



FEM

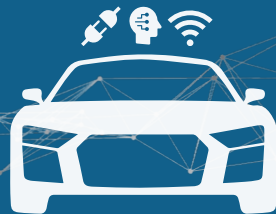
**Forschungsberichte aus dem
Fachgebiet für Elektromobilität**

apl. Prof. Dr.-Ing. Daniel Görge (Hrsg.)

Xiaohai Lin

**Robust and Stochastic Model
Predictive Control of Linear
Systems with Predictable
Additive Disturbance**

with Application to Multi-Objective
Adaptive Cruise Control



Robust and Stochastic Model Predictive Control of Linear Systems with Predictable Additive Disturbance

with Application to Multi-Objective Adaptive Cruise Control

Robuste und stochastische modellprädiktive Regelung für lineare Systeme mit vorhersagbaren additiven Störungen

mit Anwendung für die multikriterielle adaptive Geschwindigkeitsregelung

Vom Fachbereich Elektrotechnik und Informationstechnik

der Technischen Universität Kaiserslautern

zur Verleihung des akademischen Grades

Doktor der Ingenieurwissenschaften (Dr.-Ing.)

genehmigte Dissertation

von

M.Sc. Xiaohai Lin

geboren in Fujian, China

D 386

Tag der mündlichen Prüfung: 16.03.2020

Dekan des Fachbereichs: Prof. Dr.-Ing. Ralph Urbansky

Vorsitzender der

Prüfungskommission:

1. Berichterstatter:

2. Berichterstatter:

Prof. Dr.-Ing. Steven Liu

apl. Prof. Dr.-Ing. Daniel Gorges

Prof. Dr.-Ing. habil. Stefan Streif

Forschungsberichte aus dem Fachgebiet für Elektromobilität

Band 3

Xiaohai Lin

**Robust and Stochastic Model Predictive Control of
Linear Systems with Predictable Additive Disturbance**

with Application to Multi-Objective Adaptive Cruise Control

D 386 (Diss. Technische Universität Kaiserslautern)

Shaker Verlag
Düren 2020

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Kaiserslautern, TU, Diss., 2020

Copyright Shaker Verlag 2020

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, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-7403-1

ISSN 2698-7260

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: www.shaker.de • e-mail: info@shaker.de

Acknowledgments

This thesis presents the results of my work at the Division of Electromobility, Department of Electrical and Computer Engineering, University of Kaiserslautern.

Foremost, I would like to express my deep gratitude to apl. Prof. Dr.-Ing. Daniel Gorges, the head of the Division of Electromobility, for the excellent supervision and the invaluable scientific discussions throughout my research.

Furthermore, I would like to thank Prof. Dr.-Ing. habil. Stefan Streif for joining the committee as a reviewer of my thesis. I would also like to thank Prof. Dr.-Ing. Steven Liu for joining the committee as the chair.

Thanks also go to all the colleagues of the Division of Electromobility and the Institute of Control Systems, Department of Electrical and Computer Engineering, University of Kaiserslautern, for the good and enjoyable collaboration.

Besides, I am extremely grateful to my family for their love and support.

Leonberg, April 2020

Xiaohai Lin

Contents

Notation	IX
1 Introduction	1
1.1 Motivation	1
1.2 Objectives	2
1.3 Previous Work	3
1.3.1 Robust Model Predictive Control	3
1.3.2 Adaptive Cruise Control	5
1.3.3 Speed Prediction	7
1.3.4 Stochastic Model Predictive Control	8
1.4 Outline and Contributions	8
1.5 Publications	10
2 Stochastic Model Predictive Control Scheme	13
2.1 System Description	13
2.2 Mean Square Input-to-State Stability	14
2.3 Stochastic Model Predictive Control Design	16
2.3.1 Offline Computation	17
2.3.2 Online Optimization	20
2.4 Simulation Studies	24
2.5 Summary	26
3 Disturbance Prediction	27
3.1 System Description	27
3.2 Review of Disturbance Models	28
3.3 Application to Speed Prediction	29
3.3.1 Background and Frameworks	30
3.3.2 Modeling Speed	36
3.3.3 Predicting Speed	38
3.3.4 Evaluation	40
3.4 Summary	44
4 Robust Model Predictive Control Considering Predicted Disturbance Sequences	47
4.1 Control Framework	48

4.2	Feedback Gain Design	48
4.2.1	Effect of the Disturbance	48
4.2.2	Computation of the Linear Feedback Gain	49
4.3	Control Problem Formulation	52
4.4	Robustness Analysis	55
4.4.1	Feasibility Analysis	56
4.4.2	Stability Analysis	58
4.5	Design of the Ellipsoidal Terminal Constraint Set	61
4.5.1	Ensuring Assumption 4.1	61
4.5.2	Ensuring Assumption 4.2	64
4.5.3	Ensuring Assumption 4.3	65
4.5.4	Determination of the Terminal Constraint Set	65
4.6	Simulation Studies	66
4.7	Summary	69
5	Robust Model Predictive Control Considering Predicted Disturbance Sequences and Bounds	71
5.1	Control Framework	71
5.1.1	Maximal Output Admissible Set	72
5.1.2	Predicted Disturbance Polytopes	73
5.2	Control Problem Formulation	75
5.3	Design of the Polytopic Terminal Constraint Set	77
5.4	Robustness Analysis	77
5.4.1	Feasibility Analysis	79
5.4.2	Stability Analysis	82
6	Multi-Objective Adaptive Cruise Control	83
6.1	Traffic Scenarios and Control Objectives	83
6.2	Modeling	85
6.2.1	System Dynamics	86
6.2.2	Constraints	89
6.2.3	Cost Function	92
6.2.4	Reformulation of the Model	93
6.3	Robust Adaptive Cruise Control	94
6.3.1	Following Drive	95
6.3.2	Transition from the Following Drive to Free Drive	96
6.3.3	Free Drive	96
6.3.4	Transition from the Free Drive to Following Drive	97
6.3.5	Robust Adaptive Cruise Controller Design	99
6.4	Simulation Studies	100
6.4.1	Setup	100
6.4.2	Important Sets	101
6.4.3	Achievement of Multiple Objectives	104

6.5	Real-Time Implementation	108
6.5.1	Target Hardware	108
6.5.2	Sequential Quadratic Programming	109
6.5.3	Implementation	111
6.5.4	Evaluation	111
6.6	Summary	112
7	Conclusions and Outlook	115
7.1	Conclusions	115
7.2	Outlook	116
	Bibliography	119
	Zusammenfassung	132
	Curriculum Vitae	136