

F. Lamnabhi-Lagarrigue · A. Loría  
E. Panteley (Eds.)

---

# **Advanced Topics in Control Systems Theory**

**Lecture Notes from FAP 2004**

With 12 Figures

## Series Advisory Board

A. Bensoussan · P. Fleming · M.J. Grimble · P. Kokotovic ·  
A.B. Kurzhanski · H. Kwakernaak · J.N. Tsitsiklis

## Editors

Dr. Françoise Lamnabhi-Lagarigue

Dr. Antonio Loria

Dr. Elena Panteley

Laboratoire des Signaux et Systèmes

Centre National de la Recherche Scientifique

(CNRS)

SUPELEC

3 rue Joliot Curie

91192 Gif-sur-Yvette

France

British Library Cataloguing in Publication Data

Advanced topics in control systems theory : lecture notes

from FAP 2004. - (Lecture notes in control and information sciences ; 311)

1. Automatic control 2. Automatic control - Mathematical models

3. Control theory 4. Systems engineering

I. Lamnabhi-Lagarigue, F. (Francoise), 1953- II. Loria, Antonio

III. Panteley, Elena

629.8'312

ISBN 1852339233

Library of Congress Control Number: 2004117782

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency. Enquiries concerning reproduction outside those terms should be sent to the publishers.

Lecture Notes in Control and Information Sciences ISSN 0170-8643

ISBN 1-85233-923-3

Springer Science+Business Media

springeronline.com

© Springer-Verlag London Limited 2005

The use of registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant laws and regulations and therefore free for general use.

The publisher makes no representation, express or implied, with regard to the accuracy of the information contained in this book and cannot accept any legal responsibility or liability for any errors or omissions that may be made.

Typesetting: Data conversion by the authors.

Final processing by PTP-Berlin Protago- $\text{\TeX}$ -Production GmbH, Germany

Cover-Design: design & production GmbH, Heidelberg

Printed in Germany

69/3141 Yu-543210 Printed on acid-free paper SPIN 11334774

To our lovely daughters,  
AL & EP.

---

## Preface

*Advanced topics in control systems theory* is a byproduct of the European school “Formation d’Automatique de Paris” (Paris Graduate School on Automatic Control) which took place in Paris through February and March 2004. The school benefited of the valuable participation of 17 European renowned control researchers and about 70 European PhD students. While the program consisted of the modules listed below, the contents of the present monograph collects selected notes provided by the lecturers and is by no means exhaustive.

### **Program of FAP 2004:**

- P1 Nonlinear control of electrical and electromechanical systems  
A. Astolfi, R. Ortega
- P2 Algebraic analysis of control systems defined by partial differential equations  
J-F. Pommaret
- P3 Nonlinear flatness-based control of complex electromechanical systems  
E. Delaleau
- P4 Modeling and control of chemical and biotechnological processes  
Jan van Impe, D. Dochain,
- P5 Modeling and boundary control of infinite dimensional systems  
B. Maschke, A.J. van der Schaft, H. Zwart
- P6 Linear systems, algebraic theory of modules, structural properties  
H. Bourles, M. Fliess
- P7 Lyapunov-based control: state and output feedback  
L. Praly, A. Astolfi, A. Loría
- P8 Nonlinear control and mechanical systems  
B. Bonnard

P9 Tools for analysis and control of time-varying systems

J. M. Coron, A. Loria

P10 Control of oscillating mechanical systems, synchronization and chaos

J. Levine, H. Nijmeijer

In particular, the lecture notes included in the subsequent chapters stem from modules P1, P2, P5, P6, P7 and P8. The material, which covers a wide range of topics from control theory, is organized in six chapters: two chapters on Lyapunov-like methods for control design and stability analysis, one chapter on nonlinear optimal control, one chapter on modeling of Hamiltonian infinite-dimensional systems and two chapters on algebraic methods.

Each module listed above was taught over 21hrs within one week. Therefore, the contents of the present monograph may be used in support to either a one-term general advanced course on non linear control theory, thereby devoting a few lectures to each topic, or it may be used in support to more focused intensive courses at graduate level. The academic requirement for the class student or the reader in general is a basic knowledge on control theory (linear and non linear).

