Feedback and Dynamic Compensation
  - 1.6. Servo Control and Internal Model Principle
  - 1.7. Design and Analysis based on Frequency Response
  - 1.8. Control System Example
2. Control System Example
  - 2.1. Parameters of the system
  - 2.2. Conclusion

**Description and Classification in MIMO Design**

34

D.H. Owens, *The University of Sheffield, United Kingdom*J. Hätönen, *The University of Sheffield, United Kingdom*

1. Introduction
2. Models
  - 2.1. Dynamical Systems and Laplace Transform
  - 2.2. State-space Equations
  - 2.3. Transfer-function Matrices
  - 2.4. Polynomial Matrix Models
  - 2.5. Differential-delay Models
  - 2.6. A parallel Development for Discrete-time Systems
  - 2.7. Model Reduction and Approximation
3. Control Systems Design
  - 3.1. SISO Feedback Systems
  - 3.2. Nyquist Stability Test for SISO Systems
  - 3.3. Control Design Specifications
  - 3.4. Root-Locus
  - 3.5. Phase and Gain Margin
  - 3.6. Guidance from Special Cases
  - 3.7. Some Comments on State Space Methods
4. Translating SISO concepts into MIMO world
  - 4.1. Some Basic Relationships
  - 4.2. Interaction and Robustness in MIMO Systems
5. Frequency Domain Design techniques
  - 5.1. Background
  - 5.2. Design and Interaction
  - 5.3. Design and Eigenstructure of  $Q(s)$
  - 5.4. The Development of Frequency Domain Optimization Methods
  - 5.5. Multivariable Root-loci
  - 5.6. Simple MIMO Models in Design
  - 5.7. The Future?
6. Time Domain Design Approaches
  - 6.1. Introduction
  - 6.2. Eigenstructure and Pole Allocation
  - 6.3. Measurement Issues and Observers
  - 6.4. Optimal Control
  - 6.5. Interaction and Decoupling
  - 6.6. Disturbance Rejection
  - 6.7. Direct Computational Search Methods
  - 6.8. The Future?
7. Non-standard MIMO Problems
8. Conclusions

**Canonical Forms for State Space Descriptions**

59

Nicos Karcianas, *City University, London, UK*Dimitris Vafiadis, *City University, London, UK*

1. Introduction
2. State - Space Representations, Matrix Pencils, and State - Space Transformations
3. Matrix Pencils and Kronecker Form
  - 3.1. Background
  - 3.2. Matrix Pencils and Strict Equivalence
  - 3.3. Smith Forms, Invariants and Duality
  - 3.4. Regular Pencils, Elementary Divisors and Weierstrass Form
  - 3.5. Singular Pencils, Minimal Bases and Kronecker Form
4. Canonical Form under Similarity: Autonomous Descriptions with no outputs

5. Kronecker Form under the Full State Space Transformation Group
6. Brunovsky Canonical Forms under Coordinate and Feedback Transformations
  - 6.1. The System  $S(A,B)$  and its Kronecker form
  - 6.2. The system  $S(A,C)$  and its duality with  $S(A,B)$
7. Canonical Forms under Coordinate Transformations
  - 7.1. Echelon Form of Polynomial Matrices
  - 7.2. Canonical Form for  $(A,B)$ ,  $(C,A)$  pairs under similarity Transformations
  - 7.3. Relationships to MFDs and realization
8. Conclusions

### Multivariable Poles and Zeros

102

Karcanias, Nicos, *Control Engineering Research Centre, City University, London, UK*

1. Introduction
2. System Representations and Classification
3. Background on Polynomial matrices and Matrix Pencils
4. Finite Poles and Zeros of State Space Models: Dynamics and their Geometry
  - 4.1. Eigenvalues, Eigenvectors and Free Rectilinear Motions
  - 4.2. Forced Rectilinear Motions and Frequency Transmission
  - 4.3. Frequency Transmission Blocking and State Space Zeros
  - 4.4. Zero Structure and System Transformations
  - 4.5. The Zero Pencil of Strictly Proper System
  - 4.6. Decoupling Zeros
5. Finite Poles and Zeros of Transfer Function Models
  - 5.1. Dynamic Characterization of Transfer Function Poles and Zeros
  - 5.2. Smith McMillan form characterization of Poles and Zeros
  - 5.3. Matrix Fraction Description of Poles and Zeros
6. Infinite Poles and Zeros
  - 6.1. Smith McMillan form at infinity: Infinite Poles and Zeros
  - 6.2. McMillan Indices at a Point
  - 6.3. Impulsive Dynamics and Infinite Poles and Zeros
  - 6.4. Proper Compensation and the Smith-McMillan form at infinity
  - 6.5. Relationships Between the Different Types of Zeros, Poles
7. Algebraic Function Characterization of Poles and Zeros
  - 7.1. Characteristic Gain Frequency Functions
  - 7.2. Poles and Zeros of the System Algebraic Functions
8. Zero Structure Formation in Systems Design

### Frequency Domain Representation and Singular Value Decomposition

143

Athanasios C. Antoulas, *Department of Electrical and Computer Engineering, Rice University, USA*

1. Introduction
2. Preliminaries
  - 2.1. The Laplace Transform and the  $Z$ -transform
    - 2.1.1. Some Properties of the Laplace Transform
    - 2.1.2. Some Properties of the  $Z$ -transform
  - 2.2. Norms of Vectors, Matrices and the SVD
    - 2.2.1. Norms of Finite-dimensional Vectors and Matrices
    - 2.2.2. The Singular Value Decomposition
    - 2.2.3. Norms of Functions of Time
    - 2.2.4. Induced Operator Norms
    - 2.2.5. Norms of functions of complex frequency
    - 2.2.6. Connection Between time and Frequency Domain Spaces
3. External and internal representations of linear systems
  - 3.1. External Representation
    - 3.1.1. External Description in the Frequency Domain



- 3.1.2. The Bode and Nyquist Diagrams
- 3.2. Internal Representation
  - 3.2.1. Solution in the Time Domain
  - 3.2.2. Solution in the Frequency Domain
  - 3.2.3. The Concepts of Reachability and Observability
  - 3.2.4. The Infinite Gramians
- 3.3. The Realization Problem
  - 3.3.1. The Solution of the Realization Problem
  - 3.3.2. Realization of Proper Rational Matrix Functions
- 4. Time and frequency domain interpretation of various norms
  - 4.1. The Convolution Operator and the Hankel Operator
  - 4.2. Computation of the Singular Values of S
  - 4.3. Computation of the Singular Values of H
  - 4.4. Computation of Various Norms
    - 4.4.1. The  $H_2$  norm
    - 4.4.2. The  $\mathcal{H}_\infty$  norm
    - 4.4.3. The Hilbert-Schmidt Norm
    - 4.4.4. Summary of Norms
  - 4.5. The Use of Norms in Control System Design and Model Reduction
    - 4.5.1. Model Reduction

### Polynomial and Matrix Fraction Description

211

Didier Henrion, *Laboratoire d'Analyse et d'Architecture des Systèmes, Centre National de la Recherche Scientifique, Toulouse, France.*

Michael Šebek, *Center for Applied Cybernetics, Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic.*

- 1. Introduction
- 2. Scalar Systems
  - 2.1. Rational Transfer Function
  - 2.2. From Transfer Function To State-Space
    - 2.2.1. Controllable Canonical Form
    - 2.2.2. Observable Canonical Form
  - 2.3. From State-Space To Transfer Function
  - 2.4. Minimality
- 3. Multivariable Systems
  - 3.1. Matrix Fraction Description
  - 3.2. Minimality
  - 3.3. Properness
  - 3.4. Non-Canonical Realizations
    - 3.4.1. Controllable Form
    - 3.4.2. Observable Form
  - 3.5. Canonical Realizations
    - 3.5.1. Hermite Form
    - 3.5.2. Popov Form
  - 3.6. From Right MFD To Left MFD
  - 3.7. From State-Space To MFD
- 4. Conclusion

### System Characteristics: Stability, Controllability, Observability

232

J. Klamka, *Institute of Automatic Control, Technical University, Gliwice, Poland*

- 1. Introduction
- 2. Mathematical model
- 3. Stability
- 4. Controllability

- 4.1. Fundamental results
- 4.2. Stabilizability
- 4.3. Output controllability
- 4.4. Controllability with Constrained Controls
- 4.5. Controllability after the introducing of sampling
- 4.6. Perturbations of controllable dynamical systems
- 4.7. Minimum energy control
- 5. Observability
- 6. Conclusions

**Model Reduction****248**

Robert E. Skelton, *MAE, University of California at San Diego, USA.*  
 Maurício C. de Oliveira, *FEEC, University of Campinas, Brazil.*

- 1. What is Model Reduction?
  - 1.1. Single Component Model Reduction
  - 1.2. Multi-Component Model Reduction
  - 1.3. The Quality of the Reduced Order Model
  - 1.4. Characterization of the Single-Component Model Reduction Error
- 2. Linear System Properties
  - 2.1. Input-Output Transfer Function
  - 2.2. Controllability and Observability
  - 2.3. Frequency Moments and Markov Parameters
  - 2.4. Output Correlation and Power Moments
  - 2.5.  $H_2$  and  $\mathcal{H}_\infty$  Norms
  - 2.6. The Conjugate System, Inner, Outer and All-pass Transfer Functions
- 3. Model Reduction by Truncation
  - 3.1. Minimal Transfer Equivalent Realizations
  - 3.2. Component Cost Analysis
  - 3.3. Matching Frequency and Power Moments
  - 3.4. Balanced Realization and Truncation
  - 3.5. Singular Perturbation Truncation
- 4. Model Reduction by Optimization
  - 4.1.  $H_2$  Norm Model Reduction
  - 4.2.  $\mathcal{H}_\infty$  Norm Model Reduction
  - 4.3. The Numerical Solution of Optimal Model Reduction Problems
- 5. A Glimpse on the Multi-Component Model Reduction Problem
  - 5.1. Frequency Weighted Balanced Truncation
- 6. Tutorial Examples
  - 6.1. Example 1
  - 6.2. Example 2

**Index****299****About EOLSS****305****VOLUME VIII****Full-Order State Observers****1**

Bernard Friedland, *Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ, USA*

- 1. Introduction

2. Linear Observers
  - 2.1. Continuous-Time Systems
    - 2.1.1. Optimization
    - 2.1.2. Pole-Placement
  - 2.2. Discrete-Time Systems
3. The Separation Principle
4. Nonlinear Observers
  - 4.1. Using Zero-Crossing or Quantized Observations
  - 4.2. Extended Separation Principle
  - 4.3. Extended Kalman Filter

### Reduced-Order State Observers

26

Bernard Friedland, *Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ, USA*

1. Introduction
2. Linear, Reduced-Order Observers
3. Nonlinear Reduced-Order Observers

### Kalman Filters

37

Mohinder Singh Grewal, *California State University, Fullerton, US*

1. Introduction
2. White Noise
3. Linear Estimation
4. The Linear Optimal Estimator in Discrete Time (Kalman Filter)
  - 4.1. Summary of Equations for the Discrete-Time Kalman Estimator
5. The Continuous-Time Optimal Estimator (Kalman-Bucy Filter)
6. Nonlinear Estimation
  - 6.1. Linearization about a Nominal Trajectory
  - 6.2. Linearization about the Estimated Trajectory
  - 6.3. Linearized and Extended Kalman Filters
7. Implementation Methods
  - 7.1. Modified Cholesky (UD) Decomposition Algorithms
  - 7.2. Bierman-Thornton UD Filtering
    - 7.2.1. Bierman UD Observational Update
    - 7.2.2. Thornton UD Temporal Update
8. Present and Future Applications of the Kalman Filter

### Pole Placement Control

74

Ackermann, J.E., *Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany*

1. Introduction
2. Separation of state observation and state feedback
3. The single-input case
  - 3.1. Ackermann's formula
  - 3.2. Numerically stable calculation via Hessenberg form
4. The multi-input case
  - 4.1. Non-uniqueness
  - 4.2. Feedback invariants
  - 4.3. Deadbeat control
  - 4.4. Reviving the Brunovski structure
  - 4.5. Polynomial notation
  - 4.6. Calculation without canonical form
  - 4.7. Numerically stable calculation via HN form

**Eigenstructure Assignment for Control****101**Guo Ping Liu, *University of Glamorgan, Pontypridd, U.K.*  
Ron John Patton, *University of Hull, Hull, U.K.*

1. Introduction
2. Definition of Eigenstructure Assignment
3. Role of the System Eigenstructure
4. Freedom for Eigenstructure Assignment
5. Allowable Eigenvector Subspaces
6. Calculation of Controller Matrices
7. Assignment of Desired Eigenvectors
8. Compromise between Eigenvalues and Eigenvectors
9. Parametric Eigenstructure Assignment
10. Multiobjective Robust Eigenstructure Assignment
11. Various Eigenstructure Assignment Techniques
  - 11.1. Basic Eigenstructure Assignment
  - 11.2. Recursive Eigenstructure Assignment
  - 11.3. Low Sensitive Eigenstructure Assignment
  - 11.4. Robust Eigenstructure Assignment
  - 11.5. Eigenstructure Assignment for Descriptor Systems
  - 11.6. Eigenstructure Assignment for Dynamical Compensators

**Optimal Linear Quadratic Control****124**João Miranda Lemos, *INESC-ID/IST, R. Alves Redol 9. 1000-029 Lisboa, Portugal.*

1. Introduction
2. The LQ regulator in continuous time
3. The steady-state LQ regulator in continuous time
  - 3.1. The Algebraic Riccati Equation
  - 3.2. Analytic Solution of the Riccati Equation
4. Properties of the steady-state LQ regulator in continuous time
  - 4.1. Optimal Pole Locations and the Chang-Letov Design Method
  - 4.2. Relative Stability Margins
  - 4.3. The Inverse Optimal Control Problem
5. The LQ regulator in discrete time
  - 5.1. Time-varying Plants
  - 5.2. Steady-state Output Regulation
  - 5.3. Optimal Pole Locations
  - 5.4. Cheap Control
6. Numerical methods
7. Conclusions

**Pontryagin's Maximum Principle****156**Alexander B. Kurzhanski, *Faculty of Computational Mathematics and Cybernetics, Moscow State University, Russia*

1. Introduction
2. An Example
3. The problem of Optimal Control
4. A More Rigorous Formulation of the Problem
5. The Maximum Principle
6. A Discussion
7. The Time-Optimal Control Problem
8. Time-Optimal Control for Linear Systems
9. Other Performance Indices
10. Interpretations and generalizations of the Maximum Principle

**Decoupling Control****173**

M. Fikar, *Department of Process Control, Faculty of Chemical and Food Technology, Slovak University of Technology in Bratislava, Radlinského 9, SK-812 37 Bratislava, Slovakia*

1. Introduction
  - 1.1. Preliminaries
    - 1.1.1. Multivariable System Description
    - 1.1.2. Control Structures Used for Decoupling
    - 1.1.3. Square and Non-square Systems
    - 1.1.4. Problem Formulation
2. Control of a Heat Exchanger
  - 2.1. Model
  - 2.2. Static Decoupling
  - 2.3. Dynamic Decoupling
  - 2.4. Process Control Decoupling
  - 2.5. Concluding Remarks for the Heat Exchanger
3. Dynamic Decoupling
  - 3.1. Linear State Feedback with Input Dynamics
  - 3.2. Linear State Feedback
  - 3.3. Square Systems
  - 3.4. Output Feedback Decoupling
  - 3.5. Block Decoupling
  - 3.6. Triangular Decoupling
  - 3.7. Cost of Decoupling
4. Static decoupling
5. Process Control Decoupling Design
  - 5.1. Ideal Decoupling
  - 5.2. Simplified Decoupling
  - 5.3. Inverted Decoupling
6. Other Topics

**Controller Design using Polynomial Matrix Description****208**

Didier Henrion, *Laboratoire d'Analyse et d'Architecture des Systèmes, Centre National de la Recherche Scientifique, Toulouse, France.*

Michael Šebek, *Center for Applied Cybernetics, Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic.*

1. Introduction
2. Polynomial Approach To Three Classical Control Problems
  - 2.1. Dynamics Assignment
  - 2.2. Deadbeat Regulation
  - 2.3.  $H_2$  Optimal Control
3. Numerical Methods for Polynomial Matrices
  - 3.1. Diophantine Equation
  - 3.2. Spectral Factorization Equation
4. Conclusion

**Design Techniques in the Frequency Domain****225**

Edmunds, J.M, *Control Systems Center, UMIST, UK*

Munro, N, *Control Systems Center, UMIST, UK*

1. Frequency Responses and Stability
  - 1.1. Single loop stability
  - 1.2. Multivariable stability using Characteristic loci
  - 1.3. Multivariable stability using Gershgorin bands on Nyquist arrays
  - 1.4. Diagonal Dominance

2. Basic Design
  - 2.1. Multivariable Design Methods
  - 2.2. Integrating the multivariable design methods
3. A Design Example for an Unstable Chemical Reactor
  - 3.1. Description of the chemical reactor
  - 3.2. Uncompensated squared down reactor
  - 3.3. Scaling
  - 3.4. High and low frequency compensation
  - 3.5. Closed loop analysis

### **Design Techniques for Time-Varying Systems**

241

Pablo A. Iglesias, *Johns Hopkins University, USA*

1. Introduction
2. Model Descriptions
  - 2.1. State-Space Models
  - 2.2. Input-Output Models
    - 2.2.1. Impulse Response
    - 2.2.2. Polynomial Fraction Descriptions
  - 2.3. Converting from One Description to Another
  - 2.4. Frequency Domain Techniques
3. Stabilization Techniques
  - 3.1. Stability
    - 3.1.1. Lyapunov Stability
  - 3.2. State Feedback Stabilization
    - 3.2.1. Controllability, Stabilizability, Observability, and Detectability
    - 3.2.2. Cheng's Method
    - 3.2.3. Optimal State-Feedback Regulator
  - 3.3. Output Feedback
    - 3.3.1. Pole Placement
4. Causal information controllers
  - 4.1. Frozen time approach
  - 4.2. Linear parameter varying systems

### **Servo Control Design**

260

Timothy Chang, *New Jersey Institute of Technology, Newark, NJ, USA*

1. Introduction
2. Classical Servo Control Design
  - 2.1. Integrator Based Control
    - 2.1.1. Design Example: Industrial Regulator
  - 2.2. Phase Lag Control
    - 2.2.1. Design Example: Phase Lag Compensation
  - 2.3. Phase Lead Control
    - 2.3.1. Design Example: Phase Lead Compensation
3. Modern Servo Control Design
  - 3.1. Feedforward Control: Input Shaping
    - 3.1.1. Mathematical Analysis of the Input Shaping Scheme
    - 3.1.2. Design Example: Input Shaping for Unit Step Command
  - 3.2. Feedback Control
    - 3.2.1. Controller Parameterization
    - 3.2.2. Time Domain Parameter Optimization
    - 3.2.3. Frequency Domain Parameter Optimization
      - 3.2.3.1. Design Example: Frequency Domain Parameter Optimization
4. Conclusions

