Object-tacking and maneuver estimating methods for advanced driver assistance systems

Overview of PhD thesis by:

Olivér Törő

MŰEGYETEM 1782

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

Supervisor:
Tamás Bécsi, PhD
Department of Control for
Transportation and Vehicle Systems
Budapest University of Technology and
Economics

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1 Introduction

Demand for transportation is continuously rising, resulting in an increase in challenges transportation-related sciences, such as traffic management and vehicle control face. Research on the subject of autonomous vehicles has been going on for decades. Although much progress in enhancing comfort and safety has been achieved, driverless cars for the public are not a reality yet. There are different issues to be solved. On the technical side the lack of precise and at the same time inexpensive solutions for locating the vehicle position is a problem. Reliable operation of certain sensors can be ensured only in clean weather. There are sensors with performance beyond human senses, however, evaluating the measurements is a hard task and far not as effective as vision-based navigation of human drivers. One of the most important legal obstacles is that vehicles without mentally and physically capable drivers are generally not permitted in public traffic. With the increasing automation level of vehicles participating in road traffic, the number of human casualties shows a decrease. Nowadays, as the number of drivers suffering fatal accidents dropped to a level comparable to pedestrians, research towards active and passive systems for protecting them came into focus. In recent years basic Advanced Driver Assistance Systems (ADAS) functions such as Lane-Keeping and Adaptive Cruise Control became common in lower-middle-class cars, making vehicle automation available to a wider public.

Due to the increasing level of automation in road vehicles, passenger safety and driver comfort constantly improve. Cooperative environment detection and situation awareness are essential components of next-generation advanced driver assistance systems and fully autonomous vehicles too. The quantity and quality of information needed for such functionalities require new methods for data fusion. Road vehicles with autonomous functions need the ability to reliably sense and understand the environment. Advanced driver assistance systems e.g. obstacle avoidance or lane change assistant must be aware of the traffic situation the vehicle participates in. To achieve higher-level goals, such as traffic management in smart cities or route travel time estimation with floating car data [10], information from every possible vehicle and roadside unit should be collected and processed in an optimal way [2]. Information fusion in large and heterogeneous systems, where communication can be manifested by V2V and V2I solutions, is a demanding task [1]. Bayesian approach for estimation is common [3], however, the Kalman filter and its variants are inconvenient for certain state-space models, mainly because of the varying number of measurements and objects that need to be detected and tracked in road traffic.

State estimation in road traffic has several peculiarities. First of all, traffic participants navigate, and for this reason, from time to time, maneuvers are performed. Detecting, let alone predicting the maneuvers can help giving more accurate state estimates and recognize the actual traffic situation. This leads to the problem of behavior prediction, where the ego vehicle needs to predict the possible future trajectories of the surrounding traffic participants, such as vehicles or pedestrians [7]. Classic object tracking algorithms are not suitable for mid-term motion prediction because they cannot consider the interaction of participants, though their robustness is essential for the proper input generation for these algorithms. The classification ability of multiple model (MM) systems can also enhance the efficiency of the prediction. Another important characteristic of road traffic is that the number of participants, in a certain region, is varying. To this comes the problem of detectability, that is objects frequently occlude each other or move out of the sensor field of view.

Autonomous vehicles have to solve several problems to be able to navigate. Navigation is a high-level functionality that involves several subtasks. The vehicle needs to localize itself on a given map. The map may be static, dynamic, or even unknown in which case the map has to be created from the environment sensor data. The combined task is called Simultaneous Localization And Mapping (SLAM). SLAM is considered a solved problem in an isolated, static environment [8]. On the contrary, in a dynamic environment, with a varying number of objects, the problem of Detecting And Tracking of Moving Objects (DATMO) and navigating between them (SLAM In Dynamic Environment) is hard and not fully developed [9]. While the Kalman filter and its variants are popular and offer effective solutions for various filtering problems, their capabilities are limited regarding dynamic environments and handling different data imperfections [6].

