
Robust Perception from Optical Sensors for Reactive Behaviors in Autonomous Robotic Vehicles

Alexander Schaub

Robust Perception from Optical Sensors for Reactive Behaviors in Autonomous Robotic Vehicles

 Springer Vieweg

Alexander Schaub
Fürstenfeldbruck, Deutschland

Dissertation Technische Universität München, 2017

ISBN 978-3-658-19086-6 ISBN 978-3-658-19087-3 (eBook)
DOI 10.1007/978-3-658-19087-3

Library of Congress Control Number: 2017948760

Springer Vieweg

© Springer Fachmedien Wiesbaden GmbH 2018

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

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

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer Vieweg imprint is published by Springer Nature
The registered company is Springer Fachmedien Wiesbaden GmbH
The registered company address is: Abraham-Lincoln-Str. 46, 65189 Wiesbaden, Germany

Acknowledgements

First of all, I want to express my gratitude to Prof. Darius Burschka who closely supervised this thesis from the very beginning. He was a very committed supervisor, always having an ear for my questions and concerns. I was looking forward to each meeting with him, as the discussion were fruitful but also entertaining and I always left the meetings with new ideas and great motivation.

Moreover, I want to thank Prof. Martin Otter for his willingness to co-supervise this work and for his valuable remarks that helped to improve this thesis.

I could have never accomplished this work without many invaluable colleagues who co-authored my publications or advised and supported me during the years. First, I thank Dr. Ricardo de Castro for being the most accurate reviewer I can imagine and a rich source of valuable suggestions that helped to improve this thesis but also the publications. Next, I want to thank Dr. Tilman Bünte, as I could always learn from his long experience as a researcher. Moreover, I thank Lok Man Ho for being a great office mate, for all the valuable discussions, and especially for reviewing my written English. A further colleague, without whom it would not be half as fun in office as it is, is Daniel Baumgartner, who did also a great job constructing the soft-crash obstacles for the experiments and, together with Clemens Satzger, keeps the ROboMObil alive. Without their commitment, the ROboMObil would now be a resting platform.

At this point, I want to express my gratitude to Prof. Gerd Hirzinger whose vision and expertise enabled the entire ROboMObil project in 2009. Moreover, I want to thank Dr. Johann Bals for giving me the chance to work on the ROboMObil project, first in his department and later in his new Institute of System Dynamics and Control.

This leads me to the ROboMObil team, (internally) also known as the ‘ROMO Racing Team’. Here, I want to thank first the project leader Jonathan Brembeck, who is a ‘fellow combatant’ of the first hour. Moreover, I thank Juan Carlos Ramirez de la Cruz and Michael Panzirsch, who form the enclave of the ROMO Team in the Robotics and Mechatronics Institute, Michael Fleps-Deszasse and Sascha Liebhart for being great test pilots (at least in the simulator), and Peter Ritzer and Christoph Winter who did a magnificent job implementing the ROboMObil HIL setup.

I was extremely lucky to have great colleagues also outside of the ROMO Racing Team. Here, I would like to thank first Dr. Klaus Strobl for his expertise

on and help with camera calibration. Furthermore, I thank Frans van der Linden for being a great office mate and dedicated critic when it comes to presentations, Dr. Tobias Bellmann for his help with SimVis, and Dr. Dirk Zimmer and Dr. Jakub Tobolar for their Modelica support. Moreover, the vision part of the ROboMObil would not have been possible without Dr. Tim Bodenmüller helping with SensorNet (not to be confused with SkyNet) and the valuable support from Dr. Heiko Hirschmüller regarding the Semi-Global Matching.

Over the years I had the pleasure to supervise different students during their internships and Bachelor or Master thesis. Among them, I want to point out Matthias Hellerer, who did a great job with the AIA simulation environment and Markus Maier, who competently designed the camera carrier of the ROboMObil. Moreover, I would also like to thank Marc Zimmert, Bashar Al-Ani and Matthias Löckler.

A very special thanks goes also to institute secretary Monika Klauer for taking care of 'business' and also the system administrators Stefan von Dombrowski, Stefan Engelhardt and Dr. Hans-Jörg Maurer, who were always very helpful and committed when an IT problem had to be solved on an evening right before a ROMO demonstration.

Finally, I want to thank my beloved girlfriend Smaranda for her unconditional support as well as I thank my dearest family - my father Dr. Gerhard Schaub, who was always a great role model for me, my mother Ute for all her endless encouragement, and my sisters Marisa and Annalisa.