**Index** 303

**About EOLSS** 311

## VOLUME IX

**Robust Control** 1  
S.P.Bhattacharyya, *Texas A&M University, Texas, USA*

1. Introduction and Basic Elements of Control Systems
2. Feedback and Robustness
3. Robustness and Integral Control
4. A Short History of Control Theory and Robust Control
  - 4.1. The Classical Period
  - 4.2. Modern Control Theory
  - 4.3. The Servomechanism Problem
  - 4.4. Post-modern Control Theory
  - 4.5. The Parametric Theory
5. Robustness of Control Systems
  - 5.1. Performance Issues and Tradeoffs
  - 5.2. Zero Steady State Errors
6. Feedback Stabilization of Linear Systems
  - 6.1. Stabilization by Observer Based State Feedback
  - 6.2. Pole Placement Compensators
  - 6.3. YJBK Parameterization
  - 6.4. Nyquist Criterion
  - 6.5. Optimal Control: Linear Quadratic Regulator (LQR)
7. Uncertainty Models and Robustness
  - 7.1. Gain and Phase Margin
  - 7.2. Parametric Uncertainty
  - 7.3. Nonparametric and Mixed Uncertainty
8.  $\mathcal{H}_\infty$  Optimal Control
  - 8.1. State Space Theory of  $H_\infty$  Optimal Control
  - 8.2. Linear Matrix Inequalities
  - 8.3. Frequency Domain Aspects of  $H_\infty$  Optimal Control
9.  $\mu$  Theory
10. Quantitative Feedback Theory
11. Concluding Remarks

**Uncertainty Models for Robustness Analysis** 47  
A. Garulli, *Dipartimento di Ingegneria dell'Informazione, Università di Siena, Italy*  
A. Tesi, *Dipartimento di Sistemi e Informatica, Università di Firenze, Italy*  
A. Vicino, *Dipartimento di Ingegneria dell'Informazione, Università di Siena, Italy*

1. Introduction
2. Notation and definitions
3. Uncertainty representation and robustness problems
4. Unstructured uncertainty models
5. Structured uncertainty models
6. Highly structured (parametric) uncertainty models
7. State space uncertainty models
  - 7.1. Unstructured State Space Uncertainty
  - 7.2. Parametric State Space Uncertainty
8. Conclusions

**Robustness Under Real Parameter Uncertainty**

72

L. H. Keel, *Tennessee State University, Nashville, Tennessee, USA*

1. Introduction
2. Notations and Preliminaries
  - 2.1. Parametric Uncertainty
  - 2.2. Boundary Crossing and Zero Exclusion
3. Real Parameter Stability Margin
  - 3.1.  $l_2$  Real Parametric Stability Margin
  - 3.2.  $l_2$  Stability Margin for Time-delay Systems
4. Extremal Results in Parametric Robust Control Theory
  - 4.1. Kharitonov's Theorem
  - 4.2. The Edge Theorem
  - 4.3. The Generalized Kharitonov Theorem
5. Frequency Domain Analysis of Uncertain Systems
  - 5.1. Frequency Domain Properties
  - 5.2. Closed Loop Transfer Functions
6. Robust Classical Controller Design

 **$\mathcal{H}_\infty$  Optimal Control**

115

Huibert Kwakernaak, *University of Twente, the Netherlands*

1. Introduction
2. The Minimum Sensitivity Problem
3. Robustness and the Sensitivity Functions
4. The Mixed Sensitivity Problem
5. The Standard  $\mathcal{H}_\infty$  Problem and its Solutions
  - 5.1. The Standard Problem
  - 5.2. Early Solutions
  - 5.3. Solution Based on Spectral Factorization
  - 5.4. State Space Solution
  - 5.5. Other Solutions
  - 5.6. Optimal Solutions
  - 5.7. Extensions to Nonlinear and Infinite-Dimensional Systems
6. Application to Robust Control System Design

 **$l_1$  Robust Control**

137

Mustafa Khammash, *Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, CA 93101, USA*

1. Introduction
2. The  $l_1$  Norm
3. Robustness To Signal Uncertainty: The  $l_1$  Norm Minimization Problem
  - 3.1. A Duality Result
  - 3.2. The Scaled-Q Method for Solving the  $l_1$  Optimization Problem
    - 3.2.1. An Auxiliary Problem
    - 3.2.2. Relating the Auxiliary Problem to the  $l_1$  Problem
  - 3.3. Example
4. Robustness to Unmodeled Dynamics
  - 4.1. Conditions for Robustness



**$\mu$  - Synthesis****152**Gary J. Balas, *Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, MN 55455 USA*

1. Introduction
2. Control Design via D - K Iteration
  - 2.1. Linear Fractional Transformations, LFTs
  - 2.2. Robust Control Problem Formulation
  - 2.3.  $D$ - $K$  Iteration for Complex Uncertainty
    - 2.3.1. Two-Step Procedure for Scalar entries  $d$  of  $D$
    - 2.3.2. Two-Step Procedure for Full  $D$
  - 2.4.  $(D,G)$  -  $K$  Iteration for Real and Complex Uncertainty
3. Control Design Using Fixed-Order Scalings
4. Conclusion

**Controller Design Using Linear Matrix Inequalities****168**Herbert Werner, *Institute of Control Engineering, 21073 Hamburg, Germany, Technical University Hamburg-Harburg, Germany*

1. Introduction
2. Design Specifications and Linear Matrix Inequalities
  - 2.1. Pole Region Assignment
  - 2.2.  $H_2$  Performance
  - 2.3.  $\mathcal{H}_\infty$  Performance
3. Controller Design Using Linear Matrix Inequalities
  - 3.1. Linearizing Change of Variables - State Feedback
  - 3.2. Linearizing Change of Variables - Output Feedback
  - 3.3. LMI Approach to Multiobjective Design
  - 3.4. Existence of Solutions and Conservatism of Design
4. Illustrative Design Example: Robust Control of a Power System Stabilizer
  - 4.1. Problem Description
  - 4.2. Design Specifications in Terms of a Generalized Plant
  - 4.3. Modeling the Parameter Uncertainty
  - 4.4. LMI-Based Design
5. Conclusion

**Robust Control of Nonlinear Systems: A Control Lyapunov Function Approach****201**Petar Kokotović, *University of California, Santa Barbara, CA, USA*  
Murat Arcak, *Rensselaer Polytechnic Institute, Troy, NY, USA*

1. Robust Control Lyapunov Function (RCLF)
2. Disturbance attenuation
3. Construction of RCLFs by Backstepping
4. Cost-to-Come Function for Output Feedback

**Fundamentals of the Quantitative Feedback Theory Technique****211**Constantine H. Houppis, *Air Force Institute Of Technology, Wright-Patterson AFB, Ohio, 45433, USA*

1. Introduction
  - 1.1. Quantitative Feedback Theory (QFT)
  - 1.2. The Control System design Process
  - 1.3. What Can QFT Do
  - 1.4. Benefits of QFT
2. The MISO Analog Control Systems
  - 2.1. Introduction

- 2.2. MISO System
- 2.3. Synthesize Tracking Models
- 2.4. Disturbance Model
- 2.5. J LTI Plant Models
- 2.6. Plant Templates of  $\mathbf{P}_j(\mathbf{s})$ ,  $\mathfrak{P}(j\omega_i)$
- 2.7. Nominal Plant
- 2.8. U-Contour (Stability bound)
- 2.9. Optimal Bounds  $B_o(j\omega)$  on  $L_o(j\omega)$ 
  - 2.9.1. Tracking Bounds
  - 2.9.2. Disturbance Bounds
- 2.10. Synthesizing (or Loop Shaping)  $L_o(s)$  and  $F(s)$
- 2.11. Prefilter Design
- 2.12. Simulation
- 2.13. QFT CAD Packages
- 3. The MISO Discrete Control System
  - 3.1. Introduction
  - 3.2. s- To z-Plane Transformation: Tustin Transformation
  - 3.3. The MISO Sampled-data Control System
  - 3.4. QFT Technique Applied To The Pseudo-Continuous-Time (PCT) System
    - 3.4.1. Introduction To PCT System DIG Technique
    - 3.4.2. The PCT System Of Figure 17
    - 3.4.3. PCT Design Summary
  - 3.5. Controller Implementation
  - 3.6. Analysis of the Characteristic Equation  $Q_j(z)$
  - 3.7. Simulation and CAD Packages
- 4. MIMO Systems
  - 4.1. Introductions
  - 4.2. Derivation of m2 MISO System Equivalents
  - 4.3. Tracking and Cross-coupling Effect Specifications
    - 4.3.1. Tracking Specifications
    - 4.3.2. Disturbance Specification (Cross-coupling Effect)
  - 4.4. Determination of Tracking, Cross-coupling, and Optimal Bounds
    - 4.4.1. Tracking Bounds
    - 4.4.2. Cross-coupling Bounds
    - 4.4.3. Optimal Bounds
  - 4.5. QFT Methods of Designing MIMO Systems
    - 4.5.1. Method 1
    - 4.5.2. Method 2
  - 4.6. Synthesizing the Loop Transmission and Prefilter Functions
  - 4.7. Overview of the MIMO/QFT CAD Package <sup>[12]</sup>
- 5. MIMO QFT With External (Input) Disturbance(s)
- 6. QFT Application
- 7. Conclusion

**Index** 257

**About EOLSS** 263

## VOLUME X

<b>Adaptive Control</b>	<b>1</b>
<i>Kumpati S. Narendra, Yale University, New Haven, CT, USA</i>	

- 1. Introduction

2. Basic Concepts and Definitions
3. Historical Background
  - 3.1. Gradient Based Adaptive Methods
  - 3.2. The MIT Rule and Park's Proof of Instability
4. Stable Adaptive Systems
5. Lyapunov Theory Based Design
6. Identification and Adaptive Control of Higher Order Systems
  - 6.1. Identification
  - 6.2. Control
7. Adaptive Observers
  - 7.1. Non-minimal Representation
  - 7.2. Minimal Representation
  - 7.3. Error Models
8. The Adaptive Control Problem (Relative Degree  $n^*=1$ )
9. The Adaptive Control Problem (Relative Degree  $n^* \geq 2$ )
10. Persistent Excitation
11. Robust Adaptive Control
  - 11.1. Time-Varying Systems
  - 11.2. Unmodeled Plant Dynamics
12. Hybrid Adaptive Control
13. Relaxation of Assumptions
14. Multivariable Adaptive Control
15. Nonlinear Adaptive Control
16. Recent Contributions
  - 16.1. Decentralized Adaptive Control
  - 16.2. Adaptive Control Using Multiple Models

### **Relay Autotuning of PID Controllers**

31

D. P. Atherton, *University of Sussex, UK*

1. Introduction
2. Relay Autotuning
3. Analysis of Relay Autotuning using the DF method
4. Controller Design Based on the Critical Point
5. Further Considerations
6. Conclusions

### **Self-Tuning Control**

42

P.J. Gawthrop, *Centre for Systems and Control and Department of Mechanical Engineering, University of Glasgow, GLASGOW. G12 8 QQ Scotland, UK*

1. Introduction
2. Categorization of Self-Tuning Controllers.
  - 2.1. Explicit or implicit
  - 2.2. Continuous-time or discrete-time
  - 2.3. Choice of controller design method
  - 2.4. Choice of identification method
3. Implicit generalized minimum variance control
4. Practical issues
  - 4.1. Choice of design parameters
  - 4.2. Integral action
  - 4.3. Initial conditions
5. Examples
  - 5.1. Example 1: Implicit Model-Reference Control
  - 5.2. Example 2: Explicit Model-Reference Control
  - 5.3. Example 3: Explicit Pole-placement Control of non-minimum phase system

- 5.4. Examples 4 and 5 : Under-modeled systems
- 6. Future prospects

**Model Reference Adaptive Control****63**Anuradha M. Annaswamy, *Massachusetts Institute of Technology, Cambridge, MA, USA*

- 1. Introduction
- 2. Dynamic Models
  - 2.1. Identification Model
  - 2.2. Reference Model
    - 2.2.1. Explicit and Implicit Model Following
  - 2.3. Reference Model with Inputs
- 3. Model Reference Adaptive Control
  - 3.1. Algebraic Part and Analytic Part
  - 3.2. The MRAC Problem
- 4. Parameter Identification

**Adaptive Predictive Control****76**D.W. Clarke, *Department of Engineering Science, Park Road, Oxford OXI 3 PJ, UK*U.R. Halldorsson, *Control Engineering Laboratory, Ruhr-University Bochum, D-44780, Germany*

- 1. Introduction
- 2. System models and long-range prediction
  - 2.1. General long-range prediction models
  - 2.2. Dynamic matrix control prediction model
  - 2.3. Generalized predictive control prediction model
- 3. The GPC control law
- 4. Robustness analysis
- 5. Self-tuning aspects
- 6. Conclusions

**Stochastic Adaptive Control****100**T. E. Duncan, *Department of Mathematics, University of Kansas, Lawrence, KS 66045, USA*

- 1. Introduction
- 2. Adaptive Control of Markov Chains
- 3. Adaptive Control of ARMAX models
- 4. Adaptive Control of Continuous Time Linear Stochastic Systems
- 5. Some Generalizations of Adaptive Control
- 6. Conclusions

**Adaptive Dual Control****122**Björn Wittenmark, *Lund Institute of Technology, Sweden.*

- 1. Introduction
- 2. Stochastic Adaptive Control
- 3. Optimal Dual Controllers
- 4. Suboptimal Dual Controllers
  - 4.1. Perturbation Signals
  - 4.2. Constrained One-Step-Ahead Minimization
  - 4.3. Approximations of the Loss Function
  - 4.4. Modifications of the Loss Function
  - 4.5. Finite Parameter Sets
- 5. When To Use Dual Control?

**Adaptive Nonlinear Control****133**Petar Kokotovic, *Department of Electrical and Computer Engineering, University of California at Santa Barbara, USA*Miroslav Krstic, *Department of Mechanical and Aerospace Engineering, University of California at San Diego, USA*

1. Introduction
2. Backstepping
3. Tuning Functions Design: Examples
4. General Recursive Design: Procedure
5. Modular Design
  - 5.1. Controller design
  - 5.2. Identifier Design
6. Conclusions

**Control of Intermittent Processes****151**Madhukar Pandit, *Control Systems and Signal Theory Group, University of Kaiserslautern, Germany*Heiko Hengen, *Control Systems and Signal Theory Group, University of Kaiserslautern, Germany*

1. Introduction
2. Definitions, physical and mathematical models
  - 2.1. Classes of Cyclic Processes
  - 2.2. System Models
    - 2.2.1. Transfer Function Models
    - 2.2.2. Finite Horizon Operator Models
3. Repetitive and iterative learning control schemes
4. Designing ILC for real world applications
  - 4.1. ILC as an Inverse Problem
  - 4.2. Delays and Degree of Difference
  - 4.3. Derivation of the Design Equation of ILC
  - 4.4. Optimizing ILC
  - 4.5. Design Aspects
  - 4.6. Signal Conditioning
5. Robustness issues and focus of research
  - 5.1. Robustness Against Model Inaccuracies
  - 5.2. Robustness Against Measurement Noise
  - 5.3. Robustness Against Initial State Variations
  - 5.4. Focus of Research
6. Industrial application examples
  - 6.1. Iterative Learning Control of the Aluminium Extrusion Process
  - 6.2. Controlling Multiple Input/Multiple Output Systems using ILC
  - 6.3. Repetitive Control of a Scanner Mirror
7. Conclusion

**Index****181****About EOLSS****185****VOLUME XI****Model-based Predictive Control****1**Edoardo Mosca, *University of Florence, Italy*

1. Introduction

2. The Constrained Open-Loop Optimal Control (COLOC) Problem
3. Zero Terminal-State MBPC
4. Set-Membership Terminal Constraint
5. Time-Varying Ellipsoidal Terminal Constraint
6. Models, Disturbances and Robustness
7. Predictive Command Governors
8. Conclusive Remarks

### **Model Based Predictive Control for Linear Systems**

24

Robin DE KEYSER, *Ghent University, Belgium*

1. Introduction
2. The MBPC Principle
3. SISO MBPC
  - 3.1. The Process Model
  - 3.2. The EPSAC Approach to MBPC
    - 3.2.1. The Multistep Predictor
    - 3.2.2. The Predictive Controller
4. Extensions
  - 4.1. Stability and Robustness
  - 4.2. Numerical Stability: Singular Value Decomposition and Principal Components Analysis
  - 4.3. Nonlinear EPSAC (NEPSAC)
5. MIMO MBPC
  - 5.1. The Method
  - 5.2. The Control Objective
6. Constrained Control

### **Nonlinear Model Predictive Control**

59

Frank Allgöwer, *Institute for Systems Theory in Engineering, University of Stuttgart, 70550 Stuttgart, Germany*Rolf Findeisen, *Institute for Systems Theory in Engineering, University of Stuttgart, 70550 Stuttgart, Germany*Christian Ebenbauer, *Institute for Systems Theory in Engineering, University of Stuttgart, 70550 Stuttgart, Germany*

1. Introduction
  - 1.1. The Basic Principle of Model Predictive Control
  - 1.2. Mathematical Formulation of NMPC
  - 1.3. Properties, Advantages, and Drawbacks of NMPC
2. Theoretical Aspects of NMPC
  - 2.1. Stability
    - 2.1.1. Infinite Horizon NMPC
    - 2.1.2. Finite Horizon NMPC Schemes with Guaranteed Stability
  - 2.2. Performance of Finite Horizon NMPC Formulations
  - 2.3. Robust Stability
    - 2.3.1. Inherent Robustness of NMPC
    - 2.3.2. Robust NMPC Schemes
  - 2.4. Output Feedback NMPC
    - 2.4.1. Stability of Output-Feedback NMPC
3. Computational Aspects of NMPC
  - 3.1. Solution Methods for the Open-Loop Optimal Control Problem
  - 3.2. Solution of the NMPC Problem Using Direct Methods
    - 3.2.1. Efficient Solution of the Open-Loop Optimal Control Problem
    - 3.2.2. Efficient NMPC Formulations
4. Conclusions and Outlook
  - 4.1. Outline of Stability Proof for NMPC with Terminal Cost/Penalty

**Controls of Large-Scale Systems****85**M. Jamshidi, *ACE Center, The University of New Mexico, USA*

1. Historical Background
2. Modeling and Model Reduction
  - 2.1. Aggregation
    - 2.1.1. Balanced Aggregation
  - 2.2. Perturbation
    - 2.2.1. Weakly Coupled Models
3. Strongly Coupled Models
4. Hierarchical Control
  - 4.1. Goal Coordination: Interaction Balance
  - 4.2. Interaction Prediction
5. Decentralized Control
  - 5.1. Stabilization Problem
  - 5.2. Fixed Modes and Polynomials
  - 5.3. Stabilization via Dynamic Compensation
6. Conclusion

**Control of Stochastic Systems****109**P.R. Kumar, *Department of Electrical and Computer Engineering, and Coordinated Science Laboratory, University of Illinois, Urbana-Champaign, USA.*

1. Introduction
2. Models of Stochastic Systems
3. Optimal Stochastic Control
4. Stability of Stochastic Systems
5. Estimation of Stochastic Systems
6. Identification and Parameter Estimation of Stochastic Systems
7. Control of Partially Observed Systems
8. Adaptive Control

**Models of Stochastic Systems****127**Andrzej W. Ordys, *Industrial Control Centre, University of Strathclyde, UK*Joseph Bentsman, *Mechanical and Industrial Engineering Department, University of Illinois at Urbana-Champaign, USA*

1. Introduction
2. Random variables
  - 2.1. Probability Density Function
  - 2.2. Expectation Operator
    - 2.2.1. The Mean Value
    - 2.2.2. The Covariance Matrix
  - 2.3. The Gaussian Probability Density Function
  - 2.4. Conditional Probability
  - 2.5. Conditional Expectation Operator
  - 2.6. Independent Random Vectors
  - 2.7. Characteristic Function
    - 2.7.1. Characteristic Function for Gaussian Probability Density
  - 2.8. Characteristic Function for Independent Random Vectors
3. Description of stochastic process
  - 3.1. Correlation and Crosscorrelation
  - 3.2. White Noise
  - 3.3. Wiener Process, or Brownian Motion
  - 3.4. Stationary Processes
  - 3.5. Ergodicity