This thesis summarizes results in the field of state estimation in road traffic situations. Three aspects of state estimation have been considered: multi-sensor, multi-model and multi-object problems. The thesis has four main chapters, each devoted to a certain task of state estimation and object tracking problem in a road traffic environment. The mathematical tools for modeling system dynamics and giving state estimations are classic probability based methods and random finite set (RFS) theory. All of the used estimation methods can be originated from the mathematical framework of Bayesian inference. The primary estimators are the Kalman filter and the bootstrap particle filter. Based on these comes the higher level concept of multiple model estimator. Unmodeled dynamics and limitations are inserted into the estimators through state constraints. The random set based filters, namely the Bernoulli and the probability hypothesis density filter are also derived from the recursive Bayes formalism. The mathematical tool that defines and allows the evaluation of the Bayes theorem is called finite set statistics.

The first part of the thesis is dedicated to the applications of the Bernoulli filter in road traffic. The Bernoulli filter is an exact and optimal estimator for a single-object scenario, based on random finite set theory. The first chapter concerns multi-sensor object detection and state estimation. The chapter gives an overview of the used simulation environment and briefly introduces random finite set theory. After the description of the Bernoulli filter, its implementation in a multi-sensor road traffic application is presented. The filter performance is examined through several aspects.

In the second chapter, the implementation of the Bernoulli filter in the interacting multiple model (IMM) framework is considered.

Two filtering strategies are proposed. On one hand, a single-sensor filter structure is designed and tested in an abstract scenario. On the other hand, a road traffic oriented multi-sensor solution is presented in a particle filter realizations. Explicit mode-probability and existence probability values are extracted from the filters.

The third chapter concerns maneuver detection and state estimation with constrained filtering techniques. The proposed method uses constrained filters in the interacting multiple model structure that are fine-tuned to recognize certain maneuvers. The elemental filters in the IMM structure are constrained Kalman filters. The applied constraints include equality, inequality, soft and hard state constraints. The methods to integrate the constraints into the estimation algorithm are measurement augmentation and estimate projection. The filter performance is examined in an abstract and a simulated traffic situation.

The problem of multi-object detection and tracking in road traffic applications is addressed in the fourth chapter. The used estimator is the probability hypothesis density filter, based on RFS theory. The filter in the original form can detect a varying number of objects and, if the standard measurement model is used, it has linear scaling characteristics in the number of objects and measurements. The addressed issues concerning the PHD filter are the instability of the expected number of reported objects and the labeling and tracking of detected objects. The occlusion of traffic participants is considered through an analytic visibility model which allows computing state-dependent detection probabilities which in turn helps to stabilize the estimated number of objects during detection outages. On the other hand, the list of undetected but possibly present objects is propagated through the recursion which contributes to the creation of the birth pool for particles. The filter performance is evaluated through several simulated scenarios and by processing highway radar measurements.

2 Contributions of the Thesis

Thesis I

I have developed a Bernoulli filter in a multi-sensor scenario for object tracking in road traffic. The Bernoulli filter is realized as a bootstrap particle filter using a measurement-driven birth pool. The measurement likelihoods are evaluated in the state space that also allows creating the birth pool directly. The test scenario is a simulated highway traffic situation, where vehicles are observing an object that can enter and leave the sensors' field of view. The filter performance is evaluated along four aspects, the dynamic and measurement model noises, the particle number, and the used timestep.

Related publications: [Toro1], [Toro7], [Toro6]

- I have created a simulation framework in Matlab that can be used to develop and test multi-sensor multi-object estimation algorithms.
- The designed scenario involves vehicles moving along a road segment and observing an object via radar measurements.
- The Bernoulli filter is used to track and detect an object that bears varying visibility.
- The filter is realized as a bootstrap particle filter with constant velocity motion model. Although particle filters have the advantage that the measurement model needs not to be inverted, the presented solution does the inversion. The measured quantities are transformed to the state space and the likelihood computations are carried out there. The multi-sensor update step is performed iteratively.
- The birth density function is constructed with the help of the inverted measurements thus requiring no additional computation. This procedure permits the particles to be drawn directly

from the state space, saving a significant amount of computation, because essentially measurements on the particles are not performed.