Contents

List of Figures	XI
List of Tables	XV
1 Motivation	1
1.1 Why Mobile Robots Should Have an Artificial Instinct	3
1.2 Ground-based Autonomous Mobile Robots	4
1.3 The Ideal Sensor	6
1.4 Intuition as Part of the Artificial Intelligence	8
1.5 Outline - Toward Reactive Planning for Auto-nomous Vehicles	10
2 Related Work	13
2.1 Review of Autonomous Driving	13
2.1.1 The Origin of Autonomous Driving and the First Steps (1969-1987)	13
2.1.2 Autonomous Driving on Highways (1987-2003)	18
2.1.3 The DARPA Challenges (2004-2007)	19
2.1.4 Commercial Autonomous Driving (2008-present)	24
2.2 Sensors for Autonomous Vehicle	28
2.2.1 Overview of Sensor Classes	29
2.2.2 Usage of Sensors	30
2.3 Types of Planning	32
2.3.1 Reactive Obstacle Avoidance	34
2.3.1.1 Vision-Based Obstacle Avoidance	35
2.3.1.2 Obstacle Avoidance based on Optical Flow	36
2.3.1.3 Dynamic Obstacles	38
2.3.2 Vision-Based Control and Navigation	39
2.3.2.1 Reactive Navigation with Fuzzy Logic	40
2.3.2.2 Visual Servoing	41
2.3.2.3 Homography-based Techniques	43
2.3.3 Vision-Based Platooning	44
2.3.4 Concurrent Reactive Obstacle Avoidance and Navigation	44
2.4 Contributions	45

3	Vision-Based Reactive Controllers	47
3.1	Camera-based Perception	47
3.1.1	Reasons for Use of Cameras	47
3.1.2	Basic Image Processing Principles	48
3.1.3	Optical Flow	52
3.1.4	Two View Geometry	53
3.1.4.1	Essential Matrix	54
3.1.4.2	Homography Principle	56
3.2	Single Point Time-to-Collision	58
3.2.1	STTC for Planar Motions	58
3.2.2	STTC for Non-Planar Motions	61
3.3	Representations for Coupling Sensors with Actuators	65
3.3.1	Control-Interface to Autonomous Vehicle	65
3.3.2	Optical Flow Clusters for Collision Avoidance	67
3.3.2.1	Epipolar Geometry-Based Clustering	67
3.3.2.2	Expansion-Based Time-To-Collision Estimation	68
3.3.2.3	Two-Stage Clustering	73
3.3.2.4	Coupling Epipole Motions with Velocities	79
3.3.3	Direct Homography Control for Positioning and Navigation Tasks	80
3.3.3.1	Direct Homography Control for Static Targets	81
3.3.3.2	Position Estimation without Decomposition	83
3.3.3.3	Direct Homography Control for Platooning	86
3.3.4	Single Point Time-To-Collision Map	89
3.3.4.1	Derivation of the STTC-Map	89
3.3.4.2	Static STTC Objects	93
3.3.4.3	Dynamic STTC Objects	96
3.3.4.4	Velocity Estimation using the STTC Principle	102
3.3.4.5	Single Point Velocity Estimation (SPVE)	104
3.3.4.6	Comparison of the Velocity Estimation from SPVE to Stereo	107
3.4	Planning with the Representations	113
3.4.1	Obstacle Evasion by Optimal Calculation of the Motion Correction	114
3.4.1.1	Deriving a Cost-Function for Epipole Shifting	114
3.4.1.2	Choice of the Optimizer	116
3.4.2	Navigation	118
3.4.2.1	Direct Homography Control for the Static Case	118
3.4.2.2	Platooning	122
3.4.3	STTC Map-based planning	126
3.4.3.1	Nullspace STTC Calculation	126
3.4.3.2	Optimization-based planning	129
4	The ROboMObil	133
4.1	The Research Platform	133
4.2	Architecture for Autonomous Driving	135
4.3	Simulation Aided Development	137