- 3.6. Continuous and Discrete Time Random Processes
- 4. Finite dimensional approximations
  - 4.1. Markov Process
  - 4.2. The Chapman-Kolmogorov Equation
  - 4.3. Hidden Markov Processes
  - 4.4. Homogeneous Markov Process
  - 4.5. The Fokker-Planck Equation
  - 4.6. Spectra of Continuous-time Random Processes
    - 4.6.1. Power Density Spectra and Colored Noise
  - 4.7. Spectra of Discrete Time Random Processes
  - 4.8. Polynomial Approximation
    - 4.8.1. MA Model
    - 4.8.2. AR Model
    - 4.8.3. ARMA Model
- 5. Mixed stochastic-deterministic systems
  - 5.1. CARMA/CARIMA and Box-Jenkins Models
  - 5.2. State-space Approximation
- 6. Stochastic differential equations
  - 6.1. Definition of a Stochastic Differential Equation
  - 6.2. Relation between Differential Equations in the sense of Ito and Stratonovich Wong-Zakai Correction
- 7. Conclusions

**Stochastic Stability****159**H.J. Kushner, *Applied Mathematics, Brown University, Providence, RI, USA.*

- 1. Introduction: The Stochastic Stability Problem
- 2. Stability and Liapunov Functions
- 3. The Stochastic Problem: Definitions and Preliminaries
- 4. Stochastic Liapunov Functions
- 5. Examples and the Perturbed Liapunov Function

**Minimum Variance Control****176**P.J. Gawthrop, *University of Glasgow, Scotland*

- 1. Introduction
- 2. Prediction
  - 2.1. Discrete-Time Model
    - 2.1.1. Initial conditions
    - 2.1.2. Stochastic Interpretation
    - 2.1.3. Generalized prediction
  - 2.2. Continuous-time model
  - 2.3. Long-Range Prediction
- 3. Control
  - 3.1. Choice of design parameters
  - 3.2. Integral action
- 4. Further illustrative examples
- 5. Relation to other control methods
- 6. Future prospects

**LQ-stochastic Control****197**João Miranda Lemos, *INESC-ID/IST, Lisbon, Portugal*

- 1. Introduction
- 2. LQ Regulation for Discrete Time Plants



- 2.1. Complete State Information
- 2.2. Partial State Information: The LQG Regulator in Discrete Time
- 2.3. The Steady-State Solution: StateSpace (Discrete Time)
- 3. Polynomial Approach
- 4. Reduced Complexity Regulators
- 5. The Servo Problem
- 6. LQ Stochastic Control of Continuous Time Plants
  - 6.1. The LQS Regulation Problem with Complete State Observations (Continuous Time)
  - 6.2. Partial State Observations (Continuous Time)
  - 6.3. The Steady-State Solution (Continuous Time)
- 7. Relation to Other Approaches
  - 7.1. LQG/LTR Regulator Design
  - 7.2. Minimax LQS and  $H_\infty$  Regulation
  - 7.3. The Entropy Approach to LQ Stochastic Control
- 8. Conclusion

**Dynamic Programming****232**P. R. Kumar, *Department of ECE, University of Illinois, USA*

- 1. An Example to Illustrate the Dynamic Programming Method
- 2. Finite Horizon Discrete Time Deterministic Systems
  - 2.1. Extensions
- 3. Finite Horizon Continuous Time Deterministic Systems
- 4. Time Varying Systems
- 5. Finite Horizon Discrete Time Stochastic Systems
- 6. Infinite Horizon Cost Functions
- 7. The Total Cost over an Infinite Horizon
- 8. The Discounted Cost Problem
- 9. The Average Cost Problem
- 10. Continuous Time Stochastic Systems

**Index****251****About EOLSS****259****VOLUME XII****Control of Nonlinear Systems****1**Hassan K. Khalil, *Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824-1226, USA*

- 1. Introduction
- 2. Stability
  - 2.1. Lyapunov Stability
  - 2.2. Input-Output Stability
  - 2.3. Passivity
  - 2.4. Feedback Systems
- 3. Sensitivity Analysis and Asymptotic Methods
- 4. Linearization and Gain Scheduling
- 5. Nonlinear Geometric Methods
- 6. Feedback Linearization
- 7. Robust Control
- 8. Nonlinear Design
- 9. Output Feedback Control

10. Nonlinear Output Regulation
11. Further Reading

**Analysis of Nonlinear Control Systems****24**Hassan K. Khalil, *Department of Electrical and Computer Engineering, Michigan State University, USA.*

1. Introduction
2. Fundamental Properties
3. Sensitivity Analysis
4. The Small-gain Theorem
5. Passivity Theorems
6. Averaging
7. Singular Perturbations
8. Further Reading

**Lie Bracket****42**Kurt Schlacher, *Department for Automatic Control and Control Systems Technology, Johannes Kepler University Linz, Austria*

1. Introduction
2. Basics of Manifolds and Bundles
  - 2.1. Manifolds
    - 2.1.1. Fibered Manifolds and Bundles
  - 2.2. Flow, Tangent Vectors and Tangent Bundle
3. Lie Derivatives and the Lie Bracket
4. Distributions and the Theorem of Frobenius
5. A Short Example
6. Concluding Remarks

**Differential Geometric Approach and Application of Computer Algebra****63**Kurt Schlacher, *Department for Automatic Control and Control Systems Technology, Johannes Kepler University Linz, Austria*

1. Introduction
2. Remarks on Symbolic Computation
3. Some Mathematical Facts
  - 3.1. Jet Manifolds
  - 3.2. An Algebraic Picture of Submanifolds
  - 3.3. Formal Integrability of Differential Equations
  - 3.4. The Theorems of Frobenius
4. Equivalence Problems
5. Some Applications
  - 5.1. Accessibility
  - 5.2. Observability
  - 5.3. Input to State Linearization
  - 5.4. Descriptor Systems
6. Concluding Remarks

**Volterra and Fliess Series Expansion****92**Francoise Lamnabhi-Lagarrigue, *Laboratoire des Signaux et Systèmes, CNRS, Supelec, France*

1. Introduction
2. Functional representation of nonlinear systems
  - 2.1. Volterra Functional Series

- 2.2. On the Convergence of Volterra Series
- 3. Recursive computation of the kernels.
  - 3.1. Exponential Input Method
  - 3.2. Differential Geometry Approach
  - 3.3. Algebraic Approach
  - 3.4. Links between Volterra and Fliess Series
  - 3.5. Efficient Computation of Volterra Kernels
- 4. Computation of the response to typical inputs
  - 4.1. Transfer Function Approach: Association of Variables
  - 4.2. Algebraic Approach

**Lyapunov Stability****115**Hassan K. Khalil, *Department of Electrical and Computer Engineering, Michigan State University, USA.*

- 1. Introduction
- 2. Autonomous Systems
- 3. The Invariance Principle
- 4. Linear Systems
- 5. Linearization
- 6. Non-autonomous Systems
- 7. Further Reading

**Input-output Stability****128**Stephen P. Banks, *Department of Automatic Control and Systems Engineering, University of Sheffield, Sheffield S1 3JD, UK.*

- 1. Introduction
- 2. Signals and Norms
- 3. Systems and Gains
- 4. The Circle Theorem
- 5. Passivity
- 6. Interconnected Systems, Graphs and Robustness
- 7. Conclusions and Further Developments

**Controllability and Observability of Nonlinear Systems****145**Henri Huijberts, *Department of Engineering, Queen Mary University of London, , United Kingdom*  
Henk Nijmeijer, *Department of Mechanical Engineering, Eindhoven University of Technology, , The Netherlands*

- 1. Introduction
- 2. Preliminaries
- 3. Controllability and accessibility
  - 3.1. Controllability and Linearization
  - 3.2. Driftless Systems
  - 3.3. Systems with Drift
- 4. Observability

**Design for Nonlinear Control Systems****167**Alberto Isidori, *Dipartimento di Informatica e Sistemistica, Università di Rome "La Sapienza" and Department of Systems Science and Mathematics, Washington University in St. Louis, Italy*

- 1. Introduction
- 2. State-feedback design for global stability
- 3. State-feedback design for robust global stability

4. Semiglobal and practical stabilization
5. Output-feedback design
6. Conclusions

<b>Feedback Linearization of Nonlinear Systems</b>	<b>193</b>
<i>Alberto Isidori, Dipartimento di Informatica e Sistemistica, Università di Roma "La Sapienza" and Department of Systems Science and Mathematics, Washington University in St. Louis, Italy</i>	
<i>Claudio De Persis, Dipartimento di Informatica e Sistemistica, Università di Roma "La Sapienza", Italy.</i>	

1. The problem of feedback linearization
2. Normal forms of single-input single-output systems
3. Conditions for exact linearization via feedback

<b>Index</b>	<b>215</b>
--------------	------------

<b>About EOLSS</b>	<b>219</b>
--------------------	------------

## VOLUME XIII

<b>Nonlinear Output Regulation</b>	<b>1</b>
<i>Alberto Isidori, Dipartimento di Informatica e Sistemistica, Università di Roma "La Sapienza" and Department of Systems Science and Mathematics, Washington University in St. Louis, Italy.</i>	
<i>Claudio De Persis, Dipartimento di Informatica e Sistemistica, Università di Roma "La Sapienza", Italy.</i>	

1. The problem of output regulation
2. Output regulation in the case of full information
3. Output regulation in the case of error feedback
4. Structurally stable regulation

<b>Nonlinear Zero Dynamics in Control Systems</b>	<b>24</b>
<i>Pramit Sarma, Technology Consultant - Advanced Process Control, Corporate Technology, Birla Management Corporation, Mumbai 400021, India.</i>	
<i>Bijnan Bandyopadhyay, Systems and Control Engineering, Indian Institute of Technology - Bombay, Mumbai 400 076, India</i>	

1. Introduction
2. Nonlinear Control System Paradigms
  - 2.1. Exact / Feedback Linearizing Control
  - 2.2. Backstepping Control
  - 2.3. Differentially Flat Control
  - 2.4. Variable Structure Control
3. Zero Dynamics in Control Systems
  - 3.1. Zero Dynamics in Linear Control Systems
  - 3.2. Zero Dynamics in Nonlinear Control Systems
4. Nonminimum Phase Control Systems: Difficulties and Partial Solutions
  - 4.1. Linear Nonminimum Phase Control Systems
  - 4.2. Nonlinear NMP Control Systems. Case 1: Restricted input-affine
    - 4.2.1. Nonlinear NMP Control Systems. Case 2: Semi-analytic input-affine
  - 4.3. Nonlinear NMP Control Systems. Case 3: Slightly NMP input-affine
  - 4.4. Nonlinear NMP Control Systems. Case 4: Differentially Flat Systems
5. Conclusion

**Flatness Based Design****65**Ph. Martin, *Ecole des Mines de Paris, CAS, Paris, France*R. Murray, *California Institute of Technology, CDS, Pasadena, USA*P. Rouchon, *Ecole des Mines de Paris, CAS, Paris, France*

1. Introduction
2. Equivalence and flatness
  - 2.1. Control Systems as Infinite Dimensional Vector Fields
  - 2.2. Equivalence of Systems
  - 2.3. Differential Flatness
  - 2.4. Trajectory Generation
3. Feedback design with equivalence
  - 3.1. From Equivalence to Feedback
  - 3.2. Endogenous Feedback
  - 3.3. Tracking: Feedback Linearization
4. Checking flatness: an overview
  - 4.1. The General Problem
  - 4.2. Known Results
5. Concluding Remarks

**Lyapunov Design****90**Shuzhi Ge, *Department of Electrical and Computer Engineering, The National University of Singapore, Singapore*

1. Introduction
2. Control Lyapunov Function
3. Lyapunov Design via Lyapunov Equation
  - 3.1. Lyapunov Equation
  - 3.2. MRAC for Linear Time Invariant Systems
  - 3.3. MRAC for Nonlinear Systems
4. Lyapunov Design for Matched and Unmatched Uncertainties
  - 4.1. Lyapunov Design for Systems with Matched Uncertainties
    - 4.1.1. Lyapunov Redesign
    - 4.1.2. Adaptive Lyapunov Redesign
    - 4.1.3. Robust Lyapunov Redesign
  - 4.2. Backstepping Design for Systems with Unmatched Uncertainties
    - 4.2.1. Backstepping for Known Parameter Case
    - 4.2.2. Adaptive Backstepping for Unknown Parameter Case
    - 4.2.3. Adaptive Backstepping with Tuning Function
5. Property-based Lyapunov Design
  - 5.1. Physically Motivated Lyapunov Design
  - 5.2. Integral Lyapunov Function for Nonlinear Parameterizations
6. Design Flexibilities and Considerations
7. Conclusions

**Sliding Mode Control****130**Vadim Utkin, *The Ohio State University, Columbus, Ohio, USA*

1. Introduction
2. Concept “Sliding Mode”
3. Sliding Mode Equations
4. Existence Conditions
5. Design Principles
6. Discrete-Time Sliding Mode Control
7. Chattering Problem
8. Induction Motor Control

## 9. Conclusion

**Nonlinear Observers****153**A. J. Krener, *University of California, Davis, CA, USA*

1. Introduction
2. Observability
3. Construction of Observers by Linear Approximation
4. Construction of Observers by Error Linearization
5. High Gain Observers
6. Nonlinear Filtering
7. Minimum Energy and  $H^\infty$  Estimation
8. Multiple Extended Kalman Filters
9. Conclusion

**State Reconstruction in Nonlinear Stochastic Systems by Extended Kalman Filter****180**R. Unbehauen, *Friedrich Alexander University Erlangen-Nuremberg, Germany*

1. Introduction
2. The continuous-time extended Kalman filter
  - 2.1. State Estimation of Stochastically Excited Nonlinear Systems
    - 2.1.1. Preparations
    - 2.1.2. Design equations
    - 2.1.3. Dynamics of the estimation error
    - 2.1.4. Examples
  - 2.2. State Estimation of Deterministic Nonlinear Systems
    - 2.2.1. Preparations
    - 2.2.2. Dynamics of the estimation error
    - 2.2.3. Examples
3. The discrete-time extended Kalman filter
  - 3.1. Preparations
  - 3.2. Design Equations
  - 3.3. Dynamics of the estimation error
  - 3.4. Examples

**Passivity Based Control****206**Antonio Loria, *CNRS, LSS-Supélec, Plateau de Moulon, 91192, Gif sur Yvette, France*Henk Nijmeijer, *Departments of Mech. Engg., Eindhoven Univ. of Technology, The Netherlands*

1. Introduction
2. Passivity: mathematically speaking
  - 2.1. In a General Input-Output Framework
3. Stability of passive systems
  - 3.1.  $L_2$ -Stability
  - 3.2. From  $L_2$ -Stability to Lyapunov Stability
4. PBC of Euler-Lagrange systems
  - 4.1. Passivity of EL Systems
  - 4.2. PBC of EL Systems
    - 4.2.1. An Introductory Example
    - 4.2.2. Lyapunov Stability of the ES+DI Controllers
  - 4.3. EL Controllers
  - 4.4. Tracking a Time-varying Reference
5. Epilogue

**Control of Chaos and Bifurcations****230**Alexander L. Fradkov, *Institute for Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, RUSSIA*Guanrong Chen, *Center for Chaos and Complex Networks, City University of Hong Kong, CHINA*

1. Introduction
2. Features of Chaos
3. Methods of Chaos Control
  - 3.1. Feedforward Control by Periodic Signal
  - 3.2. Linearization of Poincaré Map (OGY Method)
  - 3.3. Delayed Feedback (Pyragas Method)
  - 3.4. Linear and Nonlinear Control
  - 3.5. Robust, Adaptive and Intelligent Control
  - 3.6. Generation of Chaos (Chaotization)
4. Bifurcations Control
  - 4.1. Feedback Control
  - 4.2. Washout-Filter-Aided Control
  - 4.3. Normal-Form-Based Control
  - 4.4. Frequency-Domain Method
5. Applications in Science
  - 5.1. Physics
  - 5.2. Mechanics
  - 5.3. Chemistry
  - 5.4. Economy
  - 5.5. Medicine
6. Applications in Technology
  - 6.1. Mechanical Engineering
  - 6.2. Electrical and Power Engineering
  - 6.3. Communication and Information
  - 6.4. Chemical and Material Engineering
  - 6.5. Miscellaneous Applications
7. Prospects of the Field
8. Conclusions

**Control of Bifurcations****260**Guanrong Chen, *Center for Chaos Control and Synchronization, City University of Hong Kong, P. R. China*

1. Introduction
2. Bifurcation Control - The New Challenge
3. Bifurcations in Control Systems
4. Preliminaries of Bifurcation Theory
  - 4.1. Bifurcations in One-dimensional Systems
  - 4.2. Hopf Bifurcation
5. State-Feedback Control of Bifurcations
  - 5.1. Control of Static Bifurcations
  - 5.2. Control of Hopf Bifurcation
6. Some Other Bifurcation Control Methods
  - 6.1. Washout-Filter Aided Bifurcation Control
  - 6.2. Normal Forms and Invariants Based Bifurcation Control
    - 6.2.1. Normal Forms Based Bifurcation Control
    - 6.2.2. Simplest Normal Forms and Bifurcation Control
  - 6.3. Harmonic Balance Approximations for Bifurcation Control
  - 6.4. Controlling Hopf Bifurcation in Discrete Maps
7. Controlling Multiple Limit Cycles
  - 7.1. Graphical Hopf Bifurcation Theorem
  - 7.2. Controlling the Birth of Multiple Limit Cycles

- 7.3. Controlling the Amplitudes of Limit Cycles
- 8. Potential Engineering Applications of Bifurcation Control
  - 8.1. Controlling Cardiac Alternans and Rhythms
  - 8.2. Controlling Axial Flow Compressors and Jet Engines
  - 8.3. Controlling Power Networks
  - 8.4. Application of Bifurcation Control in Mechanical Systems
- 9. Future Research Outlook

**Analysis of Chaotic Systems****298**

A.L. Fradkov, *Institute for Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia*

- 1. Introduction
- 2. Notion of chaos
  - 2.1. From Oscillations to Chaos: Evolution of the Concept of Oscillations
  - 2.2. Definition of a Chaotic System
- 3. Examples of chaotic systems
  - 3.1. Lorenz System and Chua circuit
  - 3.2. Examples of Discrete-time Chaotic Systems
- 4. Criteria for chaos
  - 4.1. Lyapunov and Bohl Exponents
  - 4.2. Poincaré Map and Delayed Coordinates
  - 4.3. Sharkovsky-Li-Yorke Criterion
  - 4.4. Homoclinic orbits, Shilnikov theorem and Melnikov function
- 5. Quantification of chaos
  - 5.1. Fractal Dimensions and Embedding
  - 5.2. Kolmogorov-Sinai Entropy

**Control of Chaotic Systems****325**

A. L. Fradkov, *Institute for Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, RUSSIA*

- 1. Introduction
- 2. Notion of chaos
- 3. Models of controlled systems and control goals
- 4. Methods of controlling chaos: continuous-time systems
  - 4.1. Feedforward Control by Periodic Signal
  - 4.2. Linearization of Poincaré Map (OGY Method)
  - 4.3. Delayed Feedback
  - 4.4. Linear and Nonlinear Control
    - 4.4.1. Feedback Linearization
    - 4.4.2. Goal Oriented Techniques
    - 4.4.3. Other Methods
  - 4.5. Adaptive Control
- 5. Discrete-time Control
- 6. Neural networks
- 7. Fuzzy systems
- 8. Control of chaos in distributed systems
- 9. Chaotic mixing
- 10. Generation of chaos (chaotization)
- 11. Other problems
- 12. Conclusions

