

Dipl.-Ing. Bernhard Lamprecht

**A Testbed for Vision-based Advanced Driver
Assistance Systems with Special Emphasis on
Multi-Camera Calibration and Depth Perception**

DISSERTATION

zur Erlangung des akademischen Grades

Doktor der Technischen Wissenschaften

Alpen-Adria-Universität Klagenfurt

Fakultät der Technischen Wissenschaften

1. Begutachter: Univ.-Prof. Dr.-Ing. Kyandoghere Kyamakya
Institut: Institut für Intelligente Systemtechnologien

2. Begutachter: ao.Univ.-Prof. Mag. DI Dr. Abdelhamid Bouchachia
Institut: Institut für Informatik Systeme

04/2008

Smart System Technologies

Band 2

Bernhard Lamprecht

**A Testbed for Vision-based Advanced Driver
Assistance Systems with Special Emphasis on
Multi-Camera Calibration and Depth Perception**

Shaker Verlag
Aachen 2008

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.: Klagenfurt, Univ., Diss., 2008

Copyright Shaker Verlag 2008

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 978-3-8322-7521-1

ISSN 1866-7791

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

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

Ehrenwörtliche Erklärung

Ich erkläre ehrenwörtlich, dass ich die vorliegende wissenschaftliche Arbeit selbstständig angefertigt und die mit ihr unmittelbar verbundenen Tätigkeiten selbst erbracht habe. Ich erkläre weiters, dass ich keine anderen als die angegebenen Hilfsmittel benutzt habe. Alle ausgedruckten, ungedruckten oder dem Internet im Wortlaut oder im wesentlichen Inhalt übernommenen Formulierungen und Konzepte sind gemäß den Regeln für wissenschaftliche Arbeiten zitiert und durch Fußnoten bzw. durch andere genaue Quellenangaben gekennzeichnet.

Die während des Arbeitsvorganges gewährte Unterstützung einschließlich signifikanter Betreuungshinweise ist vollständig angegeben.

Die wissenschaftliche Arbeit ist noch keiner anderen Prüfungsbehörde vorgelegt worden. Diese Arbeit wurde in gedruckter und elektronischer Form abgegeben. Ich bestätige, dass der Inhalt der digitalen Version vollständig mit dem der gedruckten Version übereinstimmt. Ich bin mir bewusst, dass eine falsche Erklärung rechtliche Folgen haben wird.

Dipl.-Ing. Bernhard Lamprecht

Klagenfurt, 18.04.2008

Dedication

This thesis is dedicated to Corina.

Acknowledgement

I would like to express my gratitude to all those who gave me the possibility to complete this thesis, to those that encouraged me to persevere and to those that accompanied me during my time at Klagenfurt University.

Aerodynamically, the bumble bee shouldn't be able to fly, but
the bumble bee doesn't know it so it goes on flying anyway.
[Mary Kay Ash]

Abstract

This thesis was a part of the still ongoing research project Machine Vision-based Context-aware Intelligent Driver Co-pilot (MIDCO) of the Transportation Informatics Group at Klagenfurt University. The main objective of this project is the development of an intelligent co-pilot system, which assists human drivers in their driving tasks. MIDCO is to represent a technically mature Advanced Driver Assistance System (ADAS).

As for this thesis, it focuses on both, the practical design and development of a simulation and testing framework for a vision-based ADAS and the fundamental scientific questions of moving camera systems in the context of the ADAS:

1. Can each camera of a moving multi-camera system automatically determine its extrinsic parameters without an overlapping visual field?
2. Can the distance to an object be measured with an uncalibrated moving camera in combination with the vehicle's speed?

This study explores state-of-the-art ADAS and compares them to each other from the perspective of the system and the sensors. Cameras will play an important role in the spatio-temporal modeling of the car's surroundings in the near-future since enough computational power will be available inside vehicles to process the high amount of data delivered. A basic need of ADAS is a spatio-temporal model of the vehicle's surroundings, which is why current concepts for depth determination with cameras are outlined.