- The scaling and performance of the proposed filter are evaluated by running Monte-Carlo simulations with four independent parameter sets.

Thesis II

I have designed two filtering strategies that allow the Bernoulli filter to be implemented in the interacting multiple model framework. The first solution is a direct extension of the IMM structure where explicit mode probability and object existence values are computed. The filtering equations are approximated as particle filters, communicating with the higher logic through a Gaussian interface. The second solution is a particle filter based IMM model. The proposed method can handle state-dependent survival and detection probabilities. The filter is implemented and tested in a multi-sensor simulated road traffic environment.

Related publications: [Toro8], [Toro2], [Toro3]

- I have implemented the Bernoulli filter in the interacting multiple model framework. The filter structure uses explicit mode probability and existence probability values.
- The elemental filters in the IMM framework are particle filters that communicate through a Gaussian interface.
- The filter can be implemented straightforwardly with Gaussian mixtures. If a data association step is performed prior to filtering then a multi-object estimation problem can be handled as well.
- Using the work of [13] as a starting point I derived the particle filter realization of the IMM Bernoulli filter.

- The performance of the proposed filter structure tested in a simulated multi-sensor traffic scenario.

Thesis III

I have designed a multi-model state estimation method that can identify the maneuvers of an observed vehicle. The main elements of the algorithm are a multi-model estimation and constrained filtering. The constrained filters are arranged in the structure of the interacting multiple model estimator. Each filter is customized by constraints to match a specific type of maneuver. The quality of a filter is determined by examining the post-fit residual.

Related publications: [Toro4], [Toro9], [Toro3]

- The estimator for maneuver detection runs in the Interacting Multiple Model structure where the elemental filters are Kalman or particle filters.
- The manifestation of the β-dominance effect was avoided in this structure by using the post-fit residuals after the constraints were applied. The constraints help separate the estimated states so that the residuals will differ considerably.
- I have derived a formula that can be used for mode likelihood computation involving the constrained post-fit residual and its covariance.
- The proposed filtering method can be applied with soft and hard linear equality constraints. For linear soft inequality constraints, it can be applied in special cases.
- Under linear inequality constraints finding the optimal state estimate would result in a quadratic programming problem. With certain restrictions, an analytic solution is available which allows a fast computation of the mode likelihood.

- The maneuvers are defined by setting constraints on the state variables. The motion models in the elemental filters are the same, the applied state constraints make the filters unique. For mode likelihood computation the constrained post-fit residuals are used.

- The proposed estimation structure was tested in a simulated environment created in MATLAB/Simulink and in PreScan.

Thesis IV

I have designed a multi-object estimation algorithm suitable for road traffic object tracking based on the probability hypothesis density filter. The presented work has three contributions that aim to address the limitations of the classic PHD filter. Using the standard measurement model, I have proposed a method to handle multiple detections of the same object in a single time frame. By adopting a model to estimate the state-dependent detection probability, the filter could reduce the effect of missed detection on the cardinality estimate. Regarding track management and reporting of detected objects, the proposed method introduces inertia, which the classical PHD filter lacks, to gain additional cardinality estimate stability.

Related publication: [Toro5]

- The standard measurement model is used to keep the linear scaling properties of the PHD filter.

- An occlusion model is used to compute the state-dependent probability of detection. The visibility of an object is modeled by the raised cosine PDF and its integral is considered the probability of detection.

- The PHD filter is realized as a particle filter without augmenting the state space with a label variable.