**Index****363**



## VOLUME XIV

**Distributed Parameter Systems: An Overview****1**David L. Russell, *Department of Mathematics, Virginia Polytechnic Institute and State University USA*

1. Introduction : Mathematical Control Systems
  - 1.1. Finite Dimensional Systems
  - 1.2. Function Spaces as System Spaces
  - 1.3. Distributed Parameter Systems
2. Controllability and Stabilizability of PDE Control Systems
  - 2.1. Systems Modeled by Partial Differential Equations of Parabolic Type
  - 2.2. Systems Modeled by Partial  $t \geq t_0$  Differential Equations of Hyperbolic Type
  - 2.3. Plates, Beams, Elastic Systems
  - 2.4. Control via Duality; Additional Regularity
3. Additional Controllability Topics
  - 3.1. Controllable State Characterization via the Hilbert Uniqueness Approach
  - 3.2. Control of Systems Modeled by Functional Equations; Control Canonical Systems
4. Additional Distributed Parameter Control Topics; Optimal Control
  - 4.1. Background
  - 4.2. The LQG Approach to Distributed Parameter Control System Design
  - 4.3. The  $H^\infty$  Approach to Distributed Parameter Control System Design

**Controllability and Observability of Distributed Parameter Systems****57**Jerzy Klamka, *Institute of Automatic Control, Silesian Technical University, Gliwice, Poland*

1. Introduction
2. Controllability of infinite-dimensional systems
  - 2.1. Mathematical model
  - 2.2. Controllability conditions
3. Controllability of distributed parameter systems
  - 3.1. Mathematical model
  - 3.2. Controllability conditions
  - 3.3. Boundary controllability
4. Observability
  - 4.1. General results
  - 4.2. Observability of distributed parameter systems

**Controller Design for Distributed Parameter Systems****71**Youssef Toure, *Laboratoire Vision et Robotique UPRES EA 2078, Université d'Orléans-IUT de Bourges, 63 Avenue de Lattre de Tassigny, F-18020 Bourges Cedex, France*Joachim Rudolph, *Institut für Regelungs- und Steuerungstheorie, Technische Universität Dresden, Mommsenstr. 13, D-01062 Dresden, Germany*

1. Introduction
2. Control problems and control design methods
3. State space and semigroup approach
  - 3.1. Mathematical Model of a Heat Exchange Process
  - 3.2. Representation in State Space
  - 3.3. Abstract Boundary Control System
  - 3.4. Semigroup of the Open Loop System
4. Internal model boundary control
  - 4.1. Structure of the Closed Loop System and Control Problem

- 4.2. State Space Model
- 4.3. Control Synthesis and Closed Loop Operator
- 4.4. Controller Tuning and Experimental Results
- 5. Flatness-based approach
  - 5.1. Heat Equation Example
  - 5.2. Flatness-based Open-loop Control Design
  - 5.3. Motion Planning

### State Estimation in Distributed Parameter Systems

92

A.Vande Wouwer, *Facult Polytechnique de Mons, Belgium*  
 M. Zeitz, *University of Stuttgart, Germany*

- 1. Introduction
- 2. State Estimation Problem
  - 2.1. State Space Model
  - 2.2. Observability and Optimal Sensor Location
- 3. Optimal Estimation and Kalman Filtering
  - 3.1. Early Lumping Approach
  - 3.2. Late Lumping Approach
- 4. State Observers: Extension of Luenberger's Concept
  - 4.1. Linear Observers
  - 4.2. Nonlinear Observers
  - 4.3. Case Studies and Applications

### Time Delay Systems

116

Hugues Mounier, *Université de Paris Sud, Orsay, and École Nationale Supérieure des Mines de Paris, France*  
 Joachim Rudolph, *Technische Universität, Dresden, Germany*

- 1. Introduction
- 2. Examples of Delay Systems Derived from Distributed Parameter Systems
- 3. Controllability Notions for Linear Delay Systems
  - 3.1. Various approaches
  - 3.2. Weak Controllability
  - 3.3. Spectral Controllability
  - 3.4. Behavioral Controllability
  - 3.5. Controllability for Tracking:  $\delta$ -Freeness
- 4. Quasi-finite Systems
  - 4.1. Controllability and Open Loop Tracking
  - 4.2. Stabilization and Predictors
  - 4.3. Tracking with Stability of a First Order Model
- 5. An Example Stemming from the Wave Equation
  - 5.1. The Wave Equation Model
  - 5.2. Delay System Model
  - 5.3.  $\delta$ -Freeness
  - 5.4. Open Loop Motion Planning

### Control of 2-D Systems

141

Tadeusz Kaczorek, *Institute of Control and Industrial Electronics, Warsaw University of Technology, Warsaw, Poland*

- 1. Introduction
- 2. Standard models of 2-D linear systems
- 3. Relationships between models
- 4. Solutions to the standard 2-D models

5. Transfer matrices of 2-D models
6. Realization problem for 2-D linear systems
7. Stability and eigenvalue assignment
  - 7.1. BIBO Stability
  - 7.2. Eigenvalue Assignment
8. Controllability and observability
9. Applications of 2-D systems

**Generalised Multidimensional Discrete, Continuous-Discrete and Positive Systems** **158**  
 Tadeusz Kaczorek, *Institute of Control and Industrial Electronics, Warsaw University of Technology, Warsaw, Poland*

1. Introduction
2. Models of generalised multidimensional linear systems.
3. Relationship between models.
  - 3.1. Equivalent Roesser models for general models
  - 3.2. General models equivalent to Roesser models
  - 3.3. Some further transformations of 2-D models
4. Solutions to the 2-D models.
  - 4.1. General model and Fornasini-Marchesini models
  - 4.2. General and standard 2-D Roesser models
  - 4.3. Roesser model with extended inputs
5. Singular 2-D continuous-discrete linear models.
6. Positive 2-D models.
  - 6.1. General 2-D model
  - 6.2. Roesser model
  - 6.3. Continuous-discrete model
7. Positive realization problem for 2-D Roesser model.

**Controllability and Observability of 2D Systems** **191**  
 Klamka, J. , *Institute of Automatic Control, Technical University, Gliwice, Poland*

1. Introduction
2. Unconstrained controllability
  - 2.1. Mathematical model
  - 2.2. General response formula
  - 2.3. Controllability conditions
3. Singular systems
  - 3.1. Mathematical model
  - 3.2. Controllability conditions
4. Constrained controllability
  - 4.1. Admissible controls
  - 4.2. Controllability conditions
5. Positive systems
  - 5.1. The concept of positive systems
  - 5.2. Controllability conditions
6. Continuous-discrete systems
  - 6.1. Mathematical model
  - 6.2. Controllability conditions
7. Nonlinear systems
  - 7.1. Mathematical model
  - 7.2. Controllability conditions
8. Observability
  - 8.1. Mathematical model
  - 8.2. Observability conditions

**Industrial Applications of 2D Control Systems****210**Wellstead, P.E., *Control Systems Centre, UMIST, Manchester, UK.*

1. Introduction
2. Sheet Manufacturing Processes
  - 2.1. Polymer Blown Film Production
  - 2.2. The Paper Making Process
3. 2D models for sheet forming systems
  - 3.1. 2D ARMAX Models For Sheet Forming Systems
  - 3.2. 2D State Space Models
4. 2D ARMAX Estimation for Sheet Forming Systems
  - 4.1. 2D Recursive Estimation: Sensor Array Data
  - 4.2. 2D Recursive Estimation: Scanning Sensor Data
  - 4.3. 2D Support Estimation
5. 2D Controller Design for Sheet Forming Systems
  - 5.1. Input-Output Methods
  - 5.2. State Space Methods
6. Comparison of 2D Control of Sheet Forming Processes with Other Methods
  - 6.1. Interaction Matrix Models
  - 6.2. Basis Function Models
7. Sensor and Gauges for 2D Industrial Processes
  - 7.1. Dry Line Sensors
  - 7.2. Stationary Sensor Arrays
  - 7.3. Scanning Arrays
8. Concluding Remarks: 2D Actuation

**Stability of 2D Systems****230**P. A. Cook, *Control Systems Centre, Department of Electrical Engineering & Electronics, UMIST, Manchester, U.K.*

1. Introduction
2. Discrete Systems
  - 2.1. Input-Output Stability
  - 2.2. Asymptotic Stability
    - 2.2.1. Component-wise Stability
  - 2.3. Feedback System Stability
3. Discrete-Continuous Systems
4. Continuous Systems
5. Applications
  - 5.1. Compartmental Models
  - 5.2. Iterative Processes

**Index****241****About EOLSS****247****VOLUME XV****Discrete Event Systems****1**Christos G. Cassandras, *Dept. of Manufacturing Engineering, 15 St. Mary's St., Boston University, Brookline, MA 02446, USA*

1. Introduction
2. Event-driven and Time-driven Systems

3. Abstraction Levels in the Study of Discrete Event Systems
4. Modeling Overview
  - 4.1. Automata
    - 4.1.1. Queuing Systems
  - 4.2. Petri Nets
  - 4.3. Dioid Algebras
5. Control and Optimization of Discrete Event Systems

### **Modeling of Discrete Event Systems**

27

Stéphane Lafortune, *The University of Michigan, USA*

1. Introduction
  - 1.1. Formal Languages
2. Automata
  - 2.1. Basic Concepts
  - 2.2. Languages Represented by Automata
    - 2.2.1. Blocking: Deadlock and Livelock
  - 2.3. Accessibility Properties
  - 2.4. Nondeterministic Automata
3. Operations on Automata
  - 3.1. Product and Parallel Composition
  - 3.2. Example: Two Users of Two Common Resources
  - 3.3. Observer Automata
4. Regular Languages and Finite-state Automata
5. Petri Nets
  - 5.1. Petri Net Languages
  - 5.2. Matrix Algebra and Petri Net Dynamics
  - 5.3. Composition of Petri Nets
6. Process Algebras
7. Discussion on Timed Models

### **Supervisory Control of Discrete Event Systems**

51

Stéphane Lafortune, *The University of Michigan, USA*

1. Introduction
  - 1.1. Uncontrolled System
  - 1.2. Feedback Control
  - 1.3. Industrial Applications of Supervisory Control Theory
  - 1.4. Supervisor Design: Illustrative Example
2. Control of Fully-Observed Discrete Event Systems
  - 2.1. Controllability Theorem
  - 2.2. Realization of Supervisors
3. Control of Partially-Observed Discrete Event Systems
  - 3.1. Controllability and Observability Theorem
  - 3.2. Realization of P-supervisors
4. Avoiding Deadlock and Livelock
  - 4.1. Nonblocking Controllability and Observability Theorem
5. Controller Synthesis Techniques
  - 5.1. Dealing with Uncontrollability
    - 5.1.1. Supremal Controllable Sublanguage
    - 5.1.2. BSCP: Basic Supervisory Control Problem
    - 5.1.3. BSCP-NB: Basic Supervisory Control Problem Nonblocking Case
    - 5.1.4. Infimal Controllable Superlanguage
    - 5.1.5. DuSCP: Dual Version of BSCP
  - 5.2. Dealing with Unobservability
    - 5.2.1. Observable Sublanguages

- 5.2.2. Infimal Observable Superlanguage
- 5.2.3. Supervisory Control Problems with Partial Observation
- 6. Discussion

**Sample Path Analysis of Discrete Event Dynamic Systems (DEDS)****75**Yu-Chi Ho, *Harvard University, USA*Xi-Ren Cao, *Hong Kong University of Science and Technology, Hong Kong, China*

- 1. Introduction
- 2. Perturbation Analysis
  - 2.1. Formulation of Infinitesimal Perturbation Analysis
  - 2.2. Perturbation Generation and Propagation for IPA
  - 2.3. Unbiasedness and Consistency
  - 2.4. Finite PA and Other Generalizations
- 3. Markov Potential Theory Based Sample Path Sensitivity
- 4. Other Approaches: the Likelihood Ratio Method
- 5. Sample Path Based Optimization
  - 5.1. Continuous Variables: Stochastic Approximation Plus PA
  - 5.2. Discrete Policy Space: Online Markov Decision Processes

**Hybrid Control Systems****94**Karl Henrik Johansson, *Royal Institute of Technology, Stockholm, Sweden*

- 1. Introduction
  - 1.1. Hybrid Systems
  - 1.2. Applications
- 2. What is a Hybrid Control System?
  - 2.1. Continuous and Discrete Control Systems
  - 2.2. Hybrid Automaton
- 3. Analysis and Design of Hybrid Control Systems
  - 3.1. Modeling
  - 3.2. Analysis
    - 3.2.1. Stability
    - 3.2.2. Verification
  - 3.3. Control Design
    - 3.3.1. Supervisory Control
    - 3.3.2. Optimal Control

**Modeling of Hybrid Systems****114**Karl Henrik Johansson, *Dept. of Signals, Sensors & Systems, Royal Institute of Technology, Sweden*John Lygeros, *Department of Electrical and Computer Engineering, University of Patras, Greece*Shankar Sastry, *Dept. of Electrical Engineering and Computer Sciences, University of California, Berkeley, USA*

- 1. Introduction
- 2. Examples of Hybrid Systems
  - 2.1. Water Tank System
  - 2.2. Bouncing Ball
  - 2.3. Clegg Integrator
  - 2.4. Thermostat
  - 2.5. Gear Shift Control
  - 2.6. Swing-Up of Inverted Pendulum
  - 2.7. Computer-Controlled System
  - 2.8. Automated Highway System
- 3. Mathematical Models for Hybrid Systems

- 3.1. Modeling Issues
- 3.2. Hybrid Automata
- 3.3. Executions
- 4. Properties of Hybrid Systems
  - 4.1. Overview of Issues
  - 4.2. Existence of Executions
  - 4.3. Uniqueness of Executions
  - 4.4. Zeno Executions
- 5. Software Tools

**Well-posedness of Hybrid Systems****139**M. Kanat Camlibel, *Dept. of Electronics and communication Eng., Doğus University, Istanbul, Turkey*W.P.M.H. Heemels, *Dept. of Electrical Eng., Eindhoven Uni. of Technology, Eindhoven, The Netherlands*A. J. van der Schaft, *Fac. of Mathematical Sciences, University of Twente, Enschede, The Netherlands*J. M. Schumacher, *Dept. of Econometrics and Oper. Res., Tilburg University, Tilburg, The Netherlands*

- 1. Introduction
- 2. Model Classes
  - 2.1. The Hybrid Automaton Model
  - 2.2. Explicit State-space Model
  - 2.3. Supervisor Model
  - 2.4. Differential Inclusions
  - 2.5. Complementarity Systems
  - 2.6. Event/Flow Formulas
- 3. Solution Concepts
- 4. Well-posedness Notions
- 5. Well-posedness of Hybrid Automata
- 6. Well-posedness of Multi-modal linear Systems
- 7. Complementarity systems
  - 7.1. Linear Complementarity Systems
    - 7.1.1. Linear Complementarity Systems with Index 1
    - 7.1.2. Linear Passive Complementarity Systems
  - 7.2. Piecewise Linear Systems
  - 7.3. Variations and Generalizations
- 8. Differential Equations with Discontinuous Right-hand Sides

**Stability of Hybrid Systems****167**Michael S. Branicky, *Electrical Engineering and Computer Science Department, Case Western Reserve University, USA*

- 1. Background and Motivation
  - 1.1. What is a Hybrid System?
  - 1.2. Why a Different Theory for Hybrid Systems?
- 2. Early Results
- 3. Stability via Multiple Lyapunov Functions
- 4. Further Results
  - 4.1. Applications

**Bisimulations of Discrete, Continuous, and Hybrid Systems****194**George J. Pappas, *University of Pennsylvania, Philadelphia, PA 19102. USA*

- 1. Introduction
- 2. Bisimulations of transition systems
  - 2.1. Language Equivalence and Linear Temporal Logic

- 2.2. Bisimulation Partitions
- 3. Bisimulation of continuous systems
  - 3.1. Proposition Preserving Partitions
  - 3.2. Quotient Construction
  - 3.3. Bisimulation Characterization and Algorithm
- 4. Bisimulations of hybrid systems
  - 4.1. Transition Systems of Hybrid Systems
  - 4.2. Rectangular, Multirate, and Timed Automata
  - 4.3. Bisimulations of Timed and Multirate Automata
  - 4.4. O-minimal Hybrid Systems
- 5. Conclusions

**Optimal Control of Hybrid Systems****219**

Sven Hedlund, *Department of Automatic Control, Lund Institute of Technology, Lund, Sweden*  
 Anders Rantzer, *Department of Automatic Control, Lund Institute of Technology, Lund, Sweden*

- 1. Introduction
- 2. Hybrid Dynamic Programming
  - 2.1. Dynamic Programming in Discrete Systems
  - 2.2. Dynamic Programming in Continuous Systems
  - 2.3. Dynamic Programming for Hybrid Systems
- 3. Related Theory and Special Cases
  - 3.1. A Hybrid Maximum Principle
  - 3.2. Safety Verification and Reachability
  - 3.3. Timed Automata

**Verification of Hybrid Systems****230**

Claire J. Tomlin, *Department of Aeronautics and Astronautics, Stanford University, Stanford CA 94305-4035, USA*  
 Ian Mitchell, *Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94709, USA*  
 Alexandre M. Bayen, *Department of Aeronautics and Astronautics, Stanford University, Stanford CA 94305-4035, USA*  
 Meeko Oishi, *Department of Mechanical Engineering, Stanford University, Stanford CA 94305-4035, USA*

- 1. Introduction
- 2. Hybrid Model and Verification Methodology
  - 2.1. Continuous, Discrete, and Hybrid Systems
  - 2.2. Safety Verification
- 3. Verifying Continuous Systems
  - 3.1. A Game of Two Identical Vehicles
  - 3.2. Computing Reachable Sets for Continuous Dynamic Games
  - 3.3. Collision Avoidance Example Results
- 4. Verifying Hybrid Systems
  - 4.1. Background
  - 4.2. Computing Reachable Sets for Hybrid Systems
- 5. Flight Management System Example
- 6. Conclusions

**Stabilization through Hybrid Control****258**

Joao Pedro Hespanha, *Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106-9560, USA*

- 1. Introduction



2. Switched Systems
  - 2.1. Stability under Arbitrary Switching
  - 2.2. Stability under Slow Switching
  - 2.3. Stability under State-dependent Switching
3. Supervisors
  - 3.1. Dwell-time Supervisors
  - 3.2. Hysteresis-based Supervisors
4. Case Studies
  - 4.1. Vision-based Control of a Flexible Manipulator
  - 4.2. Hybrid Adaptive Set-point Control

**Case Study: Air Traffic Management Systems****308**

Alexandre M. Bayen, *Department of Aeronautics and Astronautics, Stanford University, USA*  
 Claire J. Tomlin, *Department of Aeronautics and Astronautics, Stanford University, USA*

1. Introduction
2. A short History of Air Traffic Control
3. Organization of Air Traffic Control
  - 3.1. Airspace Structure
  - 3.2. Navigation and Surveillance
  - 3.3. Communication and Procedures
4. Levels of Automation in the Current System
  - 4.1. NAS and ATC Models
    - 4.1.1. Aircraft Model
    - 4.1.2. Lagrangian Delay Propagation Model
    - 4.1.3. Human Air Traffic Controller Model
    - 4.1.4. Validation of the Models
  - 4.2. Onboard and Ground Automation
    - 4.2.1. TCAS: Onboard Collision Avoidance System
    - 4.2.2. Ground Automation Functionalities
  - 4.3. Open Problems for Automation
    - 4.3.1. Conflict Detection and Avoidance
    - 4.3.2. Traffic Optimization
5. Conclusions

