IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

CONTRIBUTIONS TO THE DESIGN OF AN AUTOMOTIVE EMBEDDED SYSTEM FOR PEDESTRIAN PROTECTION

Doctoral thesis – Summary

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The thesis presents new analytical methods for evaluating the performance of algorithms for tracking multiple targets in road traffic and experimental results that demonstrate the practical applicability of the proposed methods. The methods can be used in various technical applications, especially in pedestrian tracking and protection problems, which usually have a dynamic model with a relatively large number (L> 4) of representative points.

The technological evolution of radar systems for tracking multiple targets in the corresponding field of view currently allows a detailed representation of the observed objects. Unlike the first generations of automotive radars, in which each detected object was represented in the internal observation model by a single characteristic point, modern radars can estimate not only the center of mass for each target, but also its precise representation in space. Additional information such as width, length, contour or angular orientation corresponding to a car or pedestrian can be collected with high accuracy, depending on the environmental conditions and the technical operating parameters of the radar, such as its internal temperature or supply voltage of the analog radio-frequency interface. The extended representation of multiple targets leads to new problems in assessing the level of performance of tracking systems. Both the real state in the multidimensional space and the estimated state are represented by a high number of characteristic points, thus making the comparison between ground truth and estimates more difficult.

Algorithms for simultaneous tracking of a high number of objects of interest are frequently used in various scientific or technical fields, such as molecular biology, transport systems, in military applications or in robotics. For sensors embedded in cars, their key function is to detect different categories of targets like cars, pedestrians or cyclists, with high levels of noise and clutter. During the presence of targets in field of view, the tracks corresponding to each target are followed iteratively, from the moment they enter the field of view until their disappearance.

Taking into account the characteristic properties of motion models for each target category, the methods applied for detection and tracking vary and enable thus the differentiation between target categories, e.g. between cars and vulnerable road users. Due to the significant improvements achieved regarding the location precision of automotive radars, the representation of tracked objects has become more accurate but also more complex, given that each target has assigned several characteristic points, usually at its geometric extremities. The set of representative points is monitored throughout the entire observation period.

In order to eliminate the disadvantages related to the problem of the association between the observations taken at a given moment and the real objects, Mahler introduced a new mathematical model, used in the meantime more frequently in automotive tracking algorithms. It is based on the representation of real and estimated states in the form of random finite sets (RFS). The model applies a principle derived from the Bayes or Kalman filters, consisting of two iterative steps, the first prediction followed by an update step. Unlike the Kalman filter, this model propagates between iterations the a-posterior statistical intensity function of the RFS, respectively the first-order statistical moment of the RFS, also called the probability density of hypotheses (PHD).

Chapter 1

This chapter is an introduction to the principle of operation of embedded radar systems. The different types of commonly used sensors as well as the relative advantages and disadvantages between radar, lidar and video camera systems, are presented first. Subsequently, different categories of automotive radars and some of their common functions are described. Both the evolved environmental sensing capacity and also the very attractive price / performance ratio pushes radar technology at the forefront of the sensing equipment needed for L5 autonomy level, when cars can navigate without the intervention of a driver.

Chapter 2

A first personal contribution of this thesis is given by the summary in Chapter 2, showing the way of operation and the theoretical principles of an automotive radar. The author studied the vast literature mentioned in the bibliography and used as well the personal experience obtained in a R&D project within the Continental company. The categories of radars with different maximal ranges and azimuth angles are described. The Doppler effect allows the estimation of the relative radial velocity between a target and the ego-vehicle, i.e. the car carrying the embedded radar. In addition, a radar can determine the distance between its mounting position and each individual target, as well as the angular orientation of each target.

The digital processing chain of the received FMCW signal is presented in detail, highlighting the need to run a high number of fast Fourier transforms (FFT). This involves hardware accelerators specialized in FFT calculation, integrated in the digital radar signal processor. Following, the relevant requirements for sizing the processor's data memory are discussed, in order to allow the storage of the radar data cube.

