PHD THESIS

(Abstract)

Real-Time Computer Vision Techniques Based on Probabilistic Estimation

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Contents

Dictionary of Technical Terms 5

1. Introduction 9

2. Probability Based Tracking Techniques 13

2.1. Theoretical Foundations of Tracking 13

2.2. The Kalman Filter 17
    2.2.1. Problem statement 17
    2.2.2. The Kalman Filter algorithm 17
    2.2.3. A graphical analogy 22
    2.2.4. Design, initialization and configuration of the Kalman filter 23
    2.2.5. The Extended Kalman filter 28
    2.2.6. The Unscented Kalman Filter 30

2.3. The Particle Filter 32
    2.3.1. Problem definition 32
    2.3.2. Filter overview 33
    2.3.3. Resampling 34
    2.3.4. Drift and diffusion 35
    2.3.5. Measurement 37
    2.3.6. Estimation 40
    2.3.7. Initialization 41
    2.3.8. Optimizations 42

3. Lane Tracking Techniques – A Survey 43

3.1. Modeling the lane 44
    3.1.1. The static clothoid representation 44
    3.1.2. The dynamic clothoid model 48
    3.1.3. Alternate 3D lane models 51

3.2. Feature extraction techniques for lane tracking 55
    3.2.1. Feature extraction in monocular grayscale images 56
    3.2.2. Feature extraction in monocular color images 65
    3.2.3. Feature extraction using stereovision 71
    3.2.4. Feature extraction using active sensors 73

3.3. Estimation techniques for lane tracking 79
    3.3.1. Lane estimation using the Kalman filter 79
    3.3.2. Lane estimation using the particle filter 85
    3.3.3. Lane model matching using other techniques 89

3.4. Additional reasoning for lane tracking 95
    3.4.1. Choosing the lane model dynamically 95
    3.4.2. Using map and GPS information 96
    3.4.3. Using obstacle information in the lane estimation process 98

4. The Stereovision Sensor 101

4.1. Stereo camera setup for highway driving assistance solutions 102

4.2. Camera calibration 102

4.3. Stereo reconstruction using epipolar geometry 103
4.4. Improving stereo reconstruction using contour-level matching 105

4.5. Dense stereo reconstruction for urban applications 107

5. Original Lane Tracking Solutions Based on Stereovision 111

5.1. Stereovision based lane tracking system for highway and rural scenarios, built on a Kalman filter framework 111
   5.1.1. Modeling the lane 111
   5.1.2. Prediction 113
   5.1.3. Measurement – the Lane Detection algorithm 121
   5.1.4. Detection of side lanes 139
   5.1.5. Road state update 144
   5.1.6. Conclusions 155

5.2. Stereovision based lane tracking system for urban scenarios, built on a Kalman filter framework 157
   5.2.1. Modeling the urban lane 157
   5.2.2. Solution overview 161
   5.2.3. Extraction of lane marking points 163
   5.2.4. Linear model matching for lane detection 169
   5.2.5. Updating the lane state using the near range linear detection results 178
   5.2.6. Dual range linear detection 180
   5.2.7. Track initialization and stopping 182
   5.2.8. Side lane detection 183
   5.2.9. Lane border classification 185
   5.2.10. Freeform lane border detection 185
   5.2.11. Updating the lane state using the freeform detection results 193
   5.2.12. Tests and results 195
   5.2.13. Conclusions 197

5.3. Particle Filter Based Lane Tracking in Difficult Road Scenarios Using Stereovision 199
   5.3.1. Modeling the lane 199
   5.3.2. Particle filter-based solution overview 203
   5.3.3. Flexible software architecture for particle filter based tracking solutions 203
   5.3.4. Track prediction – resample, drift and diffusion 207
   5.3.5. Preliminary pitch detection 208
   5.3.6. Mapping the particle state to the measurement space 211
   5.3.7. The measurement cues 214
   5.3.8. Particle weighting by measurement 216
   5.3.9. Lane estimation and validation 220
   5.3.10. Handling lane changes 222
   5.3.11. Tests and results 224
   5.3.12. Conclusions 230

5.4. System integration 231

6. Conclusions 233

References 237

Published papers 247

Relevant independent citations 251
Abstract

The Advanced Driving Assistance Systems (ADAS) intend to provide a degree of decisional autonomy for the vehicle on the road. This autonomy will help both the driver, by relieving some of the stress that is associated with long-distance driving, and the traffic safety, by correcting some of the driver’s mistakes.