**Index****349****About EOLSS****355****VOLUME XVI****Fault Diagnosis and Fault-tolerant Control****1**

Paul M. Frank, *Fellow IEEE, University Duisburg-Essen, Duisburg, Germany*  
 Mogens Blanke, *Technical University of Denmark, Lyngby, Denmark*

1. Introduction
2. Fault Diagnosis: Basic Definitions and Concepts
  - 2.1. Faults
  - 2.2. Unknown Inputs
  - 2.3. Tasks
  - 2.4. Residual Generation and Evaluation
3. Model-free Approaches to Fault Diagnosis
  - 3.1. Physical Redundancy Approach
  - 3.2. Signal-based Approach

- 3.3. Plausibility Check
4. Principles of Model-based Fault Diagnosis
  - 4.1. The Diagnostic Strategy
  - 4.2. Types of System Models
5. Analytical Methods of Model-based Residual Generation
  - 5.1. Analytical Modeling of the System
  - 5.2. Modeling of Faults
  - 5.3. Analytical Residual Generation
  - 5.4. Structured Residuals
  - 5.5. Robust Residual Generation
6. Knowledge-based Approaches to Model-based Residual Generation
7. Residual Evaluation
8. Historical Review of Fault Diagnosis Approaches
9. Fault-tolerant control
10. Determining appropriate reactions to faults
11. Analysis based on system structure
  - 11.1. Analytical Redundancy in a System
  - 11.2. Structural Controllability and Observability
12. Fault-tolerant control based on Diagnosis
  - 12.1. Active and Passive Approach to Fault-tolerant Control
  - 12.2. The Control Problem
  - 12.3. Sensor Faults
  - 12.4. Actuator Faults
  - 12.5. General Plant Faults
  - 12.6. Time to Reconfigure - A Requirement in Fault Tolerant Control
13. Conclusion

### **Fault Diagnosis for Linear Systems**

29

Paul M. Frank, *Gerhard-Mercator-University of Duisburg, Germany*

1. Introduction
2. Model of the system, faults and uncertainties
3. Methods of residual generation
4. Parity space approach to residual generation
5. Observer-based residual generation
  - 5.1. Fault Detection Filter
  - 5.2. Decoupling in the Frequency Domain - Fault Isolation
  - 5.3. Banks of Observers (Observer Schemes)
6. Fault analysis using parameter estimation
7. Residual evaluation
8. Conclusion and Perspectives

### **Fault Diagnosis for Nonlinear Systems**

54

Michel Kinnaert, *Université Libre de Bruxelles, Brussels, Belgium*  
 Joseph J. Yame, *Université Libre de Bruxelles, Brussels, Belgium*

1. Introduction
2. Model Classes
3. Residual Generator Design
  - 3.1. Problem Statement
  - 3.2. Principle of the Solution of the FPRG for Bilinear Systems
  - 3.3. Extension of the Solution to State-Affine Systems
  - 3.4. FPRG for Control Affine Systems
    - 3.4.1. Uniformly Observable System and High Gain Observer
    - 3.4.2. Fault Detection and Isolation in a Hydraulic System
  - 3.5. Analytical Redundancy Relations

4. Fuzzy Model Based Fault Detection for Nonlinear Systems
  - 4.1. Motivation
  - 4.2. Takagi-Sugeno Fuzzy Model
  - 4.3. Fuzzy Observer-Based Residual Generator
5. Conclusion

### **Design Methods for Robust Fault Diagnosis**

84

Ronald John Patton, *Department of Engineering, University of Hull, UK*  
 Jie Chen, *Department of Mechanical Engineering, Brunel University, UK*

1. Introduction
2. Model-based methods for FDI
  - 2.1. System Model
  - 2.2. Residual Generators
  - 2.3. Fault Detectability
3. Observer-based residual generation
4. The need for robustness in FDI
  - 4.1. Robustness to Disturbances
  - 4.2. Robustness to Modeling Errors
5. Robust FDI design using unknown input observers
6. Robust FDI design using eigenstructure assignment
  - 6.1. Residual Generation and Disturbance De-coupling Principle
  - 6.2. Disturbance De-coupling by Assigning Left Eigenvectors
  - 6.3. Disturbance De-coupling by Assigning Right Eigenvectors
7. Robust FDI design using  $H_\infty$  optimization
  - 7.1. Residual Generation within the  $H_\infty$  Framework
  - 7.2. Robust Residual with Disturbance Attenuation
  - 7.3. Fault Estimation with Disturbance Attenuation
8. Concluding Remarks

### **Qualitative Methods for Fault Diagnosis**

112

Jan Lunze, *Ruhr University Bochum, Germany*

1. Introduction
2. Basic properties of qualitative models
3. The diagnostic principle
4. Logic-based fault diagnosis
  - 4.1. The General Diagnostic Engine
  - 4.2. Basic Notions of Propositional Logic
  - 4.3. Assumption - Based Truth Maintenance System
  - 4.4. Extensions
5. Diagnosis of discrete-event systems
  - 5.1. Representation of Discrete-event Systems by Automata
  - 5.2. Diagnosis of Discrete-event Systems
  - 5.3. Example
6. Outlook

### **Statistical Methods for Change Detection**

130

Michele Basseville, *Institut de Recherche en Informatique et Systemes Aléatoires, Rennes, France*

1. Introduction
  - 1.1. Motivations for Change Detection
  - 1.2. Motivations for Statistical Methods
  - 1.3. Three Types of Change Detection Problems
2. Foundations-Detection

- 2.1. Likelihood Ratio and CUSUM Tests
  - 2.1.1. Hypotheses Testing
  - 2.1.2. On-line Change Detection
- 2.2. Efficient Score for Small Deviations
- 2.3. Other Estimating Functions for Small Deviations
- 3. Foundations-Isolation
  - 3.1. Isolation as Nuisance Elimination
  - 3.2. Isolation as Multiple Hypotheses Testing
  - 3.3. On-line Isolation
- 4. Case Studies-Vibrations

### **Industrial Applications of Fault Diagnosis**

146

Rolf Isermann, *Darmstadt University of Technology, Germany*  
 Dominik Fussel, *Darmstadt University of Technology, Germany*  
 Harald Straky, *Darmstadt University of Technology, Germany*

- 1. Introduction and Overview
  - 1.1. Main Application Areas
- 2. Methods
  - 2.1. Fault Detection Methods
    - 2.1.1. Parameter Estimation Methods and Signal Models
    - 2.1.2. Observers and State Estimation
    - 2.1.3. Parity Equations
  - 2.2. Fault Diagnosis Methods
    - 2.2.1. Classification Methods
    - 2.2.2. Fuzzy and Neuro-Fuzzy Approaches
- 3. Application Examples
  - 3.1. Fault Diagnosis of a Heat Exchanger
    - 3.1.1. Modeling and Identification
    - 3.1.2. Model-Based Fault Detection
    - 3.1.3. Fault Diagnosis
  - 3.2. Fault Diagnosis of an Electric Throttle Valve Actuator
  - 3.3. Fault Detection of a Solenoid Valve
    - 3.3.1. Modeling and Identification
    - 3.3.2. Fault Detection
- 4. Future Aspects

### **Off-Line Methods for Fault Diagnosis and Inspection**

168

Filbert, D., *Institute of Measurement and Control Science, Technical University Berlin, Berlin, Germany*

- 1. Introduction
- 2. Parameter Estimation
  - 2.1. Modeling the System under Test
  - 2.2. An Example of Modeling
  - 2.3. Excitation of the System under Test
- 3. Pattern Recognition for Fault Diagnosis
  - 3.1. Feature Evaluation and Selection
  - 3.2. Modeling and Simulation of the Vibration
  - 3.3. Modeling of the Vibration Generation
  - 3.4. Simulation of the Vibration Signal
  - 3.5. Modeling the Current Ripple Generation
    - 3.5.1. Modeling the Current Ripple of a Faultless Motor
    - 3.5.2. Modeling the Fault "Poor Bond at Commutator"

**Experience with Knowledge-Based Systems for Maintenance Diagnosis****191**Dieter Wach, *Institute for Safety Technology (ISTec), Garching near Munich, Germany*

1. Introduction
2. Development Steps in Methodology
  - 2.1. History of Early Fault Detection
  - 2.2. Needs for Knowledge-based Methods
3. Basic Characteristics of Early Fault Detection Methods
  - 3.1. Reference Signatures, Feature Extraction and Long-term Trending
  - 3.2. Model-based vs. Signal (Feature)-based Surveillance
  - 3.3. Signature Data Banks for Centralized Diagnosis Services
4. Condition Monitoring for Improved Maintenance in Nuclear Power Plants
  - 4.1. Systems and Diagnosis Experiences
  - 4.2. Investigations and Developments for Knowledge-based Diagnosis
5. Condition Monitoring for Improved Maintenance in Other Industries
  - 5.1. Examples from Aircraft Industry
  - 5.2. Examples from Car Industry (Motor Cars and Trucks)
  - 5.3. Examples from Railway Industry
6. Conclusions

**Fault Tolerant Systems****215**Marcel Staroswiecki, *Ecole Polytechnique Universitaire de Lille, University Lille I, France*

1. Introduction
2. Control and Fault Tolerant Control
  - 2.1. Control Problem
    - 2.1.1. Standard Control Problem
    - 2.1.2. The Control Problem with Uncertainties
  - 2.2. Fault Tolerant Control Problem
    - 2.2.1. Impact of Faults
    - 2.2.2. Passive vs Active Fault Tolerant Control
    - 2.2.3. Available Knowledge
    - 2.2.4. Active Fault Tolerant Control Strategies
    - 2.2.5. On-line vs Off-line Solution of the FTC Problem
  - 2.3. Supervision Problem
3. Model Matching and the Pseudo-inverse Method
  - 3.1. Nominal Solution
  - 3.2. Fault Accommodation
    - 3.2.1. Consistency Conditions still hold
    - 3.2.2. Consistency Conditions do not hold: Approximate Model Matching
  - 3.3. System Reconfiguration
4. Optimal Control: the LQ problem
  - 4.1. Nominal Solution
  - 4.2. Fault Tolerant Control and Admissible Solutions
    - 4.2.1. First Problem Setting
    - 4.2.2. Admissible Solutions
    - 4.2.3. General Problem Setting
  - 4.3. Fault Accommodation
    - 4.3.1. Identifying the Faulty System
    - 4.3.2. Accommodating the Control to the Faulty System
    - 4.3.3. Testing the Admissibility of the Accommodated Control
  - 4.4. System Reconfiguration
5. System reconfiguration and Structural Properties
  - 5.1. The set of system configurations
  - 5.2. Minimal Component Sets
  - 5.3. Critical Resources
  - 5.4. Evaluating the Fault Tolerance Capability

- 5.4.1. Redundancy Degrees
- 5.4.2. Reliability of Property  $p$
- 5.5. Fault Tolerance and Maintenance Design
  - 5.5.1. Condition Based Maintenance
  - 5.5.2. Systematic maintenance
- 6. Example
  - 6.1. Model Matching
  - 6.2. Optimal Control
  - 6.3. Reconfiguration and Observability
- 7. Conclusion

### **Fault-Tolerant Control Using LMI Design**

255

Jie Chen, *Department of Mechanical Engineering, Brunel University, Uxbridge, UB8 3PH, UK*  
 Ron J. Patton, *School of Engineering, University of Hull, Hull, HU6 7RX, UK*

- 1. Introduction
- 2. Active Fault-Tolerant control Systems Design Using LMI Design
  - 2.1. Fault-Tolerant Control System Formulation
  - 2.2. LMI Solution of Fault-Tolerant Control Systems Design
- 3. Fault Diagnostic Observer Design Using LMI Design for Uncertain Systems
  - 3.1. Takagi-Sugeno Fuzzy Model and Stability Analysis
    - 3.1.1. Takagi-Sugeno fuzzy Model
    - 3.1.2. Stability Analysis
    - 3.1.3. Eigenvalue assignment
  - 3.2. Fuzzy Observers and Residual Generation
- 4. Conclusion

### **Structural Analysis for Fault Detection and Isolation and for Fault Tolerant Control**

279

Marcel Staroswiecki, *LAIL-CNRS UMR 8021, Polytech'Lille, University Lille I, France*

- 1. Introduction
- 2. Structural model
  - 2.1. Structure as a Bipartite Graph
  - 2.2. Subsystems
  - 2.3. Structural Properties
- 3. Matching on a bipartite graph
  - 3.1. Definitions
  - 3.2. Oriented Graph Associated with a Matching
- 4. Causal interpretation
  - 4.1. Algebraic Constraints
  - 4.2. Differential Constraints
  - 4.3. Loops
- 5. System Decomposition
  - 5.1. Canonical Decomposition
  - 5.2. Causal Subsystems
- 6. Observability
  - 6.1. Structural Observability Conditions
  - 6.2. Graph Based Interpretation and Formal Computation
- 7. Monitorability
  - 7.1. Analytical Redundancy Based Fault Detection and Isolation
  - 7.2. The Structurally Monitorable Subsystem
  - 7.3. The Design of Robust and Structured Residual
- 8. Fault tolerant estimation
- 9. Controllability
  - 9.1. Structural Controllability Conditions
  - 9.2. Fault Tolerant Control

10. A simple example
11. Conclusion

### **Fault Accommodation Using Model Predictive Methods**

306

Jovan D. Boskovic, *Scientific Systems Company, Inc., Woburn, Massachusetts, USA*

Raman K. Mehra, *Scientific Systems Company, Inc., Woburn, Massachusetts, USA*

1. Introduction
  - 1.1. Model Predictive Control (MPC)
  - 1.2. Failure Accommodation
2. The Fault Accommodation Problem
3. Failure Modeling
4. Failure Accommodation
  - 4.1. Failure Detection and Identification (FDI)
  - 4.2. MMPC Derivation
5. Conclusions

### **Control Reconfiguration**

320

Jan Lunze, *The Institute of Automation and Computer Control, Ruhr University Bochum, Germany*

1. Introduction
2. Example
3. State of the Art
4. Reconfigurability Analysis
5. Reconfiguration Based on a Qualitative Model
6. Reconfiguration Based on Model-matching
7. Observer-based Control Reconfiguration
8. Reconfigurable Model-predictive Control
9. Outlook

### **Adaptive and Neural Approaches to Fault-tolerant Control**

334

Amit Patra, *Department of Electrical Engineering, Indian Institute of Technology, Kharagpur – 721 302, India*

S. Mukhopadhyay, *Department of Electrical Engineering, Indian Institute of Technology, Kharagpur – 721 302, India*

S. Sen, *Department of Electrical Engineering, Indian Institute of Technology, Kharagpur – 721 302, India*

1. Introduction
2. An Adaptive Approach to Actuator Fault Tolerant Control
  - 2.1. Model of a Space-craft Autopilot
  - 2.2. Design of Fixed Controllers
  - 2.3. Design of the Adaptive Controller
  - 2.4. Decision Logic
  - 2.5. Results and Discussions
3. A Neural Network Approach to Sensor Fault Tolerant Control
  - 3.1. Brief Description of the Tennessee Eastman Challenge Process
  - 3.2. Architecture of Sensor Fault Tolerant Control
    - 3.2.1. Scheme of Estimation of single sensor Faults
    - 3.2.2. ANN Model Selection and Training
      - 3.2.2.1. Modelling a Dynamic System with a Feed-forward ANN
      - 3.2.2.2. Selection of ANN Model Structure
  - 3.3. Results and discussions
4. A Neuro-Adaptive Approach to Process Fault Tolerant Control
  - 4.1. Brief description of the Adaptive Critic Algorithm

- 4.2. Realization of the Algorithm
- 4.3. Results and Discussions
- 5. Conclusions

**Index** **369**

**About EOLSS** **377**

## VOLUME XVII

### **Fuzzy Control Systems** **1**

Jens Jakel, *Institute of Applied Computer Science, Forschungszentrum Karlsruhe GmbH, Germany*  
 Ralf Mikut, *Institute of Applied Computer Science, Forschungszentrum Karlsruhe GmbH, Germany*  
 Georg Bretthauer, *Institute of Applied Computer Science, Forschungszentrum Karlsruhe GmbH, Germany*

- 1. Introduction
- 2. Fuzzy Control -A Simple Example
  - 2.1. Example
  - 2.2. Fuzzy Sets, Linguistic Variables and Fuzzy IF-THEN Rules
  - 2.3. Fuzzification - From Measurements to a Fuzzy Representation of the Input Situation
  - 2.4. Inference - From a Fuzzy Input Representation to a Fuzzy Decision
  - 2.5. Defuzzification - From a Fuzzy Decision to a Real Decision
- 3. Fuzzy Logic-related Issues in Fuzzy Control
  - 3.1. Fuzzy Sets and Operations
  - 3.2. Types of Rule-based Fuzzy Systems
  - 3.3. Information Processing in Fuzzy Systems
- 4. Control Issues in Fuzzy Control
  - 4.1. Structures in Fuzzy Control
  - 4.2. Design of Fuzzy Control Systems
  - 4.3. Analysis of Fuzzy Control Systems
  - 4.4. Applications
  - 4.5. Hardware and Software for Fuzzy Control Systems
  - 4.6. Further Concepts Based on Fuzzy Sets Applied to Control Systems
- 5. Conclusions

### **Data-Based Fuzzy Modeling** **37**

T. Slawinski, *Department of Control Engineering, University of Dortmund, Germany*  
 H. Kiendl, *Department of Control Engineering, University of Dortmund, Germany*

- 1. Introduction
- 2. Process of Data-Based Modeling
- 3. Concepts for Fuzzy Modeling
- 4. Established Methods
  - 4.1. Cluster-Based Fuzzy Modeling
  - 4.2. Neuro - Fuzzy Models
  - 4.3. Tree-Oriented Approach
  - 4.4. Rule-Oriented Approach
  - 4.5. Fuzzy Modeling based on Evolutionary Algorithms
    - 4.5.1. Pittsburgh Style
    - 4.5.2. Michigan Style
- 5. Conclusion and Perspectives



**Optimization of Fuzzy Controllers****54**J. Wernstedt, *Ilmenau University of Technology, Germany*

1. Introduction
2. Basic principles of optimization
3. Optimal Design of Fuzzy Controllers
  - 3.1. Design Steps
  - 3.2. Design of Fuzzy Systems and Fuzzy Controllers
  - 3.3. Modification of Optimality Criteria
    - 3.3.1. Integral Criteria
    - 3.3.2. Trajectory Criteria
    - 3.3.3. Guarantee of robustness
  - 3.4. Design of Parametric Fuzzy Concept
  - 3.5. Strategy of Optimum Fuzzy Control Design
4. Optimisation tools for fuzzy control
5. Applications
  - 5.1. Application for Simulation Purposes
  - 5.2. Fuzzy-adapted PID-Control of an Unstable Mechatronic System
6. Conclusions

**Analysis and Stability of Fuzzy Systems****81**Ralf Mikut, *Forschungszentrum Karlsruhe GmbH, Germany*Georg Bretthauer, *Forschungszentrum Karlsruhe GmbH, Germany*

1. Introduction
2. Transformation Approaches
  - 2.1. Overview
  - 2.2. Mamdani-type Fuzzy Systems
  - 2.3. Takagi-Sugeno-type Fuzzy Systems
3. Stability Analysis
  - 3.1. Overview
  - 3.2. Linearization
  - 3.3. Time-domain Methods
  - 3.4. Frequency-domain Methods
  - 3.5. Online Supervision with Fuzzy Methods
4. Further Tasks in the Analysis of Fuzzy Systems
  - 4.1. Fuzzy-specific Analysis Methods
  - 4.2. Performance Measures
  - 4.3. Robustness
5. Open Problems and Future Trends
6. Conclusions