The protection of vulnerable road users, such as pedestrians or cyclists, is of particular importance. For the detection of pedestrians, the aim is to identify biometric fingerprints caused by heartbeats or micro-movements of the arms and legs. The classical Doppler effect used for relatively large targets, such as cars or trucks, can has no applicability in this case. By using the micro-Doppler effect described in this chapter, it is possible to detect and localize pedestrians, cyclists or even animals crossing the road.

Chapter 3

As an additional original contribution, radar signal processing techniques are presented and critically evaluated in Chapter 3. The Rx signals contain useful information both in amplitude and in phase and must be considered as a complex signals in the processing chain. The hardware and software components typically used in radar signal processing are described further. One of the final steps in the processing chain is the iterative tracking of multiple targets. Commonly used tracking algorithms require an association phase between detections taken at each radar cycle and ground truth objects, maintained in the processor's data memory, in form of a dynamic list of hypothetical targets. The association step is one in which some information is being lost, inducing thus additional errors. To avoid this, the thesis proposes to use of a new family of tracking algorithms, namely filters which propagate the first order statistical moment of the probability density, called the probability hypothesis density, PHD. These filters consider all targets detected at a particular time as a single multi-target with associated statistical parameter.

After the first and the second FFT, the values for range and relative velocity are obtained. Determining the angular orientation of a target requires the simultaneous processing of the radar echo perceived by multiple receiving antennas, positioned at known distances in between. In order to improve the angular resolution and consequently the separability between neighboring objects, several analog radio-frequency interfaces can be cascaded, thus obtaining a larger number of Rx channels.

The target detection limit allows the separation of the useful signals from clutter and noise. In order to limit the demand of hardware resources, the CFAR limit must be dynamically adjusted, according to the form of the Rx signals and the number of targets.

The vast majority of Rx samples are below the detection limit and can be removed from the subsequent processing steps. Determining the support interval of these signals, i.e. the frequency regions in which the signal's energy is being concentrated, plays a key role in data compression. New in-vehicle architectures of electronic networks follow the trend to centralize the radar signals processing. Thus, next generations sensors will transmit poorly pre-processed Rx signals (AD samples, eventually output after first FFT) on high-speed data buses, for example over 1Gbit Ethernet interfaces. Two compressive sensing methods are investigated as personal contribution in this thesis. They allow a considerable reduction of data volume, without a significant loss of information. The corresponding mathematical models and experimental results are presented and discussed in detail in this chapter.

Chapter 4

Chapter 4 focuses on the usual target tracking algorithms. The observation and the dynamic models are analyzed in detail, thus establishing the theoretical foundation for the experimental results presented in Chapter 5. The Kalman and the extended Kalman filters are briefly presented, being considered widely-known, with a large number of descriptive publications.

The mathematical modeling of extended objects is discussed as personal contribution.

Chapter 5

Chapter 5 gives the methods to assess the performance of multiple target tracking algorithms. This chapter begins with the classification and the critical review of the usual metrics, currently used to validate multiple object tracking (MOT) algorithms. The CLEAR metric set is relatively simple and can be calculated with little computational effort. Its main disadvantages are the weak ability to identify mismatches and the invariance of the MOT accuracy related to the time in which these mismatches persist. The OSPA metric combines the MOT values for accuracy and precision and eliminates the mentioned disadvantages related to mismatches.

This thesis proposes as an original contribution the use of the Mahalanobis distance as a basic distance in the calculation of the OSPA metric. The Mahalanobis distance allows the integration of the degree of uncertainty in the performance evaluation of tracking algorithms. Thus, by using the M-OSPA metric, we can distinguish the differences in performance between algorithms with identical mean values for range, velocity and angular position, but with different statistical parameters. An additional personal contribution, also presented in this chapter, introduces an efficient method to calculate the M-OSPA value for extended multi-target scenarios. The proposed method reduces the processing time by about 20%.

Main types of PHD tracking algorithms are presented in detail. The advantages and limitations of each filter are discussed in the corresponding subchapters.

The last personal contribution is given by an extensive set of simulations and experimental results. It demonstrates that the M-OSPA form factor metric can be used with remarkable success and in an efficient way to identify the most powerful multi-object tracker from a given set of algorithms.

Chapter 6

Chapter 6 contains the conclusions of the doctoral thesis. It summarizes the previous chapters and highlights the personal contributions made by the author within this thesis.

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