What is documented in the practical/technical part of the thesis are a car-like robot testbed, a virtual reality simulator and vision modules for tracking, background segmentation, and object recognition.

The scientific part describes the investigations and the developed approaches.

The thesis closes with a summary of the main contributions and results achieved. The appendix includes two additional papers on the topic of intelligent vehicular technology. Moreover, one chapter of the appendix is dedicated to an accepted application for a research scholarship in connection to this thesis which presents parts of the future research in this field.

Contents

1	Introduction	9
1.1	Organizational Background	9
1.2	Objectives and Outline of the Thesis	11
2	Advanced Driver Assistance Systems	15
2.1	Introduction	15
2.2	System Perspective	17
2.2.1	Adaptive Cruise Control - ACC	18
2.2.2	Lane Departure Warning System - LDWS	19
2.2.3	Parking Assistants	20
2.2.4	Forward Collision Warning System - FCWS	21
2.2.5	Intelligent Speed Adaptation - ISA	22
2.2.6	Night Vision Systems	23
2.2.7	Blind Spot Monitoring	24
2.2.8	Pedestrian Detection and Protection	25
2.3	Sensor Perspective	26
2.3.1	Radar	26
2.3.2	Lidar	29
2.3.3	Ultrasonic	30
2.3.4	Cameras	30
2.4	Conclusion	32
3	Depth Perception with Cameras	34
3.1	Pinhole Camera and Projection Equation	35
3.2	Intrinsic and Extrinsic Camera Parameters	37
3.3	Projection Equation in Matrix Notation	38
3.4	Epipolar Geometry	39
3.5	Optical Flow	46
3.6	Conclusion	48
4	ADAS Testbeds and Vision Modules	49
4.1	ADAS VR-simulator	49
4.2	Car-like Robot	51

4.2.1	Mechanical and Electrical Assembly	51
4.2.2	Remote Control and Video Streaming	52
4.3	Background Segmentation Module	54
4.4	Car Detection and Tracking Module	55
4.5	Pedestrian Detection Module	57
4.6	License Plate Recognition Module	57
4.7	Conclusion	59
5	Extrinsic Two-Camera Calibration	60
5.1	Abstract	60
5.2	Introduction	60
5.3	Related Work	63
5.3.1	Overlapping FoV	63
5.3.2	Non-overlapping FoV	63
5.3.3	Contributions of this work	64
5.4	Preliminaries and Notation	64
5.5	Model Derivation	65
5.5.1	Projection Model	65
5.5.2	Concept	67
5.6	Experiments	68
5.7	Conclusion and Future Work	70
6	Distance Measurement from a Moving Camera on Highways	73
6.1	Abstract	73
6.2	Introduction	73
6.3	Preliminaries and Notation	75
6.4	Projection Model	75
6.5	Focal Length Analysis	77
6.5.1	Translation Analysis	77
6.5.2	Rotation Analysis	79
6.6	Simulation	80
6.6.1	Setup	80
6.6.2	Simulation Results	82
6.6.3	Curve Radius	83
6.7	Synthetic Data	85
6.8	Real Data	86
6.9	Conclusion	87
7	Conclusion and Outlook	89

A	Research Scholarship	92
A.1	Abstract	92
A.2	Economic Relevance	93
A.3	Short Technical Description	94
A.4	Scientific, Technical and General Aims	98
A.5	State-of-the-art and Previous Work	99
A.6	Technical and Scientific Problems	100
A.7	Economic Relevance	101
B	Computer Vision and Artificial Intelligence On-Road	104
B.1	Abstract	104
B.2	Introduction	104
B.3	Object Recognition	105
B.4	Context and World Modeling	106
B.5	Learning and Adaptation	108
B.6	Conclusion	109
C	Semantics on the Road	110