

Reinforcement Learning-Enabled Intelligent Energy Management for Hybrid Electric Vehicles

Synthesis Lectures on Advances in Automotive Technology

Editor

Amir Khajepour, *University of Waterloo*

The automotive industry has entered a transformational period that will see an unprecedented evolution in the technological capabilities of vehicles. Significant advances in new manufacturing techniques, low-cost sensors, high processing power, and ubiquitous real-time access to information mean that vehicles are rapidly changing and growing in complexity. These new technologies—including the inevitable evolution toward autonomous vehicles—will ultimately deliver substantial benefits to drivers, passengers, and the environment. Synthesis Lectures on Advances in Automotive Technology Series is intended to introduce such new transformational technologies in the automotive industry to its readers.

Reinforcement Learning-Enabled Intelligent Energy Management for Hybrid Electric Vehicles

Teng Liu
2019

Narrow Tilting Vehicles: Mechanism, Dynamics, and Control

Chen Tang and Amir Khajepour
2019

Dynamic Stability and Control of Tripped and Untripped Vehicle Rollover

Zhilin Jin, Bin Li, and Jungxuan Li
2019

Real-Time Road Profile Identification and Monitoring: Theory and Application

Yechen Qin, Hong Wang, Yanjun Huang, and Xiaolin Tang
2018

Noise and Torsional Vibration Analysis of Hybrid Vehicles

Xiaolin Tang, Yanjun Huang, Hong Wang, and Yechen Qin
2018

Smart Charging and Anti-Idling Systems

Yanjun Huang, Soheil Mohagheghi Fard, Milad Khazraee, Hong Wang, and Amir Khajepour
2018

Design and Advanced Robust Chassis Dynamics Control for X-by-Wire Unmanned Ground Vehicle

Jun Ni, Jibin Hu, and Changle Xiang
2018

Electrification of Heavy-Duty Construction Vehicles

Hong Wang, Yanjun Huang, Amir Khajepour, and Chuan Hu
2017

Vehicle Suspension System Technology and Design

Avesta Goodarzi and Amir Khajepour
2017

© Springer Nature Switzerland AG 2022
Reprint of original edition © Morgan & Claypool 2019

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means—electronic, mechanical, photocopy, recording, or any other except for brief quotations in printed reviews, without the prior permission of the publisher.

Reinforcement Learning-Enabled Intelligent Energy Management for Hybrid Electric Vehicles
Teng Liu

ISBN: 978-3-031-00375-2 paperback
ISBN: 978-3-031-01503-8 ebook
ISBN: 978-3-031-00008-9 hardcover

DOI 10.1007/978-3-031-01503-8

A Publication in the Springer series
SYNTHESIS LECTURES ON ADVANCES IN AUTOMOTIVE TECHNOLOGY

Lecture #9
Series Editor: Amir Khajepour, *University of Waterloo*
Series ISSN
Print 2576-8107 Electronic 2576-8131

Reinforcement Learning-Enabled Intelligent Energy Management for Hybrid Electric Vehicles

Teng Liu
University of Waterloo

SYNTHESIS LECTURES ON ADVANCES IN AUTOMOTIVE TECHNOLOGY
#9

ABSTRACT

Powertrain electrification, fuel decarbonization, and energy diversification are techniques that are spreading all over the world, leading to cleaner and more efficient vehicles. Hybrid electric vehicles (HEVs) are considered a promising technology today to address growing air pollution and energy deprivation. To realize these gains and still maintain good performance, it is critical for HEVs to have sophisticated energy management systems. Supervised by such a system, HEVs could operate in different modes, such as full electric mode and power split mode. Hence, researching and constructing advanced energy management strategies (EMSs) is important for HEVs performance. There are a few books about rule- and optimization-based approaches for formulating energy management systems. Most of them concern traditional techniques and their efforts focus on searching for optimal control policies offline. There is still much room to introduce learning-enabled energy management systems founded in artificial intelligence and their real-time evaluation and application.

