

A. GALIP ULSOY | HUEI PENG | MELIH ÇAKMAKCI



AUTOMOTIVE CONTROL SYSTEMS

CAMBRIDGE

AUTOMOTIVE CONTROL SYSTEMS

This engineering textbook is designed to introduce advanced control systems for vehicles, including advanced automotive concepts and the next generation of vehicles for Intelligent Transportation Systems (ITS). For each automotive-control problem considered, the authors emphasize the physics and underlying principles behind the control-system concept and design. This is an exciting and rapidly developing field for which many articles and reports exist but no modern unifying text. An extensive list of references is provided at the end of each chapter for all topics covered. This is currently the only textbook, including problems and examples, that covers and integrates the topics of automotive powertrain control, vehicle control, and ITS. The emphasis is on fundamental concepts and methods for automotive control systems rather than the rapidly changing specific technologies. Many of the text examples, as well as the end-of-chapter problems, require the use of MATLAB and/or Simulink.

A. Galip Ulsoy is the C. D. Mote Jr. Distinguished University Professor and the William Clay Ford Professor of Manufacturing at the University of Michigan. He served as director of the Ground Robotics Reliability Center and deputy director of the Engineering Research Center for Reconfigurable Manufacturing Systems. He has been on the faculty of the Department of Mechanical Engineering at Michigan since 1980 and was the founding director of the Program in Manufacturing. He served as technical editor of the American Society of Mechanical Engineers' (ASME) *Journal of Dynamic Systems, Measurement, and Control* and is the founding technical editor of the *ASME Dynamic Systems and Control Magazine*. Professor Ulsoy is a member of the National Academy of Engineering and a Fellow of the ASME, the International Federation of Automatic Control, and the Society of Manufacturing Engineers; a Senior Member of IEEE; and a member of several other professional and honorary organizations. He is the past president of the American Automatic Control Council. He co-authored, with Warren R. DeVries, *Microcomputer Applications in Manufacturing*, and he is a co-author, with Sun Yi and Patrick W. Nelson, of *Time Delay Systems*. He has published more than 300 refereed technical articles in journals, conferences, and books.

Huei Peng is a Professor in the Department of Mechanical Engineering at the University of Michigan. He served as the executive director of interdisciplinary and professional engineering programs. His research interests include vehicle dynamics and control, electromechanical systems, optimal control, human-driver modeling, vehicle active-safety systems, control of hybrid and fuel-cell vehicles, energy-system design, and control for mobile robots. He has received numerous awards and honors, including the Chang-Jiang Scholar Award, Tsinghua University; a 2008 Fellow of the ASME; the Outstanding Achievement Award, Mechanical Engineering Department, University of Michigan (2005); the Best Paper Award, 7th International Symposium on Advanced Vehicle Control (2004); and the CAREER Award, National Science Foundation (July 1998–June 2002). He has published more than 200 refereed technical articles in journals, conferences, and books. Professor Peng is co-editor of *Advanced Automotive Technologies* with J. S. Freeman and co-author of *Control of Fuel Cell Power Systems – Principles, Modeling, Analysis and Feedback Design*, with Jay T. Pukrushpan and Anna G. Stefanopoulou.

Melih Çakmakçı is a professor of Mechanical Engineering at Bilkent University in Ankara, Turkey. His research areas include modeling, analysis and control of dynamic systems, control systems, smart mechatronics, modeling of manufacturing systems and their control, automotive control systems, optimal energy-management algorithms, and design and analysis of network control systems. Prior to joining Bilkent University, he was a senior engineer at the Ford Scientific Research Center.

Automotive Control Systems

A. Galip Ulsoy

University of Michigan

Huei Peng

University of Michigan

Melih Çakmakcı

Bilkent University



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9781107010116

© A. Galip Ulsoy, Huei Peng, and Melih Çakmakçı 2012

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without the written
permission of Cambridge University Press.

First published 2012

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication Data

Ulsoy, Ali Galip.

Automotive control systems / A. Galip Ulsoy, University of Michigan, Huei Peng,
University of Michigan, Melih Çakmakci, Bilkent University.

p. cm.

Includes index.

ISBN 978-1-107-01011-6 (hardback)

1. Automobiles – Automatic control. 2. Adaptive control systems.

3. Automobiles – Motors – Control systems. I. Peng, Huei. II. Çakmakci,
Melih. III. Title.

TL152.8.U47 2012

629.25'8–dc23 2011052559

ISBN 978-1-107-01011-6 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of
URLs for external or third-party Internet Web sites referred to in this publication
and does not guarantee that any content on such Web sites is, or will remain,
accurate or appropriate.

Contents

Preface *page ix*

PART I INTRODUCTION AND BACKGROUND

| | |
|---------------------------------------------------------|-----|
| 1 Introduction | 3 |
| 1.1 Motivation, Background, and Overview | 3 |
| 1.2 Overview of Automotive Control Systems | 7 |
| 2 Automotive Control-System Design Process | 21 |
| 2.1 Introduction | 21 |
| 2.2 Identifying the Control Requirements | 22 |
| 3 Review of Engine Modeling | 33 |
| 3.1 Engine Operations | 33 |
| 3.2 Engine Control Loops | 37 |
| 3.3 Control-Oriented Engine Modeling | 42 |
| 4 Review of Vehicle Dynamics | 54 |
| 4.1 Coordinates and Notation for Vehicle Dynamics | 54 |
| 4.2 Longitudinal Vehicle Motion | 58 |
| 4.3 Lateral Vehicle Motion | 64 |
| 4.4 Vertical Vehicle Motion | 77 |
| 5 Human Factors and Driver Modeling | 93 |
| 5.1 Human Factors in Vehicle Automation | 93 |
| 5.2 Driver Modeling | 101 |