There are two problems that are the focus of any driving assistance sensor, from the beginning of the work in the field to the present day: obstacle tracking and lane tracking. These two aspects of reality form a large part of the driving environment. The lane will tell the car the way it should go, while the obstacles will tell the car the places where it is allowed to go. If we combine these two sets we obtain the input for the driving control, which will steer, accelerate or brake the vehicle.

The main objective of the work described in this thesis is the development of original lane tracking solutions for driving assistance in multiple difficult traffic scenarios, by using the advantages of the stereo sensor. Beside the use of stereo information, another defining feature of our solutions will be the reliance on probabilistic tracking frameworks. These frameworks are model-driven, allow uncertainty reasoning, and allow the integration of multiple features derived from multiple ways of processing the available sensor data.

This thesis is organized in such a manner that the original results are presented after the basis for the research work is clearly described for the reader. The first chapter presents a non-exhaustive introduction to the probability based tracking techniques. This chapter describes briefly the theoretical concepts, and then makes a detailed description of the most popular tracking schemes, the Kalman filter and the Particle filter, along with their variations. The description of tracking schemes covers both the theoretical aspects and the practical details, and I am hoping that the reader will find some valuable practical information.

The second chapter provides a survey of lane tracking techniques. This survey is organized in such a way that the reader will be presented multiple ways of modeling the lane geometry and dynamics, multiple techniques for extraction of lane delimiting features, multiple ways of matching the model to the features, and additional reasoning that may be employed in the lane tracking process. The survey was intended to cover all problems of lane tracking, from multiple points of view. The techniques described in the survey form the foundation for the original contributions.

The third chapter presents the stereovision techniques that provide the 3D and image data which will be used by the lane tracking algorithms. This chapter provides a brief presentation of the stereo reconstruction problem, of camera calibration techniques, and of edge-based and dense stereo systems, all the crucial work that our team at TU Cluj-Napoca has done to ensure that the high level algorithms, such as lane tracking, can work on reliable data.

The fourth chapter will present the original contributions of this thesis. This chapter presents three lane tracking techniques, developed using Kalman filters and particle filters, aimed at different lane scenarios: highway and country road, urban, and complex discontinuous roads. The defining feature of these methods is that they rely on stereo information, expressed as a set of 3D points in the Cartesian space. The stereo data allows the development of algorithms for direct detection of the vertical profile of the road, and for a more accurate selection of the road delimiting features. Also, the calibrated camera parameters allow us to employ
reasoning in the 3D space even when processing image data – a concept that marks the algorithms in several stages.

The first original contribution is a lane tracking system built for highway scenarios, using the 3D information provided by the edge-based stereo system. This solution introduced a novel technique for vertical profile detection, based on the lateral projection of the 3D point set in the Cartesian space. This contribution had an impact on lane tracking and object detection techniques, as an accurate road point separation can help in development of solution to both problems. Also, by direct estimation of the vertical profile parameters, the degrees of freedom for probabilistic model matching are greatly reduced, ensuring a higher robustness of results. The most common assumptions that characterized the existing lane tracking systems, such as flat road, constant pitch angle, absence of roll angle, could be removed. The highway lane tracking system brings additional original achievements: the development of an original mapping between the 3D and the 2D space, which takes into account the general camera geometry and the general lane model geometry, and which allows a 1 to 1 correspondence between spaces when the vertical profile is available, the 3D point based side lane detection technique, and the additional validations to ensure correctness.