In this book, a series hybrid electric vehicle was considered as the powertrain model, to describe and analyze a reinforcement learning (RL)-enabled intelligent energy management system. The proposed system can not only integrate predictive road information but also achieve online learning and updating. Detailed powertrain modeling, predictive algorithms, and online updating technology are involved, and evaluation and verification of the presented energy management system is conducted and executed.

KEYWORDS

energy management, hybrid electric vehicles, reinforcement learning, deep learning, intelligent transportation information, real-time updating, velocity and power prediction, optimality and adaptability

Contents

Preface	ix
1 Introduction	1
1.1 Motivation	1
1.2 HEV Powertrain	2
1.3 Literature Review	4
1.3.1 Review Literature	5
1.3.2 Algorithm Literature	6
1.4 Summary	8
2 Powertrain Modeling and Reinforcement Learning	11
2.1 Control-Oriented Modeling	11
2.1.1 Transmission Modeling	11
2.1.2 Engine and Generator Modeling	13
2.1.3 Battery Modeling	15
2.1.4 EM Modeling	16
2.1.5 Energy Management Modeling	17
2.2 Reinforcement Learning	18
2.2.1 Overview of Reinforcement Learning	19
2.2.2 Markov Decision Processes	20
2.2.3 Algorithms for RL: Q-Learning and Sarsa	22
2.2.4 Algorithms for RL: Dyna-Q and Dyna-H	23
2.3 Summary	26
3 Prediction and Updating of Driving Information	27
3.1 Predictive Algorithms	27
3.1.1 Nearest Neighborhood	28
3.1.2 Fuzzy Coding	29
3.1.3 Long Short-Term Memory	31
3.2 Online Updating Algorithm	34
3.3 Evaluation of Prediction Performance	35
3.3.1 NND-Enabled Prediction Results	35

3.3.2	Comparison of NND and FCG	37
3.3.3	Evaluation of LSTM	39
3.4	Summary	41
4	Evaluation of Intelligent Energy Management System	43
4.1	Benchmark Energy Management Methods	43
4.1.1	Dynamic Programming-Based Controller	43
4.1.2	Stochastic Dynamic Programming-Based Controller	44
4.2	Optimality of RL-Based Energy Management	45
4.2.1	Evaluation of Q-Learning and Sarsa	45
4.2.2	Evaluation of Dyna-Q and Dyna-H	50
4.3	RL-Based Predictive Energy Management	57
4.4	Evaluation of Real-Time Energy Management	61
4.5	Summary	72
5	Conclusion	75
	References	79
	Author's Biography	89

Preface

Electrified powertrains are encouraged as potential solutions to environmental concerns, desire for mobility, and safety concerns. Hybrid vehicles have been on the scene since the successful development of Prius by Toyota and Insight by Honda. Energy management strategies play a significant role in hybrid electric vehicles to achieve the goal of fuel economy improvement and pollution emissions reduction. Thanks to the existence of the internal combustion engine, battery pack, generator, and electric motor, the hybrid powertrain can work in pure electric and hybrid electric mode to accommodate driving conditions.

This book focuses on developing reinforcement learning-enabled energy management strategies for different hybrid powertrains. To the best of my knowledge, there has not been a book that systematically discusses the energy management strategies founded in artificial intelligence. Hence, this book aims to introduce the fundamental elements of reinforcement learning and various applications of reinforcement learning algorithms in the energy management field. The material assembled in this book is an outgrowth of the experience that the author gained while studying as a Ph.D. student in Beijing Institute of Technology, China, and working as a Postdoctoral Fellow of University of Waterloo, Canada.

The text mainly discusses the applications of reinforcement learning in energy management fields, including the optimality of signal algorithm and the mixture of multiple techniques. To apply the proposed system, methods, and framework into real-time applications of hybrid electric vehicles is the author's constant objective. I hope this book will interest graduate students, practitioners, and vehicle engineers in the area of hybrid electric vehicles.

Finally, I would like to express my heartfelt gratitude for the guidance and help of my family, supervisor, and colleagues. I am also grateful to all the editors for their support and patience in the production of this book. This book is also for my younger daughter, who was born on June 25, 2019.

Teng Liu
July 2019