**Fuzzy System Applications****107**Jens Jakel, *Institute of Applied Computer Science, Forschungszentrum Karlsruhe, Germany*Georg Bretthauer, *Institute of Applied Computer Science, Forschungszentrum Karlsruhe, Germany*

1. Introduction
2. Overview
  - 2.1. Perspectives of Fuzzy Systems
  - 2.2. Task-Oriented Classification
  - 2.3. Domain-Oriented Classification
3. Selected Examples
  - 3.1. Iron and Steel Production
  - 3.2. Waste Incineration
  - 3.3. Medicine and Biomedical Engineering
  - 3.4. Household and Consumer Appliances

## 4. Conclusions

**Neural Control Systems****131**Campos, J. , *Montavista Software Inc., USA*Lewis, F. L. , *University of Texas at Arlington, USA*

1. Introduction
2. Neural Network Structures and Properties
  - 2.1. Static Feedforward Neural Networks
  - 2.2. Universal Function Approximation Property
  - 2.3. Weight-Tuning Algorithms
  - 2.4. Functional-Link Basis Neural Network
  - 2.5. Gaussian or Radial Basis Function Networks
  - 2.6. Fuzzy Neural Networks
  - 2.7. Dynamic/Recurrent Neural Networks
3. Dynamical Systems and Feedback Control
  - 3.1. Mathematical Notation
  - 3.2. Stability Theorems
  - 3.3. Dynamics of a  $mn$ -th Order MIMO Nonlinear System
    - 3.3.1. Continuous Time Dynamical Systems
    - 3.3.2. Discrete Time Dynamical Systems
  - 3.4. Feedback Control Application: Robot Control
    - 3.4.1. Robot Dynamics and Properties
    - 3.4.2. Tracking a Desired Trajectory, and Error Dynamics
    - 3.4.3. The Controller and the Error System
4. Tracking Control Using Static Neural Networks
  - 4.1. Neural Net Feedback Tracking Controller
    - 4.1.1. Multiloop Feedback Control Topology
    - 4.1.2. NN Weight Tuning for Stability and Robustness
    - 4.1.3. Neural Net Robot Controller
    - 4.1.4. Partitioned NN and Preprocessing NN Inputs
  - 4.2. Applications and Extension
    - 4.2.1. Inner Feedback Loops: Force Control with Neural Networks
    - 4.2.2. Feedforward Control Loops: Actuator Deadzone Compensation
    - 4.2.3. Backstepping-Based Neural Network for Active Suspension Control
    - 4.2.4. Discrete Time Actuator Backlash Compensation
5. Output Feedback Control using Dynamic Neural Networks
6. Implementation of Neural Network Control Systems
  - 6.1. Hardware Description
  - 6.2. ATB-1000 Army Tank Gun Barrel Testbed
  - 6.3. Derivation of Neural Net Control System for Flexible Systems
    - 6.3.1. Flexible Link Robot Dynamics
    - 6.3.2. Singular Perturbation Approach
    - 6.3.3. Neural Network Control Algorithm
  - 6.4. Implementation of NN Controller on ATB-1000 Testbed
    - 6.4.1. Proportional-Plus-Derivative Control
    - 6.4.2. PD Control Plus Neural Network

**Expert Control Systems****196**Spyros G. Tzafestas, *National Technical University of Athens, Zografou 15773, Athens, Greece*

1. Introduction
2. Expert Control
3. Expert systems approach to control system development
4. Uncertainty management in expert control
5. Supervisory expert control

6. A General expert system architecture for process control
7. More on supervisory expert control
8. An example of supervisory expert control
  - 8.1. General Issues
  - 8.2. PID Controller Tuning
9. Outline of Topic D on expert control systems
10. Conclusion

### **Expert Control Systems: An Introduction with Case Studies**

219

Spyros G. Tzafestas, *National Technical University of Athens, Zografou 15773, Athens, Greece*

1. Introduction
2. Expert control system architecture
3. Knowledge representation in expert control
  - 3.1. Control Knowledge
  - 3.2. Rule-Based Systems
  - 3.3. Systems Using Semantic Networks and Frames
4. Knowledge acquisition in expert control
  - 4.1. General Issues
  - 4.2. Psychological KA Techniques
  - 4.3. Other KA Techniques
5. Reasoning in expert control
6. Real time expert systems
7. Expert systems in computer-aided control systems design
8. Anticipatory expert control
9. Case studies
  - 9.1. Case Study 1: Expert Reactive Power and Voltage Control
  - 9.2. Case Study 2: An Expert Supervisory Control System
  - 9.3. Case Study 3: An Expert System - Based CACSD Package
10. Concluding Remarks

### **Knowledge-Based and Learning Control Systems**

249

Z. Bubnicki, *Wroclaw University of Technology, Poland*

1. Introduction
2. General Concepts of Knowledge-Based and Learning Control Systems
3. Specific Features of the Knowledge-Based Control Systems
4. Relational and Logical Knowledge Representation
5. Statements and Solutions of Control Problems
6. Learning Processes in Knowledge-Based Control Systems
7. Descriptions of Initial Uncertainty
8. Related Problems

### **Fuzzy Expert Control Systems: Knowledge Base Validation**

270

Pedro Albertos, *Universidad Politécnica de Valencia, Spain*

Antonio Sala, *Universidad Politécnica de Valencia, Spain*

1. Introduction
2. Integrated Control Systems
  - 2.1. The Knowledge Base
3. Fuzzy Expert Control System Methodology
  - 3.1. Fuzzy Control System
  - 3.2. Expert Control System
  - 3.3. Fuzzy Expert Control System
4. Knowledge in Fuzzy Expert Control Systems

5. Main Design Issues
  - 5.1. General and Knowledge Base Structure Issues
  - 5.2. Rule Design and Inference
  - 5.3. User Interface
  - 5.4. The Role of Formal Methods in Expert Fuzzy Control
6. Objectives of Knowledge Validation for Control
7. Inference
  - 7.1. Rules as Equations or Inequalities
  - 7.2. Validation Definitions
  - 7.3. Inference Error
8. Validation of Fuzzy Expert Controllers
  - 8.1. Validation of Rulebases
  - 8.2. Validation of Interpolative Inference Algorithms
  - 8.3. Rule Extraction
  - 8.4. Validation and Rule Extraction in the Zadeh-Mamdani Approach
9. Uncertain Models
10. Conclusions and Perspectives

### **Blackboard Architecture for Intelligent Control**

303

Grantham Kwok-Hung Pang, *Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong*

1. Introduction
2. Characteristics for Intelligent Control
3. Blackboard Architecture
  - 3.1. Blackboard
  - 3.2. Knowledge Sources
  - 3.3. Control Unit
4. Development of Blackboard Systems
5. The Structure of a Blackboard System
  - 5.1. VLSI (Very Large Scale Integrated) Circuit Design
  - 5.2. Control of a Mobile Robot
6. A Framework for Intelligent Control
7. Future Trends and Perspectives

### **Genetic Algorithms in Control Systems Engineering**

317

P. J. Fleming, *Department of Automatic Control and Systems Engineering, University of Sheffield, UK*  
 R. C. Purshouse, *Department of Automatic Control and Systems Engineering, University of Sheffield, UK*

1. Introduction
2. What are genetic algorithms?
  - 2.1. Overview
  - 2.2. Landscapes
  - 2.3. Diversity
    - 2.3.1. Genetic Programming
    - 2.3.2. Multiobjective Evolutionary Algorithms
3. How can GAs be of benefit to control?
  - 3.1. Suitability
  - 3.2. Representation
  - 3.3. Available Tools
4. Design applications
  - 4.1. Controllers
    - 4.1.1. Parameter optimization
    - 4.1.2. Structure Selection
    - 4.1.3. Application to Fuzzy / Neural Control
  - 4.2. Identification

- 4.2.1. Model Structure
- 4.2.2. Model Parameters
- 4.2.3. Simultaneous Optimization of Structure and Parameters
- 4.3. Fault Diagnosis
- 4.4. Robustness Analysis
- 4.5. Robotics
- 4.6. Control-related Combinatorial Problems
- 5. On-line applications
- 6. Future perspectives

**Index** **351**

**About EOLSS** **359**

## VOLUME XVIII

<b>Architectures and Methods for Computer-based Automation</b>	<b>1</b>
<i>Peter Gohner, Institute of Industrial Automation and Software Engineering, University of Stuttgart, Germany</i>	

1. Definition of some Basic Terms
  - 1.1. The Term "Technical Process"
  - 1.2. The Term "Industrial Automation"
  - 1.3. The Industrial Automation System as a Real-time System
  - 1.4. Computers for Industrial Automation
2. Degree of Automation and Computer Operation Types
  - 2.1. Definition of Degree of Automation
  - 2.2. Types of Computer Operation
3. Automation of Technical Products and Technical Plants
4. The Elements of a Industrial Automation System
  - 4.1. Partial Systems of a Industrial Automation System
  - 4.2. Sensors and Actuators
  - 4.3. The Communication System
  - 4.4. The Automation Computer System
  - 4.5. The Automation Software System
5. Levels of Process Management and Automation Functions
  - 5.1. Level Model in Technical Process Management
  - 5.2. Automation Functions
6. Basic Types of Process Events in Technical Systems
  - 6.1. Common Classification Methods for Technical Processes
  - 6.2. Classification according to Process Events which produce Process Values of certain Types
  - 6.3. Continuous, Sequential and Object-related Processes
  - 6.4. Classification of Technical Processes according to the dominating Process Types
  - 6.5. Graphic Presentation of Technical Processes
7. Examples for Industrial Automation Systems
  - 7.1. Example for a Industrial Automation System for Product Automation
  - 7.2. Example of a Industrial Automation System for Plant Automation
8. Effects of Industrial Automation on People, Society and Environment
  - 8.1. Desired (positive) and undesired (negative) Effects
  - 8.2. The Responsibility of the Automation Engineer for the Effects of Industrial Automation

<b>Supervisory Distributed Computer Control Systems</b>	<b>49</b>
<i>Epple, U. ,RWTH Aachen, D52056 Aachen, Germany</i>	

1. Introduction
2. System and Component Structure
  - 2.1. The classical decentralized process control system
  - 2.2. Modern process control system
3. General System Services
  - 3.1. Monitoring
  - 3.2. Operator control
  - 3.3. Message Handling
  - 3.4. Archiving
  - 3.5. Time Synchronization
  - 3.6. Process Control Hardware Diagnostics
4. Conclusions

### **Automation and Control of Thermal Processes**

74

Reinhard Leithner, *Technische Universität Braunschweig, Germany*

1. Introduction
2. Thermal Processes
  - 2.1. Plants
  - 2.2. Main Plant Components
  - 2.3. Measuring Instruments
  - 2.4. Simulation and Optimization
3. Structures and Technologies of Automation and Control Systems
  - 3.1. Structures
  - 3.2. Technologies
  - 3.3. Actuators
  - 3.4. Duties and Functions
4. Future Developments

### **Steam Generators and Steam Distribution Networks**

92

Reinhard Leithner, *Technische Universität Braunschweig, Germany*

1. Steam Generators
  - 1.1. Types and Technologies
  - 1.2. Operating Modes
  - 1.3. Furnaces and Heat Sources
2. Steam Distribution Networks
3. Laws, Regulations, Guidelines, and Standards
4. Main Control Systems
  - 4.1. Fuel and Air Control
  - 4.2. Feedwater Control
  - 4.3. Steam Temperature Control
  - 4.4. Nuclear Reactor Control
  - 4.5. (Programmable) Logic Control
5. Advanced Control Methods, Signal Processing, and Plant Management Systems.
  - 5.1. Advanced Control Methods
  - 5.2. Monitoring, Analysis, and Diagnosis
    - 5.2.1. Monitoring
    - 5.2.2. Analysis
    - 5.2.3. Diagnosis
    - 5.2.4. Diagnosis Programs
  - 5.3. Validation
  - 5.4. Expert Systems
  - 5.5. Power Plant Management
6. Experience and Practical Suggestions

**Automation and Control of HVAC Systems****147**

So, Albert T. P., Asian Institute of Intelligent Buildings, and Department of Building &amp; Construction, City University of Hong Kong

1. Introduction
2. Conventional HVAC Control and Automation
  - 2.1. Indoor Air Quality
  - 2.2. Sensors in HVAC Systems
  - 2.3. HVAC Systems
  - 2.4. Conventional HVAC Control
    - 2.4.1. A Control Example
    - 2.4.2. Principles of PID Control
    - 2.4.3. Programmable Logic Control
    - 2.4.4. Actuators
    - 2.4.5. Direct Digital Control
  - 2.5. HVAC Automation
    - 2.5.1. The Networks
    - 2.5.2. Building Automation
3. Advanced HVAC Control
  - 3.1. System Modeling
  - 3.2. Digital Control
  - 3.3. Multivariable Control
  - 3.4. System Identification and Adaptive Control
  - 3.5. Robust Control
  - 3.6. Expert System based Control
  - 3.7. Artificial Neural Network based Control
  - 3.8. Fuzzy Logic based Control
  - 3.9. Computer Vision based Control
  - 3.10. Comfort based Control
4. Conclusions

**Automation and Control of Electrical Power Generation and Transmission Systems****175**Hans Glavitsch, *Swiss Federal Institute of Technology, ETH Zentrum, CH 8092 Zurich, Switzerland*

1. General
  - 1.1. Objectives
  - 1.2. Control Concepts
  - 1.3. Historical Review
  - 1.4. Sensors and Actuators
2. Unit Control
  - 2.1. Synchronous Machines
  - 2.2. Voltage Regulation of the 3rd Order Model of the Synchronous Machine
  - 2.3. Effective Voltage Regulation and Stabilization of Synchronous Machines
  - 2.4. Transient Stability of Synchronous Machines
  - 2.5. Speed and Frequency Control
3. Stability and Voltage Regulation of Multi-machine Systems
  - 3.1. Excitation Control of Multi-Machine Systems
  - 3.2. General Measures for Stability Improvement
4. System control
  - 4.1. Area Control - Automatic Generation Control (AGC)
  - 4.2. General Control Structures and Functions
5. Sequence Control - Startup and Shutdown

**Control of Synchronous Generators****224**Jorg Hugel, *Swiss Federal Institute of Technology, Zürich, Switzerland*

1. Introduction
2. Voltage Control of Individual Synchronous Generators
3. Voltage Control with Electronic Power Converters
4. Excitation with Auxiliary Generators
5. Compounding
6. Indirect Generator Control

**Gas Turbines****234**

Hans-Kaspar Scherrer, *ABB Switzerland, Power Technologies Division, Switzerland*  
 Christopher Ganz, *ABB Switzerland, Power Technologies Division, Switzerland*  
 Wolfgang Weisenstein, *ABB Switzerland, Power Technologies Division, Switzerland*

1. Power Plant Setups
2. Gas Turbine Components
  - 2.1. Air Intake
  - 2.2. Compressor
  - 2.3. Combustor
    - 2.3.1. Gas Turbine Combustion Basics
    - 2.3.2. The Classic Gas Turbine Combustor
    - 2.3.3. Dry Low Emission Combustors
  - 2.4. Turbine
    - 2.4.1. Auxiliary Systems
3. The Ideal Gas Turbine Cycle
  - 3.1. Gas Turbine Cycle with Losses
4. Gas Turbine Control
5. Turbine Control System
  - 5.1. Open Loop Control
  - 5.2. Gas Turbine Start-up
  - 5.3. Closed Loop Control
  - 5.4. Protection System

**Automation and Control of Electric Power Generation and Distribution Systems: Steam Turbines****261**

Bennauer, M. , *Siemens AG, PG, Mülheim, Germany*  
 Egner, E.-G. , *Siemens AG, PG, Mülheim, Germany*  
 Schlehuber, R. , *Siemens AG, PG, Mülheim, Germany*  
 Werthes, H. *Siemens AG, PG, Mülheim, Germany*  
 Zimmer, G. , *Siemens AG, PG, Mülheim, Germany*

1. Introduction
2. Functional Specifications
  - 2.1. Fundamentals of a Steam Turbine
    - 2.1.1. Sectioning and Reheating
    - 2.1.2. Steam Bypass
    - 2.1.3. Combined Heat and Power Generation
  - 2.2. Conversion from Mechanical Power into Electrical Power (Generator)
  - 2.3. Connecting Units
    - 2.3.1. Steam Generator
    - 2.3.2. Consumer Net
  - 2.4. Operating Conditions and Load Dispatching
    - 2.4.1. Base-Load Plant
    - 2.4.2. Peak-Load Plant
3. Turbine Controller Design
  - 3.1. Steam Turbine Controller (Turbine Governor)
    - 3.1.1. Operating Modes
    - 3.1.2. Transition Between Different Operation Modes



- 3.1.3. Set-Up of the Turbine Controller
- 3.2. Bypass Controller
- 3.3. Heat Extraction/Pressure Control
- 4. Future Developments

### **Automatic Control for Hydroelectric Power Plants**

283

Adolf Hermann Glattfelder, *ETH Zürich, Switzerland*

Ludwig Huser, *VA Tech Escher Wyss AG, Zürich, Switzerland*

Peter Dorfler, *VA Tech Escher Wyss AG, Zürich, Switzerland*

Johann Steinbach, *VA Tech Escher Wyss AG, Kriens, Switzerland*

- 1. Introduction
- 2. Safety Systems for Hydropower Units
- 3. Standard Control Algorithms
  - 3.1. Basic Concepts
  - 3.2. The Electric Power System Perspective
    - 3.2.1. Speed Run-up
    - 3.2.2. Operation on a Very Large Grid (“Infinite Bus”)
    - 3.2.3. Parallel Operation in a Small Grid
    - 3.2.4. Isolated Operation of One Unit
  - 3.3. The Water Flow System Perspective
    - 3.3.1. Level Control
    - 3.3.2. Outflow Control
  - 3.4. Standard Control Structures
- 4. Implementation issues
  - 4.1. Oil Pressure Supply System
  - 4.2. Sensors and Actuators
  - 4.3. Electronic Control Subsystems and Computer Networks
- 5. Advanced Control Features
  - 5.1. Modules for Low-Head Hydro Plants
    - 5.1.1. Joint Control: Optimal Allocation of Resources
    - 5.1.2. Turbine and Weir Dispatching
    - 5.1.3. Level Control
    - 5.1.4. Gain Scheduled Frequency Control
    - 5.1.5. Transient Load-Frequency Control Support
    - 5.1.6. Cascaded Power Plants: Coordinating Control
  - 5.2. Modules for High-Head Hydro Plants
    - 5.2.1. Limiting Algorithms for Protection of Surge Tanks
    - 5.2.2. Stabilizing Algorithms Based on Pressure Feedback
    - 5.2.3. Power Constraints
    - 5.2.4. Control Assisted by Jet Deflector (“Water Wasting Mode”)
    - 5.2.5. Control Assisted by Bypass Valves
    - 5.2.6. Isolated Grid Operation of High-Head Francis Units
  - 5.3. Concepts for Pumped Storage Plants
    - 5.3.1. Adjustment of Speed in Pump Turbine Sets
    - 5.3.2. Hydraulic Short-Circuit Operation
  - 5.4. Diagnostic and Monitoring Systems
- 6. Outlook: Driving Forces for Further Development

### **Electrical Network Control**

314

Edmund Handschin, *Chair of Electric Energy Systems, University of Dortmund, D-44221 Dortmund, Germany*

- 1. Introduction
- 2. Power system engineering
- 3. Evolution of electrical network control technology
- 4. System engineering aspects