The achievements and the experience gathered in developing the highway lane tracking system allowed us to tackle a more difficult and complex problem, tracking the lane in the urban environment. We developed a system that had to overcome limited visibility, presence of near obstacles that obstructed the field of view, presence of road features that may or may not be a legitimate lane delimiter, and more difficult lane geometries. In order to achieve robust results in these adverse scenarios, we had to design a novel lane marking extraction algorithm, which relies on the classical dark light dark transition pattern detection, but achieves this detection using a variable filter width image differentiation method combined with a perspective aware validation of the marking width. The differentiation kernel width and the distance for validation are established using the camera parameters. Besides detecting lane markings in the image space, the lane tracking system reuses the vertical profile extraction algorithm developed for highway scenarios, and the road point selection based on this profile, thus combining stereovision with grayscale image processing for road delimiting feature extraction. Next, the urban lane tracking solution relies on multiple intermediate results, such as lines and curves, some of which are extracted using original algorithms, and some are extracted using existing algorithm adapted for our problem. These intermediate results are combined by an original probability-based framework which is able to integrate multiple heterogeneous cues.

The highway and urban lane tracking systems are developed using the Extended Kalman Filer generic tracking scheme. The Kalman filter proved to be a very reliable tracker, which ensured stable results and low response time, due to the filtering and search space limitation characteristics that it provides. However, many real traffic situations imply discontinuous lanes. These situations include intersections, highway exits and entrances, road forking and so on. Aiming to improve the response of the lane tracking system in such situations, we developed a particle filter based solution, able, we hope, to cover both urban and extra-urban situations. A particle filter based solution does not use detection in the classical sense, there is no track initialization or track loss, and thus the processing time is kept constant, regardless of scenario. Besides the use of another tracking scheme, this solution brought several other original improvements. One such improvement is the pitch extraction technique, a considerable improvement over the also original method first developed for the highway solution, a technique which considerably improves the robustness of vertical profile
estimation and the road and obstacle feature discrimination. The particle filter based solution was developed using an original, flexible software architecture framework which can be used for multiple heterogeneous tracking solutions. The set of cues selected for measurement and the algorithms used for their extraction, the way the particles are matched with these cues and the methods for result validation, all of these features of our solution are original contributions.

Here is a summary of the contributions of this thesis:

1. A study of the lane tracking literature, and of the literature of the related fields, lead to:
   - A detailed description of the tracking problem in terms of probability based reasoning
   - A detailed presentation of the Kalman filter and its variants, the Extended Kalman Filter and the Unscented Kalman, in a manner that combines the theoretical aspects with solutions to engineering problems that one may encounter when building a tracking system.
   - A detailed description of the particle filter and its variants, explaining the theoretical mechanisms, implementation considerations, and variations in initialization and estimation techniques.
   - A survey of lane models used by the top researchers in the field. For this survey, an original demonstration of the derivation of the static and dynamic models is presented. The reader can compare multiple models, adapted for different problems
   - A survey of lane delimiting feature extraction techniques, comparing image processing methods applied to grayscale, color and stereoscopic images, or range data processing techniques.
   - A survey of model matching techniques, some based on probability, which aimed at fitting the lane models to the feature data. In this chapter, some methods are presented in detail, and some original demonstrations are added to the material found in the literature.

By these studies and surveys, the first part of the thesis is a valuable material that builds the scientific base for the original developments that follow, and a possible handbook for potential scientists in the field.

2. The design and development of an original lane tracking system for highways and rural streets, using the Kalman filter framework and the stereovision sensor, which includes:
   - The use of the most general static and dynamic lane model available, without the assumptions that were common in the existing solutions
   - The use of vehicle dynamics data (odometry data) for lane state prediction. The vehicle dynamics systems, available in modern cars, such as ABS and ESP, provided speed, yaw rate, and steering angle data through the CAN bus, and this data was integrated in the lane state prediction.
   - The original integration of a horizon detection algorithm for the prediction of the pitch angle variation.
   - The original algorithm for state space to image space mapping of the lane parameters, which removes many assumptions which were traditionally used.
   - The original histogram-based detection of the vertical profile, which relies for the first time on the stereo data in the form of 3D points, instead of disparities, and which includes the road vertical curvature.
   - The separation of road features and obstacle features using the vertical profile.
   - The original feature class based multiple segment fitting algorithm for processing of search regions in the process of lane model matching in the image space
   - The original method for recovering the 3D parameters from the results of the model fitting in the image space
- The original stereovision based method for the detection of the roll angle
- The original method for detecting the side lanes using the stereovision-derived road points and the assumptions of common orientation of all lanes of the road
- The original methods for the validation of the lane initialization