4.3.1	Simulation of Artificial Intelligence Agents	137
4.3.2	The ROMO Hardware-In-the-Loop Test Setup	138
4.4	The Perception System	139
4.4.1	Placement of the Cameras	140
4.4.2	Sensor Attention Management	140
4.5	Actuation of the ROboMObil	142
4.5.1	Vehicle Dynamics Controller Interface	143
4.5.2	Exemplary Application: Autonomous Parking	145
5	Results	149
5.1	Results - Perception	149
5.1.1	STTC Calculation	149
5.1.1.1	Evaluation of the Sensitivity of the STTC Calculation to Non-Planar Motions	149
5.1.1.2	The 3 Points Method for Changing Velocities	150
5.1.2	Configuration of the Sensor System	156
5.2	Results - Representations	159
5.2.1	Control-Interface Autonomous Vehicle	159
5.2.2	Evaluation of the Optical-Flow Clustering Representation	160
5.2.2.1	The Epipolar Geometry-Based Clustering	160
5.2.2.2	The Two-Step Clustering	163
5.2.3	Navigation / Homography Presentation	167
5.2.3.1	Estimation of the Orientation Deviation	167
5.2.3.2	Position Estimation using a Projection Model	170
5.2.3.3	Position Estimation using Artificial Images	171
5.2.3.4	Velocity Estimation for the Target Vehicle	175
5.2.4	STTC Map	175
5.2.4.1	Comparison of Different STTC Representations	175
5.2.4.2	Velocity Estimation	179
5.3	Results of the Planning Methods	190
5.3.1	Evaluation of the Obstacle Evasion based on Optical Flow Clusters	190
5.3.1.1	Evaluation of the Optimization	190
5.3.1.2	Evaluation of the Obstacle Evasion Approach in HIL Tests	195
5.3.1.3	The Obstacle Evasion in Real World Tests	199
5.3.2	The Direct Homography Control for Navigation Tasks	204
5.3.2.1	Static DHC	204
5.3.2.2	Results of the Platooning	209
5.3.3	STTC Map-Based Planning	214
5.3.3.1	Nullspace Calculation for STTC Map Objects	214
5.3.3.2	Optimization-based Planner	217
6	Conclusion	219
6.1	Discussion	219
6.2	Contributions	221

6.3	Future Work	222
6.3.1	Future Work regarding the Three Representations	222
6.3.2	Possible Transfers and Further Extensions	223
Publications		225
References		227
A Appendix		255
A.1	Applicability to a Conventional Vehicle	255
A.2	Utilization of the Essential Matrix	256
A.3	Car-2-X-Aided Visual Platooning	256
A.4	Tentacle Tree - Hybrid Motion Planning for the ROMO	258
Symbols and Mathematical Notation		261
List of Abbreviations		265

List of Figures

1.1	Perception to Action Cycle [254]	3
1.2	Ground-Based (Autonomous) Mobile Robots	5
1.3	Architectures for Autonomous Mobile Robots	9
2.1	Shakey the Robot	14
2.2	The Stanford Cart	15
2.3	The CMU Rover	16
2.4	The Navlab I Van	16
2.5	The VaMoRs Van	17
2.6	The VaMoRs-P	19
2.7	The Lancia Thema 2000 from the ARGO Project	19
2.8	The Winner of the DARPA Grand Challenge 2005	20
2.9	The Winner of the DARPA Urban Challenge	22
2.10	Team AnnieWAY, TerraMax and MuCAR3	22
2.11	Googles Prius and Lexus	24
2.12	The Google Car	25
2.13	Audi's RS7 "Jack"	26
2.14	Freightliner Inspiration Truck	27
2.15	Mercedes F-015	28
2.16	Classification of Planning Algorithms	33
2.17	Overview Planning Algorithms	34
3.1	Pinhole Camera Model	49
3.2	The Image Plane	50
3.3	Stereo Principle	51
3.4	Optical Flow Principle	53
3.5	Optical Flow Scene	54
3.6	Epipolar Geometry Principle	55
3.7	Homography Principle	56
3.8	STTC Flow Vectors	58
3.9	Side-view STTC Principle	59
3.10	Sensor and Actuator Coordinate Systems	66
3.11	Exemplary Optical Flow Object	67
3.12	The Epipole's Dependency on Relative Velocities	69
3.13	Estimation of the TTC via Flow Expansion	70

3.14	Sideview: TTC Estimation	70
3.15	Angle to the Epipole	72
3.16	Geometry of Colliding Objects	72
3.17	Three Different Dynamic Objects with Different Velocities	74
3.18	Output of the Two-Stage Clustering	78
3.19	Optional Check for Large Clusters	78
3.20	Relative Error Approximation DHC	85
3.21	Platooning Setup using the Direct Homography Control	87
3.22	Basic STTC Principle	90
3.23	STTC Map Principle	91
3.24	STTC Map β	93
3.25	Static Object in the STTC Map	94
3.26	Impact of Δv_Y for Static Objects	95
3.27	Impact of Rotation $R_{(-\Delta\psi)}$ for Static Objects	96
3.28	STTC Representation for Dynamic Objects	98
3.29	Impact of Δv_Y on Dynamic Objects	99
3.30	Impact of $\Delta\psi$ on Dynamic Objects	101
3.31	Principle of Single Point Velocity Estimation	105
3.32	SPVE in Image Space	109
3.33	Classification of the Proposed Approaches	113
3.34	Plot of ω_{TTC} over TTC	114
3.35	The Shaping Parameter k	115
3.36	ALIS Working Principle	118
3.37	DHC Control Structure	119
3.38	Visibility Restriction	123
3.39	Extended Controller Scheme	123
3.40	Robustness Evaluation with Parameter Space Approach.	127
3.41	STTC Map Weighted Regions	130
4.1	The ROboMObil	134
4.2	A Wheel-Robot	134
4.3	ROMO Operational Modes	135
4.4	ROMO Autonomy Architecture	136
4.5	AIA Simulation Scheme	137
4.6	AIA HIL Scheme	139
4.7	Coverage of the Cameras	140
4.8	Simulation of the Cameras	141
4.9	Sensor Attention Management	141
4.10	The VDC Architecture	143
4.11	Feasible Region of the ROMO's ICR	144
4.12	Planning Scheme of the Parking Maneuver	146
4.13	Blob Segmentation for Parking Space Identification	147
4.14	Parking Experiment	148
5.1	Impact of v_{Y_C} on STTC Calculation	150

