Advances in Industrial Control

Bram de Jager
Thijs van Keulen
John Kessels

Optimal Control of Hybrid Vehicles

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Advances in Industrial Control

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Optimal Control of Hybrid Vehicles

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Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies, new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

Identifying the drivers of technological change in today's automotive industry and the related fields of motorized transportation systems is not a simple task. One set of factors is simply involved with obtaining commercial advantage; vehicle manufacturers must innovate and provide new features in their products to ensure their vehicles sell, thereby preserving, and preferably increasing their market share. Quite a different set of factors is regulatory concerning such issues as reduced vehicle emissions, enhanced energy use and better driver-passenger safety features. As an example of regulatory pressures, an article on the "Carbon Car" in *IEEE Spectrum* (January 2013 issue, p. 28) reported: "In the United States, President Obama has called for manufacturers of cars and trucks to double their fuel economy by 2025, to a lofty 54.5 miles per gallon (4.3 liters per 100 kilometers). The European Union targets a 40 percent reduction in automotive CO_2 emissions by 2018; the target of 130 grams of CO_2 per kilometer driven equates to 5.6 L/100 km or 42 mpg." These commercial and regulatory motivating pressures are intertwined with what can be achieved by the ingenuity of today's engineers, and the potential advances from using new materials, digital electronics, and new mechanical and electrical technology.

For a number of years now the application of control in the field of automobile design, construction, and operation has been growing ever more confident with new sophisticated and complex control proposals. These developments have been regularly reported at key control conferences through invited sessions, specialist workshops and regular papers. An interesting feature of many automotive control sessions at control conferences has been the valuable and significant presence of

participants from the automotive industry. Consequently control techniques have made real contributions to automotive engine and power-train control, to emission reduction and better fuel utilization, to driver-assistance systems, to driver and passenger comfort and to the management of road transportation systems and vehicle behavior where future developments may even involve increasing vehicular autonomy.

The *Advances in Industrial Control* monograph series has long sought entries reporting new control developments in the automotive and transportation field, but it has taken some time for the monograph literature in this field to develop. Contributions are beginning to appear in the series, for example:

- *Dry Clutch Control for Automotive Applications* by Pietro J. Dolcini, Carlos Canudas de Wit and Hubert Béchart (ISBN 978-1-84996-067-0, 2010);
- *Active Braking Control Systems Design for Vehicles* by Sergio M. Savaresi and Mara Tanelli (ISBN 978-1-84996-349-7, 2010); and
- *Nonlinear Control of Vehicles and Robots* by Béla Lantos and Lőrinc Márton (ISBN 978-1-84996-121-9, 2011);

and in the related field of transportation management:

- *Feedback Control Theory for Dynamic Traffic Assignment* by Pushkin Kachroo and Kaan Özbay (ISBN 978-1-85233-059-0, 1999); and
- *Hybrid Predictive Control for Dynamic Transport Problems* by Alfredo Núñez, Doris A. Sáez and Cristián E. Cortés (ISBN 978-1-4471-4350-5, 2013).

To this group of monographs we can now add a long-sought-after title on hybrid vehicles. The monograph is entitled *Optimal Control of Hybrid Vehicles* and the authors are Bram de Jager, Thijs van Keulen and John Kessels. A very useful introductory chapter that discusses the fuel-economy motivational origins of hybrid vehicles opens the monograph. In this opening chapter a hybrid vehicle is defined as a vehicle constructed with energy recovery options and the monograph itself deals with the hybrid electric drivetrain that combines an internal combustion engine with energy recovery using an electrical machine and battery storage. Chapter 2 presents the modeling framework and Chap. 3 is a short chapter that concisely defines the increasingly constrained performance optimization problems to be solved. The final four chapters of the monograph deal with optimal control analytical solution procedures, numerical solutions, real-time implementation strategies and finally some experimental case-study investigations, respectively. With its focus on the optimized energy management of hybrid electric power-trains, this monograph will be of considerable interest to industrial practitioners in the automotive field and to academics and postgraduate researchers working in control, mechanical, and automotive engineering.

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Preface

This book presents recent results in the area of control of hybrid vehicles, with an emphasis on energy management for hybrid electric vehicles. The scope of the book covers both light-duty vehicles as well as heavy-duty ones, but the optimization of gear-shifting, vehicle velocity, or route traveled, although they contribute to energy management in a broader sense, are outside the scope.

The book's main audience consists of persons that are interested in techniques that deliver the best fuel economy, the lowest emissions, or smoothest drivability, taking advantage of advanced control freedom provided by hybridization. Those persons may come from industry, being employed in specifying, developing, or calibrating energy management systems, or that foresee they will be more intensively involved in these areas. They could also come from academia, where they carry out projects aiming to improve the performance of hybrid systems or to design better or more cost effective hardware solutions. Furthermore, the book addresses students who envision a career in control in the automotive industry, be it research, development, production, or support. Lastly, it addresses persons that are involved in emission legislation or in designing test procedures for vehicle homologation, so they are well informed about the intricacies that hybrid systems add to conventional vehicles. The authors have tried to make this book easily accessible to all those people with different backgrounds. Probably the presentation is too rigorous for some persons, and too lax for others, so we would very much appreciate reader comments. A part of the text has been used for teaching purposes, and the comments received from our students have been beneficial.

The increased market acceptance of hybrid vehicles, which are a key ingredient in meeting environmental targets for fuel economy and/or CO_2 emissions while still allowing the usual freedom to travel, has led to accelerated research and development paths to make the necessary technology mature for series production in large numbers. The knowledge gained in a specific area, namely optimal control of the drivetrain focusing on energy management, is shared with this book.

Persons reading this book can expect to receive answers to questions like: How can hybrid vehicles provide any fuel economy or emissions benefits? What is necessary to realize those benefits, what is useful, and what could be omitted? Is it

possible to prove that those benefits are realized with maximum performance? Is the energy management system intricate, or can it be simplified, achieving practically the same benefits? Can hybrid vehicles be made more cost effective?

The text does not provide a blue print for an automated design procedure for energy management systems, although the accompanying software tools allow the reader to reproduce the results presented in this book. Those tools are open and adaptable, so allow the reader to plug in his/her own numbers or characteristics and generate results matching the conditions he/she is designing for.

The book is an excerpt from research activities carried out at Eindhoven University of Technology during the last decade, with the help of several industrial partners and research institutes. Especial beneficial in shaping our thoughts that have been codified in this book have been Michiel Koot, Paul van den Bosch, Maarten Steinbuch and Maurice Heemels. The support and valuable feedback from our research partners is highly appreciated: Daniel Kok, Engbert Spijker, Edo Aneke (Ford Research Center Aachen), Loek van Seeters, Jack Martens (DAF Trucks N.V. Eindhoven) and Olaf op den Camp (TNO Helmond). For the experimental case studies the help of Will Hendrix, Ruud van den Bogaert, Toon van Gils, Erwin Meinders and Dominique van Mullem was invaluable. Barbara Cornelissen-Milner was of great help in fine-tuning the text.

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