3. The design and development of an original lane tracking system for the urban scenarios, using the Kalman filter framework and the stereovision sensor, which includes:
- An original method for modeling the urban lane, combining a clothoid based model with a freeform model for the nonstandard borders
- An original tracking architecture, which is able to fuse multiple heterogeneous cues to update a single unified model. This architecture is based on the Extended Kalman filter, but uses multiple measurement models for multiple measurement sources. The defining feature of this system is the possibility of using very simple measurement cues to refine a complex model.
- The original solution for lane marking extraction, which uses a perspective aware variable width filter for computing the horizontal derivative of the grayscale image, in order to find dark light dark transition patterns. The camera parameters are used for accurate assessment of the perspective effect, and the stereo 3D information is used to validate the possible markings extracted in the image space.
- The original method for fitting line segments to lane delimiting features, which relies on a new, more computationally efficient method for representing a line, and uses geometric constraints to limit the search space and select only those lines that may form lane delimiters. Another novel feature of this algorithm is the use of feature weights, derived from feature classes.
- The original dual range linear detection approach, which ensures that detection can be achieved in a very limited distance range, but also allows more accurate results when the visible distance ahead is larger.
- The original freeform lane border detection method, which relies on lane markings in the 3D space to fit a spline curve to each lane border independently.

4. The design and development of an original lane tracking system for difficult urban and non-urban scenarios, based on stereovision and particle filtering, which includes:
- An original model for lane tracking, extending the most complex ones existing in literature. This model includes a vertical offset for the vertical profile, the width of the left and right lane markings, and the width variation of the lane along its length.
- An original software architecture which implements the particle filter mechanism in a polymorphic manner which can be extended to any tracking problem with minimum changes.
- The original method for the detection of the pitch angle, which extends our first original contribution in this field, considerably improving the results.
- The original measurement cue set used for particle measurement process: the original method for extraction 3D point density maxima used for vertical profile tracking, the original combination of edges, curbs and lane markings for the image space feature set, and the use of the variable width gradient image as a primary feature for estimating the lane marking width.
- The original methods for comparing the particles with the measurement data, using a small set of points and simple calculations, which allow the system to achieve a high frame rate even when using a large number of particles.
- The original method for lane tracking result validation, based on an original quality factor which monitors the distribution of resampled particles versus the measurement data and the random initialization particles.
- The original method for handling lane changes by monitoring the vehicle trajectory and anticipating the transition point, followed by the transfer of the whole particle set to the new lane.

Our research and our results are well integrated in the international scientific activity. The basis for our research is the state of the art in the field; our results are published 28 scientific papers, one in an *ISI rated journal*, 16 in *ISI conference proceedings*, and top researchers are quoting this work. This means that the results of the work presented in this thesis are actively contributing to the development of the scientific and engineering knowledge in the field.

I want to thank all the people that made this thesis possible. I thank my advisor, Prof. Dr. Ing. Sergiu Nedevschi, for having faith in my abilities and for patiently and expertly guiding my work. I also want to thank our present and former research partners from Volkswagen, Dr. Rolf Smith, Dr. Marian Andrzej Obojski, Dr. Thorsten Graf, Dr. Marc Michael Meinecke, Dr. Alexander Kirchner, Dr. Thanh Binh To, and Matthias Koenig, who supported my work, and the work of our team, through research contracts since 2001. I want to thank Hans Joachim Grove and Dr. Maria Grove, who made the cooperation between UT Cluj and Volkswagen possible.

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