- 4.1. Classification
- 4.2. Time decomposition
- 4.3. Mode decomposition
- 4.4. Operation state decomposition
- 4.5. Network management
- 4.6. Control decomposition
- 4.7. User oriented decomposition
- 4.8. Analysis decomposition
- 4.9. Control flow decomposition
5. Typical control center functions
  - 5.1. Network monitoring and security
  - 5.2. Network economy
  - 5.3. Network control
  - 5.4. Restorative control
  - 5.5. Specific control tasks in transmission network
  - 5.6. Specific control tasks in distribution networks

### **Combined Cycle and Combined Heat and Power Processes**

338

Andrzej W. Ordys, *University of Strathclyde, Glasgow, UK*

Michael J. Grimble, *University of Strathclyde, Glasgow, UK*

Ilhan Kocaarslan, *Kirikkale University, Kirikkale, Turkey*

1. Introduction
  - 1.1. Economic Justification for CC/CHP Power Plants
  - 1.2. Environmental Justification for CC/CHP Power Plants
2. Elements of Combined Cycle / Combined Heat and Power Processes
  - 2.1. Gas Turbine
    - 2.1.1. Classification
    - 2.1.2. Properties of Gas Turbines
  - 2.2. Boiler
  - 2.3. Steam Turbine
  - 2.4. Condenser
  - 2.5. De-aerator and Feed-water System
3. Typical CC/CHP Configurations
  - 3.1. Combined Heat and Power (CHP) Plant
  - 3.2. Combined Cycle Power Plant
4. Operation of CC/CHP Plants
  - 4.1. Start-up and Shut Down
  - 4.2. Steady-state Operation
  - 4.3. Dynamic Operation
5. Automatic Control in CC/CHP Plants
  - 5.1. The Tasks of Control System
  - 5.2. Gas Turbine Control
  - 5.3. Boiler Control
  - 5.4. Steam Turbine Control
  - 5.5. Coordinated Boiler and Steam Turbine Control
  - 5.6. Feedwater Control
  - 5.7. Auxiliary Controls
6. Control Philosophy in Future Combined Cycle Power Plants
  - 6.1. System-wide Communication
  - 6.2. Plant Management
7. Conclusions

### **Control of Large Nuclear Reactors by State and Output Feedback Techniques**

367

A. P. Tiwari, *Reactor Control Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, INDIA.*

Bijnan Bandyopadhyay, *Interdisciplinary Programme in Systems and Control Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, INDIA*

1. Introduction
2. On certain Preliminaries on Nuclear Reactor
  - 2.1. Components of a Nuclear Reactor
  - 2.2. Reactor Types
  - 2.3. Neutron Balance
  - 2.4. Reactivity Control
  - 2.5. Cross section for Neutron Reactions
  - 2.6. Fission Rate and Reactor Power
  - 2.7. Prompt and Delayed Neutrons
  - 2.8. Neutron Life time
  - 2.9. Neutron Flux Measurement
3. Modeling of Nuclear Reactors
  - 3.1. Neutron Diffusion Equation
  - 3.2. Point Kinetics Model
  - 3.3. Space-Time Kinetics Model
  - 3.4. Analysis of Core Composition Changes
    - 3.4.1. Fission Product Poisoning
    - 3.4.2. Xenon-induced Power Oscillations
    - 3.4.3. Analysis of Very Short Term Transients
  - 3.5. Linearization and Standard State Space Representation of Reactor Model
4. Control of Nuclear Reactor
  - 4.1. Control of Global Power
  - 4.2. Model Approximation
  - 4.3. Singularly Perturbed form of Nodal Model of the Reactor
  - 4.4. Linear State Feedback Control
  - 4.5. Periodic Output Feedback Design
    - 4.5.1. Block Triangular Form Representation of Singularly Perturbed Systems
    - 4.5.2. Periodic Output Feedback
    - 4.5.3. Piecewise Constant Periodic Output Feedback Control for Singularly Perturbed Systems
    - 4.5.4. Closed Loop Performance Consideration
    - 4.5.5. Spatial Control of Reactor by Periodic Output Feedback
5. Application to a large Pressurized Heavy Water Reactor
  - 5.1. Brief Description of the Reactor
  - 5.2. Control of Global Power output of PHWR
  - 5.3. Spatial Control of PHWR based on State Feedback Design
  - 5.4. Spatial Control of PHWR based on Periodic Output Feedback Design
6. Conclusion

**Index** **409**

**About EOLSS** **419**

## VOLUME XIX

**Automation and Control in Process Industries** **1**  
 Ján Mikleš, *Faculty of Chemical and Food Engineering, Slovak University of Technology in Bratislava, Slovakia*

1. Introduction to Process Control and Automation
2. Process Control History
3. Process Models and Dynamical Behavior of Processes

- 3.1. First-Order Dynamic Processes
- 3.2. Second and Higher-Order Dynamic Processes
- 3.3. Processes with Time Delay
- 3.4. Processes and Systems
- 4. Feedback Process Control
- 5. Structure of Complex Process Control
- 6. Trends in Process Control

**Automation and Control in Iron and Steel Industries**

**34**

Jurgen Heidepriem, *University of Wuppertal, Germany*

- 1. Introduction
- 2. Overview of Processes in Integrated Steelworks
  - 2.1. Metallurgical Processes
  - 2.2. Rolling Processes and Processing Lines
  - 2.3. Principles of Control Tasks
- 3. Control of Metallurgical Processes
  - 3.1. Sintering Process
  - 3.2. Blast Furnace Process
  - 3.3. Steel Production
  - 3.4. Continuous Casting
- 4. Control of Rolling Processes and Processing Lines
  - 4.1. Technology of Rolling
  - 4.2. Principles of Thickness (Gauge) Control
  - 4.3. Principles of Flatness (Shape) Control
  - 4.4. Control of Processing Lines
  - 4.5. Rolling of Long Products
- 5. Overall Automation Systems
- 6. Development Trends
  - 6.1. Technological Developments
  - 6.2. Application of CI Methods
    - 6.2.1. Expert Systems
    - 6.2.2. Fuzzy Control
    - 6.2.3. Artificial Neural Networks
  - 6.3. Replacement of First-Generation Automation Equipment

**Automation and Control of Chemical and Petrochemical Plants**

**57**

Dale E. Seborg, *University of California, Santa Barbara, U.S.A.*

- 1. Introduction
- 2. The Chemical and Petrochemical Industries
- 3. Historical Perspective
- 4. Overview of Industrial Process Control
  - 4.1. Process Design and Process Control
- 5. Traditional Process Control Strategies
- 6. Control System Design
- 7. Advanced Control Techniques
  - 7.1. Model Predictive Control
  - 7.2. Adaptive Control

**Automation and Control in Cement Industries**

**73**

Keviczky, L. , *Computer and Automation Research Institute, Hungarian Academy of Sciences, Hungary*

- 1. Introduction
- 2. Description of the Technology

- 2.1. Quarrying and Preparation
- 2.2. Raw Material Blending
- 2.3. Clinker Kilning
- 2.4. Cement Grinding
3. Control Problems and Systems
  - 3.1. Quarrying and Preparations
  - 3.2. Raw Material Blending
  - 3.3. Clinker Kilning
  - 3.4. Cement Grinding
4. Control Systems Technology
5. Application of the Advanced Control Theory
  - 5.1. Raw Material Blending
  - 5.2. Cement Kilning
  - 5.3. Cement Grinding
6. Summary

**Automation and Control of Pulp and Paper Processes**

98

H. N. Koivo, *Helsinki University of Technology, Espoo, Finland*

1. Introduction
2. Pulping Processes
3. Paper Mill
  - 3.1. Stock Preparation
  - 3.2. Short Cycle
  - 3.3. Headbox
  - 3.4. Dry End
4. Control of Mechanical Pulp Making
  - 4.1. Control of Stone Groundwood Process
  - 4.2. Thermomechanical Pulping (TMP) Refiner Control
5. Control of Chemical Pulp Making
  - 5.1. Control of Recovery Boiler
6. Control of Papermaking
  - 6.1. Grade Change Automation
  - 6.2. Control of Quality Variables
  - 6.3. Machine Direction (MD) Control
  - 6.4. Cross-Machine Direction (CD) Control
  - 6.5. Headbox Control
  - 6.6. Consistency
  - 6.7. Retention Control
  - 6.8. Wet End Management
7. Future Control Issues

**Automation in Wastewater Treatment**

115

G. Olsson, *Lund University, Lund, Sweden*

C. Rosen, *Lund University, Lund, Sweden*

1. The urban water system
2. Wastewater Treatment Operation
3. Incentives for Automation
4. Automation today in Wastewater treatment
  - 4.1. Objectives for Automation
    - 4.1.1. Keep the Plant Running
    - 4.1.2. Satisfy the Effluent Requirements
    - 4.1.3. Minimize the Cost
    - 4.1.4. Integrate the Plant Operation
  - 4.2. Constraints for Automation

- 4.2.1. Economy
- 4.2.2. Plant Constraints
- 4.2.3. Software
- 4.2.4. Legislation
- 4.2.5. Education, Training and Understanding
- 5. Modeling wastewater treatment
  - 5.1. Models for Information and Understanding
  - 5.2. Models for Control
- 6. Automation components
  - 6.1. Instrumentation
    - 6.1.1. Current Practice
    - 6.1.2. State of the Art
  - 6.2. Process Monitoring
    - 6.2.1. Current Practice
    - 6.2.2. State of the Art
  - 6.3. Process Control
    - 6.3.1. Current Practice
    - 6.3.2. State of the Art
- 7. Discussion

### **Modeling and Control of Complex River and Water Reservoir Systems**

132

Wernstedt, J., *Ilmenau University of Technology, Department of automatic control and system engineering, D-98684 Ilmenau, Germany*

- 1. Introduction
- 2. Models of water plants
  - 2.1. Catchment area models
    - 2.1.1. Snow melting process models (snow-melt-models)
    - 2.1.2. Rainfall runoff process models (Rainfall-runoff-models)
  - 2.2. River models
    - 2.2.1. Waterflow – models
    - 2.2.2. River water level models
    - 2.2.3. River overflow models
    - 2.2.4. Models of retention rooms (controlled)
    - 2.2.5. Models of backflow effects (uncontrolled retention rooms)
    - 2.2.6. Models of flow and level at back water of dam
- 3. Control strategies for water plants
  - 3.1. Automation system structures
    - 3.1.1. Decentralized control structure
    - 3.1.2. Hierarchical control structure
  - 3.2. Cost criteria for water plant control
    - 3.2.1. Integral criterion
    - 3.2.2. Constraints criterion
    - 3.2.3. Multicriteria
  - 3.3. Decentralized control
    - 3.3.1. PID-controller
    - 3.3.2. Fuzzy-controller
    - 3.3.3. Hybrid Controller
  - 3.4. Hierarchical control
- 4. Conclusion

### **Automation and Control in Production Processes**

153

D. Popovic, *Institute of Automation Technology, University of Bremen, Germany*

- 1. Introduction
- 2. Manufacturing

- 2.1. Intelligent Manufacturing
- 2.2. Virtual Manufacturing
- 2.3. Internet Controlled Manufacturing
- 2.4. Internet Controlled Robots
- 2.5. Intelligent Agents
3. Distributed Computer Systems in Production Automation
  - 3.1. Some Relevant Application Issues
    - 3.1.1. System Reliability and Safety
    - 3.1.2. Communication Links in Production Systems
    - 3.1.3. MAP/TOP Communication Standards
4. Automation and Control in Food Manufacturing Process
  - 4.1. Sensors Employed
  - 4.2. Food Processing Operations
5. Machine Tool and Welding
6. Automation and Control in Electronic Industry
  - 6.1. Product Design
  - 6.2. Process Monitoring and Control
  - 6.3. Product Inspection
  - 6.4. Assembly and Packaging
7. Discrete Event Systems in Manufacturing
8. Automation in Fisheries and Aquaculture Technology
9. Advanced Control in Production Engineering
10. Conclusions and Outlook

### **Automation and Control in Food Production**

191

Antonio Delgado, *Technische Universität München, Germany*

1. Introduction
  - 1.1. Scope
  - 1.2. Basic Considerations on the Automation of Food Processing
2. Automation of Food Production in the Processing Oriented Levels
  - 2.1. System Theoretical Considerations of a Food Production Plant
    - 2.1.1. Definition of the System Related to a Food Production Plant
    - 2.1.2. System Description
    - 2.1.3. Dynamics of Food Treatment Systems
  - 2.2. Online Measuring Techniques for Food Production Systems
    - 2.2.1. Requirements Concerning Process Measuring Quantities
    - 2.2.2. Online Sensing Devices
  - 2.3. Peculiarities of the Actuators for Food Processes
  - 2.4. Management of Food Production Processes: Modeling, Control and Optimization
    - 2.4.1. Fuzzy Logic Systems used in Food Production
    - 2.4.2. Automation of Food Processing on ANN based strategies
3. Future Trends in the Automation of Food Production Processes

### **Machine Tools**

219

D. Popovic, *Institute of Automation Technology, University of Bremen, Germany*

1. Introduction
2. Machine tool Monitoring and Control
  - 2.1. Machine Monitoring
  - 2.2. Tool Wear Detection
  - 2.3. Intelligent Approaches to Tool Wear Detection
  - 2.4. Modeling of Machining Process
  - 2.5. Adaptive Control
3. Machine Monitoring and Tool Inspection
  - 3.1. Machine Status Monitoring

- 3.2. Quality Control
- 3.3. Automated Visual Inspection
- 4. Outlook

**Welding**

234

S. Nordbruch, *University of Bremen, Germany*

- 1. Introduction
- 2. Model Building of welding Process
- 3. Welding Control
  - 3.1. Control Approaches
  - 3.2. Adaptive Control
  - 3.3. Intelligent Control
    - 3.3.1. Expert Controllers
    - 3.3.2. Fuzzy Logic Controllers
    - 3.3.3. Neurocontrollers
    - 3.3.4. Neuro-fuzzy Controllers
- 4. Welding Sensors
- 5. Welding Robots
- 6. Monitoring and Inspection
- 7. Future Trends

**Automation and Control in Electronic Industries**

255

D. Popovic, *University of Bremen, Germany*

- 1. Introduction
- 2. Design and Test Automation
  - 2.1. Design Approaches
  - 2.2. Rapid Prototyping
  - 2.3. Intelligent Design and Test Tools
- 3. Automatic Test Equipment
- 4. Semiconductor Manufacturing
  - 4.1. Process Monitoring and Control
  - 4.2. Model Building
  - 4.3. Closed-Loop Control
  - 4.4. Run-to-Run Process Control
  - 4.5. Application Example
- 5. Automated Visual Inspection
  - 5.1. Principles of Automated Visual Inspection
    - 5.1.1. Feature Extraction
    - 5.1.2. Pattern Classification
  - 5.2. Applications
    - 5.2.1. Automated Inspection of PCBs
    - 5.2.2. Automated Inspection of ICs
    - 5.2.3. Automated Surface Inspection
- 6. Packages and Interconnections
- 7. Automated Assembly
  - 7.1. Standard Approaches
  - 7.2. Robotic Assembly
- 8. Future Trends

**Advanced Technologies and Automation in Agriculture**

284

J. De Baerdemaeker, *K.U. Leuven, Leuven, Belgium*H. Ramon, *K.U. Leuven, Leuven, Belgium*J. Anthonis, *K.U. Leuven, Leuven, Belgium*



H. Speckmann, *Federal Agricultural Research Centre (FAL), Braunschweig, Germany*  
 A. Munack, *Federal Agricultural Research Centre (FAL), Braunschweig, Germany*

1. Introduction
2. Examples of Advanced Precision Agriculture Components: Combine Harvester, Sprayer, Fertilizer Spreader
  - 2.1. Objectives
  - 2.2. Mass Flow Sensor for Combines
    - 2.2.1. Sensor requirements
    - 2.2.2. Grain yield sensor
    - 2.2.3. Grain yield maps
  - 2.3. Site-Specific Spraying
    - 2.3.1. Chemical Crop Protection
    - 2.3.2. Necessary Equipment for Real-time Targeted Application
  - 2.4. Fertilizer Spreader
    - 2.4.1. The problem of spreading liquid manure
    - 2.4.2. Sensors and actuators
    - 2.4.3. Control
3. Networks in Agriculture
  - 3.1. Network Realizations in Plant Production
  - 3.2. ISO 11783: The International Standard for an Agricultural Bus System

### **Automation in Fisheries and Aquaculture Technology**

321

Balchen, Jens G. *Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway*

1. Introduction
2. Traditional harvesting technology. Relations to instrumentation, mechanization, control and automation.
  - 2.1. Modern harvesting gear
  - 2.2. Control of gear behavior
  - 2.3. Fishing vessels
  - 2.4. Integrated control of a vessel with fishing gear
  - 2.5. General ship automation technology
  - 2.6. Handling of catch
3. New harvesting concepts.
4. Processing of fish and other products.
  - 4.1. Processing of fish
  - 4.2. Quality control (inspection)
5. Aquaculture. Relations to automation and control.
  - 5.1. Hatcheries and smolt production
  - 5.2. Traditional cage-based fish farming
  - 5.3. Control of mechanized feeding system
  - 5.4. Measurement of total biomass in a cage
  - 5.5. Alternative concepts in fish farming
  - 5.6. A trend towards more automation?