*Advanced topics in control systems theory* also constitutes an ideal start for researchers in control theory who wish to broaden their general culture or to get involved in fields different to their expertise, while avoiding a thorough book-keeping. Indeed, the monograph presents in a concise but pedagogical manner diverse aspects of modern control theory.

This book is the first of a series of yearly volumes, which shall prevail beyond the lectures taught in class during each FAP season. Further information on FAP, in particular, on the scientific program for the subsequent years is updated in due time on our URL <http://www.supelec.lss/cts/fap>.

FAP is organized within the context of the European teaching network “Control Training Site” sponsored by the European Community through the Marie Curie program. The editors of the present text gratefully acknowledge such sponsorship. We also take this opportunity to acknowledge the French national center for scientific research (C.N.R.S.) which provides us with a working environment and resources probably unparalleled in the world.

Gif-sur-Yvette, France.  
September 2004

Françoise Lamnabhi-Lagarigue,  
Antonio Loria,  
Elena Panteley.

---

# Contents

## **1 Nonlinear Adaptive Stabilization via System Immersion: Control Design and Applications**

<i>D. Karagiannis, R. Ortega, A. Astolfi</i> .....	1
1.1 Introduction .....	1
1.2 Nonlinear Stabilization via System Immersion .....	3
1.3 Adaptive Control via System Immersion .....	4
1.3.1 Systems Linear in the Unknown Parameters .....	5
1.3.2 Systems in Feedback Form .....	7
1.4 Output Feedback Stabilization .....	11
1.4.1 Linearly Parameterized Systems .....	12
1.4.2 Control Design Using a Separation Principle .....	14
1.5 Applications .....	16
1.5.1 Aircraft Wing Rock Suppression .....	16
1.5.2 Output Voltage Regulation of Boost Converters .....	17
1.6 Conclusions .....	21
References .....	21

## **2 Cascaded Nonlinear Time-Varying Systems: Analysis and Design**

<i>Antonio Loría, Elena Panteley</i> .....	23
2.1 Preliminaries on Time-Varying Systems .....	24
2.1.1 Stability Definitions .....	25
2.1.2 Why <i>Uniform</i> Stability? .....	27
2.2 Cascaded Systems .....	29

2.2.1 Introduction .....	29
2.2.2 Peaking: A Technical Obstacle to Analysis .....	31
2.2.3 Control Design from a Cascades Point of View .....	33
2.3 Stability of Cascades .....	36
2.3.1 Brief Literature Review .....	36
2.3.2 Nonautonomous Cascades: Problem Statement .....	38
2.3.3 Basic Assumptions and Results .....	39
2.3.4 An Integrability Criterion .....	43
2.3.5 Growth Rate Theorems .....	44
2.4 Applications in Control Design .....	48
2.4.1 Output Feedback Dynamic Positioning of a Ship .....	49
2.4.2 Pressure Stabilization of a Turbo-Diesel Engine .....	51
2.4.3 Nonholonomic Systems .....	54
2.5 Conclusions .....	60
References .....	61

### **3 Control of Mechanical Systems from Aerospace Engineering**

<i>Bernard Bonnard, Mohamed Jabeur, Gabriel Janin</i> .....	65
3.1 Introduction .....	65
3.2 Mathematical Models .....	67
3.2.1 The Attitude Control Problem .....	68
3.2.2 Orbital Transfer .....	69
3.2.3 Shuttle Re-entry .....	71
3.3 Controllability and Poisson Stability .....	73
3.3.1 Poisson Stability .....	73
3.3.2 General Results About Controllability .....	74
3.3.3 Controllability and Enlargement Technique (Jurdjević-Kupka) .....	76
3.3.4 Application to the Attitude Problem .....	77
3.3.5 Application to the Orbital Transfer .....	77
3.4 Constructive Methods .....	78
3.4.1 Stabilization Techniques .....	78
3.4.2 Path Planning .....	82
3.5 Optimal Control .....	84