- The filter distinguishes detected, hidden, and undetected particles for object tracking.
- For labeling and data association the Kullbach-Leibler divergence is used.
- The presented algorithm's performance is evaluated in synthetic tests using simulations and logged sensor data originating from real-world traffic situations.
- The OSPA metric is used to evaluate the filter performance. Simulations show that the performance of the proposed filter is significantly better than the classic one.

3 Practical aspects

For ADAS functionalities, as realtime realization of the algorithms is a necessity, one should be aware of the computational demands and scaling properties of a given procedure. Particle filters give approximate solutions for filtering problems in a way that optimization can be performed at runtime. The particle filter implementation of the multi-sensor Bernoulli filter, in the presented approach, exploits that the evaluation of the sensor model can be avoided and the measurements from different moving sensors can be directly used for likelihood computation. This approach can save computation in cases, where evaluating the measurement model is costly and a large number of particles are used. The number of particles and possibly the partitioning of them can be modified to adapt the algorithm for the current traffic situation and the number of measurements that need to be processed.

A possible application of the maneuver detection method is to serve as a classification and data provider system for a higher-level logic, e.g. a collision warning system detailed in [12]. The extracted information can be used to detect possible dangerous situations or unavoidable collisions and draw the interacting graph of the vehicles involved.

In road traffic applications the multi-object estimation task naturally arises. The PHD filter is relatively easy to implement, however, to ensure its effective functionality care must be taken to supply it with reliable information. Besides state estimation, labeling, and tracking the PHD filter can be used to estimate the clutter background or consider multi-path signal propagation or sensor characteristics that cannot be described by the standard measurement model.

4 Future work

Observer state uncertainty is not considered in this work, however, in [5] a method is provided for handling observer uncertainty in a single-sensor single-target scenario, which could be extended to multi-sensor detection. Vehicles should be able to detect and track each other, in addition to the object, which requires the implementation of the multi-sensor multi-Bernoulli filter [11]. Also, vehicles moving on a road are under soft constraints, and this information could be used in the prediction step, e.g. adopting a constant acceleration (constant speed and constant angular velocity) model. A more complex system, using the output of a lane detecting/keeping algorithm would predict the trajectory of the vehicle and integrate this information into the motion model. For cooperating vehicles, the performance and quality of communication must be considered in any scenario.

The Bernoulli filter in the IMM framework serves as a proof of concept of the filter functionality in a simple multi-sensor situation, however further development directions can be pointed out. Using state vectors with different components or dimensions can enhance the filter performance and flexibility [4]. Maximizing the number of measurements to evaluate to a certain amount would reduce the computational demand of the algorithm. In this case, one has to calculate the amount of information each sensor would provide and select a limited number of measurements accordingly.

The presented maneuver detection algorithm could be improved along with several aspects. Further research would include combining different motion models and constraints in various state space representations and create a measure to quantify the maneuver detection and state estimation capabilities of the filters. The proposed maneuver detection method is flexible regarding the type of constraints used and could involve other type of maneuvers too. A comprehensive study would reveal which maneuvers are best detectable by which constraint, possibly using different motion models. If curved road is detected CT motion model could be used to better estimate the state of the observed vehicle which would lead to the variable structure IMM estimator. A particle filter based solution could offer more flexibility regarding the system model and noise characteristics and, more importantly the formulation of constraints. Drawing particles from a distribution that reflects a certain constraint would allow more sophisticated classification.

Regarding the implementation of the PHD filter, besides the state-dependent probability of detection, the filter could benefit from the introduction of state-dependent survival probabilities that would allow to model objects exiting the scene or discard objects in irrelevant regions. Modeling the ego vehicle motion is another possible extension as it would make tracking more effective during a lane-changing maneuver. Regarding radar detections, the problem of clutter filtering is not a solved problem. Creating effective, possibly state-dependent clutter models would allow tracking objects more robustly. In particular, if the filtering of clutter measurements can be separated from the filter, the application of the zero-false-alarm CPHD filter would be possible, which has linear scaling properties but propagates the first and second moment of the estimated number of objects present.

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