### **Index**

341

### **About EOLSS**

349

**VOLUME XX****Automation and Control in Traffic Systems 1**Ernst Dieter Dickmanns, *University of the Bundeswehr, Munich, Germany*

1. Introduction
2. General Aspects of Automation and Control of Traffic Systems
  - 2.1. Planning of Optimal Trajectories
  - 2.2. Realization of Trajectories for Transportation
    - 2.2.1. Subdivision into Mission Elements (Navigation)
    - 2.2.2. Dealing with Perturbations and Uncertainties
  - 2.3. Cascaded Coarse to Fine Control
  - 2.4. Self-monitoring
3. Global Infrastructure for the Automation of Traffic Systems
4. Onboard Means for the Automation of Traffic Systems
5. Machine Vision for Flexible Automation of Traffic Systems
6. Conclusions

**Automotive Control Systems 24**Uwe Kiencke, *University of Karlsruhe (TH), Germany*

1. Introduction
2. Potential of Alternate Fuels and Propulsion Systems
3. Basic Engine Operation
4. Lambda Control
5. Idle Speed Control
6. Knock Control in SI Engines
  - 6.1. Knock Control
7. Vehicle Modeling
8. ABS Control Systems
9. Yaw Dynamic Control
  - 9.1. Derivation of Simplified Control Law

**Intelligent Control of Road Vehicles for Automated Driving: Path Architecture for Automated Highway Systems and Lateral Guidance 52**M. Tomizuka, *University of California, Berkeley, California, U.S.A.*P. Hingwe, *University of California, Berkeley, California, U.S.A.*J.-Y. Wang, *University of California, Berkeley, California, U.S.A.*M. Tai, *University of California, Berkeley, California, U.S.A.*

1. Introduction
2. AHS Architecture
3. Vehicle Models for Lateral Control
4. Road Reference System
5. Lateral Controllers for AHS
  - 5.1. FSLQ Controller
  - 5.2. Sliding Mode Controllers
  - 5.3. Lateral Controllers for High Speed Driving
  - 5.4. Lane Change Maneuvering and Backward Driving
6. Modeling and Lateral Control of Heavy Duty Vehicles
  - 6.1. Motivations for and Introduction to Automated Driving of Heavy Duty Vehicles
  - 6.2. Linearized Model of Heavy Duty Vehicles
    - 6.2.1. Linearized HDV Model in Unsprung Mass Reference Frame
    - 6.2.2. Linearized HDV Model in Road Reference Frame
  - 6.3. Linear Robust Controller for Heavy Duty Vehicles

- 6.3.1. Theoretical Backgrounds for  $H^\infty$  Loop-Shaping Design
- 6.3.2. Control Synthesis and Simulation
- 6.3.3. Experimental Results
- 6.4. Sliding Mode Controller for Heavy Duty Vehicles
  - 6.4.1. Sliding mode controller
    - 6.4.1.1. Model reformulation
    - 6.4.1.2. Design of Sliding Mode Control
    - 6.4.1.3. Simulation results of SMC
- 7. Concluding Remarks

**Ship Steering****88**Job van Amerongen, *University of Twente, Enschede, the Netherlands*

- 1. Introduction
  - 1.1. History
- 2. Modeling
  - 2.1. Hydrodynamic Models
  - 2.2. Transfer Functions
    - 2.2.1. Models of Nomoto
    - 2.2.2. Multivariable Model
    - 2.2.3. Roll Model
    - 2.2.4. Model of the Steering Machine
  - 2.3. Disturbance Models
- 3. Automatic Steering
  - 3.1. Control of the Steering Machine
  - 3.2. PID Course Control
  - 3.3. Course Keeping
    - 3.3.1. LQG Solution
  - 3.4. Course Changing
  - 3.5. Adaptive Control
    - 3.5.1. Model-Reference Adaptive-Control Systems
    - 3.5.2. Self-Tuning Regulator
  - 3.6. Fuzzy Control
  - 3.7. Roll Reduction
    - 3.7.1. Rudder-Roll Stabilization
  - 3.8. Other Approaches
- 4. Review of the Different Controller Strategies for Different Classes of Ships
- 5. Conclusions, Future Developments, and Further Reading

**Control for Railway Vehicles****108**T. X. Mei, *Department of Electronic and Electrical Engineering, Loughborough University, Loughborough, LE11 3TU, UK*R. M. Goodall, *Department of Electronic and Electrical Engineering, Loughborough University, Loughborough, LE11 3TU, UK*

- 1. Introduction
- 2. Overview of Railway Vehicle, Vehicle Models and Track Inputs
  - 2.1. Vehicle Configurations
  - 2.2. Railway Track Inputs
  - 2.3. Modelling of Vehicle Dynamics and Wheel-Rail Contact
  - 2.4. Performance Requirements
- 3. Traction and Braking Control Systems
  - 3.1. Traction Characteristics
  - 3.2. DC and AC Traction Drives
  - 3.3. Braking Control
  - 3.4. Anti-slip Control

4. Pantograph Control
5. Suspension and Guidance
  - 5.1. Tilting Control
  - 5.2. Active Secondary Suspensions
  - 5.3. Active Steering of Wheelsets
  - 5.4. Technology of Control
6. Conclusion and Trends

**Train and Railway Operations Control**

**132**

Eckehard Schnieder, *Institute for Traffic Safety and Automation Engineering, Technical University of Braunschweig, Germany*

1. Introduction
2. Control system overview
3. Single train control
  - 3.1. Control Objectives and Restrictions
  - 3.2. Process and Control Model
  - 3.3. Control Objectives and Tasks
  - 3.4. Control Structures for Train Motion Control
4. Multiple train control and protection on a single track
  - 4.1. Controlled Objects and Objectives
  - 4.2. Control Model
  - 4.3. Control and Protection Tasks
  - 4.4. Control Structure
5. Multiple train on multiple track (Network control)
  - 5.1. Controlled Objects and Objectives
  - 5.2. Process Model
  - 5.3. Control Tasks
  - 5.4. Control Structure

**Aerospace**

**150**

Donald McLean, *Southampton University, UK*

1. Introduction
2. Control of Aeronautical Vehicles
3. Aircraft Flight Control Systems
  - 3.1. General
  - 3.2. Air Traffic Control
  - 3.3. Flight Phases
  - 3.4. AFCS Reliability
4. The Principles of Flight Control
5. Primary Flying Controls
6. AFCS Modes
7. Fly-by-Wire and "Fly-by-Light" Systems
8. Flight Control Functions
9. Future Flight Control Systems
10. Conclusions

**Index**

**167**

**About EOLSS**

**173**

## VOLUME XXI

### **Elements of Automation and Control**

**1**

Tariq Samad, *Honeywell Laboratories, 3660 Technology Drive, Minneapolis, MN 55418, U.S.A.*

1. Introduction
2. Elements of the Control Loop
  - 2.1. "Plant" and "Controller"
  - 2.2. The Role of Automation
  - 2.3. Sensing, Feedback, and Actuation
3. Information Technology Elements of Automation
  - 3.1. Processors for Digital Control
  - 3.2. Human-Machine Interfaces-Output
  - 3.3. Human-Machine Interfaces-Input
  - 3.4. Communication Networks
  - 3.5. Wireless
4. Trends in Automation and Control
  - 4.1. Enterprise Optimization
  - 4.2. Autonomous and Semi-Autonomous Systems
  - 4.3. Embedded Systems and Control
5. Conclusions

### **Sensors in Control Systems**

**23**

David Zook, *Dresden Associates, Golden Valley, MN, U.S.A*

Ulrich Bonne, *Honeywell Laboratories, Plymouth, MN, U.S.A*

Tariq Samad, *Honeywell Laboratories, Minneapolis, MN, U.S.A*

1. Introduction
2. Sensor Fundamentals and Classifications
3. Sensors in Control Systems
  - 3.1. Desirable Sensor Attributes
  - 3.2. A Tradeoff between Sensor Performance and Power Dissipation
4. Sensor Technology Developments
  - 4.1. Compensation through Signal Processing
  - 4.2. Inferential and Higher-value Sensors
  - 4.3. Self-checking and Self-compensating Sensors
    - 4.3.1. Chopper as Auto-zero Device
    - 4.3.2. Self-checking Flame Sensors
    - 4.3.3. Self-checking Oxygen Sensor
    - 4.3.4. Self-compensated Flow Sensor
    - 4.3.5. Rebalanced Sensors
  - 4.4. Sensor Manufacturing
  - 4.5. Other Drivers for R&D
5. Biological Systems, Chemical sensors, and Biosensors
  - 5.1. Chemical and Olfactory Sensing in Biological Systems
  - 5.2. Audition
  - 5.3. The Role of Sensors in Biological Control Systems
6. Sensor-Enabled Visions for the Future

### **Self-Sensing Solid-State Actuators**

**48**

K. Kuhnen, *Saarland University, Saarbrücken, Germany*

H. Janocha, *Saarland University, Saarbrücken, Germany*

1. Introduction
2. Solid-state transducers

- 2.1. Piezoelectric Transducers
- 2.2. Magnetostrictive Transducer
- 2.3. Operator-based Modeling for Large-signal Operation
3. Measurement and power electronics
  - 3.1. Circuit for Measuring Voltage and Polarization Charge
  - 3.2. Power Electronics for Piezoelectric and Electrostrictive Solid-state Transducers
  - 3.3. Circuit for Measuring Current and Magnetic Flux
  - 3.4. Power Electronics for Magnetostrictive Solid-state Transducers
4. Compensation and reconstruction filters
  - 4.1. Large-signal Operation
  - 4.2. Small-signal Operation
  - 4.3. Electrical Large-signal Operation, Mechanical Small-signal Operation
5. Application example - piezoelectric micropositioning system with one degree of freedom
6. Conclusions

## Bus Systems

74

Klaus Bender, Institute for Information Technology in Mechanical Engineering (itm), Technical University of Munich, Boltzmannstrasse 15, 85748 Garching, Germany  
 Rolf Birkhofer, Institute for Information Technology in Mechanical Engineering (itm), Technical University of Munich, Boltzmannstrasse 15, 85748 Garching, Germany  
 Markus Bregulla, Institute for Information Technology in Mechanical Engineering (itm), Technical University of Munich, Boltzmannstrasse 15, 85748 Garching, Germany  
 Peter Wenzel, Profibus International, Haid-und-Neu-Strasse 7, 76131 Karlsruhe, Germany

1. General Reflections
  - 1.1. Bus Systems within Automation
  - 1.2. Basic Functions
  - 1.3. ISO/OSI Layer Model
  - 1.4. Implementation Aspects
2. Parallel Bus Systems
  - 2.1. Bus Physics
    - 2.1.1. Bus Wires
    - 2.1.2. Physical Interface
  - 2.2. Initialization
  - 2.3. Bus Access
  - 2.4. Data Transfer
    - 2.4.1. Structures and Mechanisms
    - 2.4.2. Operations for Data Communication
  - 2.5. Bus Management
  - 2.6. Common Parallel Busses
3. Serial Bus Systems
  - 3.1. Basic Concepts
  - 3.2. Bit Transmission
    - 3.2.1. RS 485
    - 3.2.2. IEC 1158-2
    - 3.2.3. Coaxial Cable
    - 3.2.4. Optical Waveguide (Fiber Optic)
  - 3.3. Bus Access
    - 3.3.1. CSMA/CD
    - 3.3.2. Polling (Master-Slave)
    - 3.3.3. Token-Passing
  - 3.4. Application Services
  - 3.5. Examples of Serial Bus Systems
    - 3.5.1. CAN (Controller Area Network)
    - 3.5.2. Profibus
  - 3.6. Comprehensive Standardization

**Programmable Logic Controllers**

98

Thiele G. *Institute of Automation, University of Bremen, Germany*Renner L. *Institute of Automation, University of Bremen, Germany*Neimeier R. *Institute of Automation, University of Bremen, Germany*

1. Introduction
2. Historical Aspects
3. PLC Programming Languages
  - 3.1. Importance
  - 3.2. Extent of Conformity
  - 3.3. Function Block Diagram (FBD) Language
    - 3.3.1. Features
    - 3.3.2. Function-Blocks as Objects
    - 3.3.3. Online Parameterisation
    - 3.3.4. Further Features of Function Block Diagrams
  - 3.4. Sequential Function Chart (SFC) Language
  - 3.5. Tasks
    - 3.5.1. Task Declaration and Scheduling
    - 3.5.2. On-line Configuration of Tasks
    - 3.5.3. Software-in-the-Loop Simulation
4. Professional Practice
  - 4.1. PLC Software-Architectures
  - 4.2. PLC Hardware-Architectures
    - 4.2.1. Separate PLC and SW-Development Environment
    - 4.2.2. SW-development environment partly on PC and PLC
    - 4.2.3. PLC as Co-Processor
    - 4.2.4. Software PLC
    - 4.2.5. Process Peripherals with PLC Intelligence
  - 4.3. Areas and Levels of IEC 6 1131 Language Consideration
5. Future Trends and Perspectives
  - 5.1. General Remarks
  - 5.2. PLC Process Reliability and Safety
  - 5.3. Fault-Tolerance oriented SW-Components on FB- and Task-Level

**Computer-Aided Control System Engineering Tools**

120

Christian Schmid, *Institute of Automation and Computer Control, Ruhr-Universität Bochum, Germany*

1. Introduction
  - 1.1. Historical Background in Control Engineering
  - 1.2. Historical Background in First-generation CAD Tools
  - 1.3. Historical Background in Second-generation CAD Tools
2. CAD techniques
  - 2.1. Numerical Aspects
  - 2.2. Efficient Software Libraries
  - 2.3. The Role of MATLAB as a Standard CAD System
  - 2.4. Engineering Domain versus Multidisciplinary Modeling
  - 2.5. Principles of Interaction
3. Trends

**Human-Machine Interaction**

132

Gunnar Johannsen, *Department of Mechanical Engineering, University of Kassel, Germany*

1. Introduction
2. Human Tasks with Automation and Control
3. Human-Machine Interfaces
  - 3.1. Traditional and Advanced Functionalities

- 3.2. Dialogue Systems
- 3.3. Control Devices
- 3.4. Visual Displays
- 3.5. Functional Displays and Information Preprocessing
- 3.6. Auditory Displays
- 3.7. Multimedia and Multimodal Displays
- 3.8. Adaptive Interfaces
- 4. Knowledge-Based Support
  - 4.1. User-Oriented and Application-Oriented Functionalities
  - 4.2. Procedural Support
  - 4.3. Human Error Prevention and Recovery
  - 4.4. Fault Management Support
- 5. Design and Evaluation
- 6. Conclusions

**Control of Electrical Machines for Drives**

**163**

J. Hugel, *Electrical Engineering and Design Laboratory, Swiss Federal Institute of Technology, Zurich, Switzerland*

- 1. Introduction
- 2. General Remarks on Electrical Machines
- 3. DC Drives
- 4. DC-Power Amplifier
- 5. Speed Control of DC Machines
- 6. Vector Representation for the Quantities of AC Machines
- 7. The Two-Axis Machine Model
- 8. The PARK Transformation
- 9. AC-Power Converter
- 10. Vector Control of AC Machines

**Index**

**191**

**About EOLSS**

**197**

**VOLUME XXII**

**Robotics**

**1**

T.Fukuda, *Department of Micro Systems, Nagoya University, JAPAN*

N.Kubota, *Department of Human and Artificial Intelligent Systems, Fukui University, JAPAN*

- 1. Introduction
- 2. Historical Perspective
  - 2.1. Mobile and Walking Robots
  - 2.2. Robot Manipulators
  - 2.3. Humanoid Robots
- 3. Mechanism and Components of Robots
  - 3.1. Mechanism
  - 3.2. Kinematics and Dynamics
  - 3.3. Sensors and Perception
  - 3.4. Actuators and Controller
  - 3.5. Programming and Motion Planning
  - 3.6. Human-Robot Interface
  - 3.7. Mathematical Techniques
- 4. Streams of Robotics



- 4.1. Intelligent Robotics
- 4.2. Behavior-Based Robotics
- 4.3. Evolutionary Robotics
- 4.4. Distributed Robotics
- 4.5. Micro-Robotics and Nano-Robotics
- 5. Robotics Applications
  - 5.1. Space Robotics
  - 5.2. Medical Robotics
  - 5.3. Rescue Robotics
  - 5.4. Human-Friendly Robotics
- 6. Summary

### **Robot Kinematics and Dynamics**

37

Haruhisa Kawasaki, *Faculty of Engineering, Gifu University, Yanagido, Japan*

- 1. Introduction
- 2. Kinematics
  - 2.1. Mechanical Structure of Robot Manipulator
  - 2.2. Orientation of a Rigid Body
  - 2.3. Homogeneous Transformation
  - 2.4. Forward Kinematics
  - 2.5. Inverse Kinematics
  - 2.6. Differential Kinematics
  - 2.7. Statics
  - 2.8. Manipulability Measure
- 3. Dynamics
  - 3.1. Lagrange's Formulation
  - 3.2. Newton-Euler Formulation
  - 3.3. Properties of Dynamic Model
  - 3.4. Forward Dynamics
  - 3.5. Cartesian Space Dynamic Model
  - 3.6. Dynamics of the Closed-Link Robot
  - 3.7. Reduced Dynamic Model of Constrained Robot
- 4. Dynamic Parameter Identification
  - 4.1. Weighted Least Square Method
  - 4.2. Identification of Payload
  - 4.3. Minimum Set of Dynamic Parameters
- 5. Symbolic Modelling

### **Trajectory and Task Planning**

72

Toshio Fukuda, *Department of Micro Systems, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Japan*

Naoyuki Kubota, *Department of Human and Artificial Intelligent Systems, Fukui University, Fukui, Japan*

- 1. Introduction
- 2. Path Planning for Mobile Robots
  - 2.1. Map Building
  - 2.2. Numerical Optimization for Path Planning
  - 2.3. Combinatorial Optimization for Path Planning
- 3. Trajectory Planning of Robot Manipulators
  - 3.1. Configuration Space
  - 3.2. Joint-Interpolated Trajectories
  - 3.3. Collision Avoidance in Trajectory Planning
  - 3.4. Hierarchical Trajectory Planning
- 4. Task Planning
- 5. Optimization Methods for Motion Planning
  - 5.1. Numerical Methods

- 5.2. Enumeration Methods
- 5.3. Random Methods
- 5.4. Genetic Algorithm for Hierarchical Trajectory Planning
- 6. Concluding Remarks

### **Robot Control and Programming**

98

Haruhisa Kawasaki, *Faculty of Engineering, Gifu University, JAPAN*

- 1. Introduction
- 2. Robot Dynamics
- 3. Motion Control
  - 3.1. Servo Control
    - 3.1.1. Servo Control in Joint Space
    - 3.1.2. Servo Control in Cartesian Space
  - 3.2. Dynamic Control
  - 3.3. Adaptive Control
- 4. Force Control
  - 4.1. Constraints
  - 4.2. Dynamics of Constrained Manipulators
  - 4.3. Impedance Control
  - 4.4. Hybrid Position/Force Control
  - 4.5. Adaptive Hybrid Position/Force Control
- 5. Robot Programming
  - 5.1. On-Line Programming
  - 5.2. Off-Line Programming
  - 5.3. Robot Programming Language
  - 5.4. Toward Automatic Robot Program Generation
    - 5.4.1. Graphical Task-Level Robot Language
    - 5.4.2. Teaching by Showing
    - 5.4.3. Virtual Teaching

### **Intelligent Robots**

129

Naoyuki Kubota, *Fukui University, JAPAN*  
 Toshio Fukuda, *Nagoya University, JAPAN*

- 1. Introduction
- 2. Fuzzy Computing
  - 2.1. Fuzzy Control
  - 2.2. Mamdani Fuzzy Models
  - 2.3. Functional Fuzzy Inference Methods
  - 2.4. Simplified Fuzzy Inference Methods
  - 2.5. Learning of Fuzzy If-Then Rules
- 3. Neural Computing
  - 3.1. The Basic Model of a Neuron
  - 3.2. Network Structure
  - 3.3. Perceptron
  - 3.4. Multilayer Perceptron
  - 3.5. Recurrent Neural Networks
  - 3.6. Learning Algorithms
- 4. Evolutionary Computing
  - 4.1. Genetic Algorithms
  - 4.2. Genetic Operators for Combinatorial Optimization Problems
  - 4.3. Evolutionary Programming
  - 4.4. Evolution Strategy
  - 4.5. Coevolutionary Computing
- 5. Reinforcement Learning

- 5.1. Learning from Reinforcement
- 5.2. Temporal Difference Learning
- 5.3. Sarsa
- 5.4. Q-Learning
- 5.5. Actor-Critic Methods
- 5.6. Genetics-Based Machine Learning
- 6. Intelligence on Robotics
  - 6.1. Emerging Synthesis of Intelligent Techniques
  - 6.2. Information and Representation
  - 6.3. Learning and Adaptation
  - 6.4. Search and Evolution
- 7. Concluding Remarks

<b>Robotic Applications to Life Support Systems</b>	<b>172</b>
<i>Axel Gräser, Institut für Automatisierungstechnik, Bremen, Germany</i>	

- 1. Introduction
- 2. Basic Technologies
  - 2.1. Wheelchairs
  - 2.2. Manipulators
  - 2.3. User Interfaces
  - 2.4. Speech Control of the Robot Arm MANUS<sup>(R)</sup>
- 3. Intelligent Wheelchair Control
  - 3.1. Navigation Skills, Obstacle Avoidance
- 4. Intelligent Manipulator Control
  - 4.1. Visual Servoing
  - 4.2. Visual Servoing Using Gripper-Mounted Cameras
  - 4.3. Visual Servoing Using Stereo Systems
- 5. Programing by Demonstration
- 6. Agent Orientated Software Design

<b>Index</b>	<b>189</b>
--------------	------------

<b>About EOLSS</b>	<b>195</b>
--------------------	------------