PART II POWERTRAIN CONTROL SYSTEMS

| | |
|---------------------------------------------------|-----|
| 6 Air-Fuel Ratio Control | 119 |
| 6.1 Lambda Control | 119 |
| 6.2 PI Control of a First-Order System with Delay | 120 |
| 7 Control of Spark Timing | 124 |
| 7.1 Knock Control | 124 |

| | | |
|----------------------------------|--------------------------------------------------------|-----|
| 8 | Idle-Speed Control | 126 |
| 9 | Transmission Control | 131 |
| 9.1 | Electronic Transmission Control | 131 |
| 9.2 | Clutch Control for AWD | 133 |
| 10 | Control of Hybrid Vehicles | 148 |
| 10.1 | Series, Parallel, and Split Hybrid Configurations | 148 |
| 10.2 | Hybrid Vehicle-Control Hierarchy | 152 |
| 10.3 | Control Concepts for Series Hybrids | 157 |
| 10.4 | Control Concepts for Parallel Hybrids | 166 |
| 10.5 | Control Concept for Split Hybrids | 177 |
| 10.6 | Feedback-Based Supervisory Controller for PHEVs | 178 |
| 11 | Modeling and Control of Fuel Cells for Vehicles | 187 |
| 11.1 | Introduction | 187 |
| 11.2 | Modeling of Fuel-Cell Systems | 189 |
| 11.3 | Control of Fuel-Cell Systems | 196 |
| 11.4 | Control of Fuel-Cell Vehicles | 201 |
| 11.5 | Parametric Design Considerations | 205 |
| PART III VEHICLE CONTROL SYSTEMS | | |
| 12 | Cruise and Headway Control | 213 |
| 12.1 | Cruise-Controller Design | 213 |
| 12.2 | Autonomous Cruise Control: Speed and Headway Control | 224 |
| 13 | Antilock Brake and Traction-Control Systems | 232 |
| 13.1 | Modeling | 234 |
| 13.2 | Antilock Braking Systems | 236 |
| 13.3 | Traction Control | 247 |
| 14 | Vehicle Stability Control | 257 |
| 14.1 | Introduction | 258 |
| 14.2 | Linear Vehicle Model | 261 |
| 14.3 | Nonlinear Vehicle Model | 263 |
| 14.4 | VSC Design Principles | 266 |
| 15 | Four-Wheel Steering | 272 |
| 15.1 | Basic Properties | 272 |
| 15.2 | Goals of 4WS Algorithms | 274 |
| 16 | Active Suspensions | 287 |
| 16.1 | Optimal Active Suspension for Single-DOF Model | 288 |
| 16.2 | Optimal Active Suspension for Two-DOF Model | 290 |
| 16.3 | Optimal Active Suspension with State Estimation | 294 |

PART IV INTELLIGENT TRANSPORTATION SYSTEMS

17 Overview of Intelligent Transportation Systems 309

 17.1 Advanced Traffic Management Systems 310

 17.2 Advanced Traveler Information Systems 312

 17.3 Commercial Vehicle Operations 314

 17.4 Advanced Vehicle-Control Systems 314

18 Preventing Collisions 322

 18.1 Active Safety Technologies 322

 18.2 Collision Detection and Avoidance 322

19 Longitudinal Motion Control and Platoons 332

 19.1 Site-Specific Information 332

 19.2 Platooning 337

 19.3 String Stability 343

20 Automated Steering and Lateral Control 348

 20.1 Lane Sensing 348

 20.2 Automated Lane-Following Control 352

 20.3 Automated Lane-Change Control 356

APPENDICES

Appendix A: Review of Control-Theory Fundamentals 363

 A.1 Review of Feedback Control 363

 A.2 Mathematical Background and Design Techniques 370

Appendix B: Two-Mass Three-Degree-of-Freedom Vehicle Lateral/Yaw/Roll Model 385

Index 391

Preface

This textbook is organized in four major parts as follows:

- I. *Introduction and Background* is an introduction to the topic of automotive control systems and a review of background material on engine modeling, vehicle dynamics, and human factors.
- II. *Powertrain Control Systems* includes topics such as air–fuel ratio control, idle-speed control, spark-timing control, control of transmissions, control of hybrid-electric vehicles, and fuel-cell vehicle control.
- III. *Vehicle Control Systems* covers cruise control and headway-control systems, traction-control systems (including antilock brakes), active suspensions, vehicle-stability control, and four-wheel steering.
- IV. *Intelligent Transportation Systems (ITS)* includes an overview of ITS technologies, collision detection and avoidance systems, automated highways, platooning, and automated steering.

With multiple chapters in each part, this textbook contains sufficient material for a one-semester course on automotive control systems. The coverage of the material is at the first-year graduate or advanced undergraduate level in engineering. It is assumed that students have a basic undergraduate-level background in dynamics, automatic control, and automotive engineering.

This textbook is written for engineering students who are interested in participating in the development of advanced control systems for vehicles, including advanced automotive concepts and the next generation of vehicles for ITS. This is an exciting and rapidly developing field for which numerous articles and reports exist. An extensive list of references, therefore, is provided at the end of each chapter for all topics covered. Due to the breadth of topics treated, the reference lists are by no means comprehensive, and new studies are always appearing. However, the lists cover many major contributions and the basic concepts in each sub-area. This textbook is intended to provide a framework for unifying the vast literature represented by the references listed at the end of each chapter. It is currently the only textbook, including problems and examples, that covers and integrates the topics of automotive powertrain control, vehicle control, and ITS.

The emphasis is on fundamental concepts and methods for automotive control systems rather than the rapidly changing specific technologies. For each