5.2	Impact of v_{y_C} on STTC Calculation for Different Set Points	151
5.3	Impact of Δv on STTC Calculation	152
5.4	Impact of Δv on STTC Calculation for Different Set Points	153
5.5	Impact of v_{z_C} and Z_C on STTC Calculation	154
5.6	Impact of v_{z_C} and Z_C on STTC Calculation for Different Set Points	155
5.7	Impact of Δv on STTC Calculation	156
5.8	Epipolar Geometry-Based Clustering Scene	161
5.9	Detected Collision Candidate	161
5.10	Detection of Dynamic Clusters	162
5.11	Motion Cluster Closeup	162
5.12	Expansion-Based TTC Calculation Exemplary for One Feature.	163
5.13	Two-Stage Clustering in Simulation.	165
5.14	Determining the Angular State	168
5.15	Cost-function for Determination of α	169
5.16	DHC Simulation Scenario	170
5.17	RMS Errors for the Homography-Based Position Estimation.	172
5.18	Position Estimation Evaluation with Artificially Rendered Images.	173
5.19	Error Evaluation DHC-PE vs. Decomposition.	174
5.20	DHC PV Velocity Estimation	176
5.21	Exemplary Representations	178
5.22	Exemplary STTC Map	179
5.23	Stereo-Based vs. Flow-Based Velocity Estimation	180
5.24	Observability SPVE	181
5.25	Error Propagation SPVE vs. SSVE	185
5.26	Velocity Estimation Simulated Scenarios Images	186
5.27	Comparison Velocity Estimation Methods	187
5.28	Velocity Estimation Real Images	188
5.29	The Optical Flow-Based Obstacle Evasion	190
5.30	Optical Flow Objects Simulation Scenario.	191
5.31	Cost-Function of the Simulated Scenario.	192
5.32	Cost-Function for Different k Values.	193
5.33	Obstacle Evasion - Simulated Scenario.	196
5.34	Plot of the Velocities for the Evasion	197
5.35	Aggressive Obstacle Avoidance	198
5.36	Real-World Test: Evasion with Incorrect k Value.	200
5.37	Real-World Test: Evasion with Incorrect Start-Value Settings.	202
5.38	Real-World Test: Evasion with a Static Obstacle.	203
5.39	Real-World Test: Evasion with a Dynamic Obstacle.	205
5.40	Real-World Test: Evasion with a Static and a Dynamic Obstacle.	206
5.41	DHC Principle	207
5.42	DHC Simulation Scenario	207
5.43	DHC: State Variables for a Simulated Run.	210
5.44	Simulated Platooning Experiment	211
5.45	DHC Platooning: Simulation Plots	212

5.46	DHC Platooning: The ROboMObil's Measured Motion Vector.	213
5.47	DHC Platooning: Homography Matrix Elements.	214
5.48	STTC Map-Based Planning Principle	215
5.49	Evaluation Nullspace Method	216
5.50	Velocity States STTC Map Planning	218
5.51	Scenario STTC Map Planning	218
A.1	The Tentacle Tree	259

List of Tables

2.1	Sensor Overview	30
2.2	Sensor Equipment Autonomous Vehicles	31
5.1	Clustering Results: Static Obstacle	165
5.2	Clustering Results: Dynamic Obstacle	166
5.3	Comparison AKAZE and BRISK	166
5.4	Pose Estimation Scenarios	174
5.5	STTC Map Example	177
5.6	Scenarios for SPVE vs. SSVE Comparison	183
5.7	Comparison SPVE vs. SSVE	184
5.8	Comparison of $\hat{\alpha} = 0$ and $\hat{\alpha} = \alpha$	208
5.9	Competition Results of \hat{C}_{DHC} vs. \hat{C}_D	209
5.10	Evaluation STTC Nullspace Approach: In-plane	215
5.11	Evaluation STTC Nullspace Approach: non-planar	216
A.1	Symbols and Notation I	261
A.2	Symbols and Notation II	262
A.3	Symbols and Notation III	263
A.4	Abbreviations I	265
A.5	Abbreviations II	266
A.6	Abbreviations II	267