3.5.1 Geometric Framework . . . . .	84
3.5.2 Weak Maximum Principle . . . . .	84
3.5.3 Maximum Principle . . . . .	86
3.5.4 Extremals in SR-Geometry . . . . .	87
3.5.5 SR-Systems with Drift . . . . .	88
3.5.6 Extremals for Single-Input Affine Systems . . . . .	93
3.5.7 Second-Order Conditions . . . . .	95
3.5.8 Optimal Controls with State Constraints . . . . .	101
3.6 Indirect Numerical Methods in Optimal Control . . . . .	109
3.6.1 Shooting Techniques . . . . .	109
3.6.2 Second-Order Algorithms in Orbital Transfer . . . . .	112
References . . . . .	113
 <b>4 Compositional Modelling of Distributed-Parameter Systems</b>	
<i>Bernhard Maschke, Arjan van der Schaft</i> . . . . .	115
4.1 Introduction . . . . .	115
4.2 Systems of Two Physical Domains in Canonical Interaction . . . . .	117
4.2.1 Conservation Laws, Interdomain Coupling and Boundary Energy Flows: Motivational Examples . . . . .	118
4.2.2 Systems of Two Conservation Laws in Canonical Interaction . . . . .	123
4.3 Stokes-Dirac Structures . . . . .	129
4.3.1 Dirac Structures . . . . .	129
4.3.2 Stokes-Dirac Structures . . . . .	130
4.3.3 Poisson Brackets Associated to Stokes-Dirac Structures . . . . .	132
4.4 Hamiltonian Formulation of Distributed-Parameter Systems with Boundary Energy Flow . . . . .	134
4.4.1 Boundary Port-Hamiltonian Systems . . . . .	134
4.4.2 Boundary Port-Hamiltonian Systems with Distributed Ports and Dissipation . . . . .	136
4.5 Examples . . . . .	138
4.5.1 Maxwell's Equations . . . . .	138
4.5.2 Telegraph Equations . . . . .	140
4.5.3 Vibrating String . . . . .	141
4.6 Extension of Port-Hamiltonian Systems Defined on Stokes-Dirac Structures . . . . .	143



4.6.1 Burger's Equations . . . . .	143
4.6.2 Ideal Isentropic Fluid . . . . .	143
4.7 Conserved Quantities . . . . .	148
4.8 Conclusions and Final Remarks . . . . .	151
References . . . . .	152

## 5 Algebraic Analysis of Control Systems Defined by Partial Differential Equations

<i>Jean-François Pommaret</i> . . . . .	155
5.1 Introduction . . . . .	155
5.2 Motivating Examples . . . . .	161
5.3 Algebraic Analysis . . . . .	168
5.3.1 Module Theory . . . . .	168
5.3.2 Homological Algebra . . . . .	179
5.3.3 System Theory . . . . .	183
5.4 Problem Formulation . . . . .	197
5.5 Problem Solution . . . . .	200
5.6 Poles and Zeros . . . . .	211
5.7 Conclusion . . . . .	220
5.8 Exercises . . . . .	220
References . . . . .	222

## 6 Structural Properties of Discrete and Continuous Linear Time-Varying Systems: A Unified Approach

<i>Henri Bourlès</i> . . . . .	225
6.1 Introduction . . . . .	225
6.2 Differential Polynomials . . . . .	227
6.2.1 Differential Fields . . . . .	227
6.2.2 Rings of Differential Polynomials . . . . .	229
6.2.3 Properties of General Rings . . . . .	230
6.3 Modules and Systems of Linear Differential Equations . . . . .	236
6.3.1 Modules . . . . .	236
6.3.2 Autonomous Linear Differential Equations . . . . .	244
6.3.3 Systems of Linear Differential Equations . . . . .	249
6.4 Linear Time-Varying Systems: A Module-Theoretic Setting . . . . .	256

6.4.1 Basic Structural Properties ..... 256

6.4.2 Finite Poles and Zeros ..... 263

6.5 Duality and Behaviors ..... 265

6.5.1 The Functor **Hom** ..... 265

6.5.2 Behaviors ..... 274

6.6 Concluding Remarks ..... 277

References ..... 278