Automotive Radar Based Object Detection and Tracking for Perception in ADAS and Autonomous Driving: A Review

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***Abstract*—Environment perception, as the essential functionality of advanced driving assistance system(ADAS) and autonomous driving(AD) system, should be designed to understand the surrounding environment accurately and efficiently. Automotive radar, as the only sensor has the ability to sense the range information in almost any weather conditions, with comparably low cost, is the key factor to meet such requirements of environment perception. In this paper, we go through every aspect required for designing the automotive radar based environment perception module in detail, summarize the most relevant papers published recently and from years before, and highlight the most significant technologies which provide the fundamental of architecture of environment perception system.**

***Index Terms*—ADAS, Autonomous Driving, Environment Perception, Object Classification, Instance Segmentation, Clustering, Object Detection, Target Tracking, Automotive Radar, Camera, Sensor Fusion**

I. INTRODUCTION

AUTOMOTIVE radar has already attracted lots of interesting in the application of Advanced Driving Assistance System(ADAS) and Autonomous Driving(AD), as the key sensor[13, 14, 15, 16, 17] to provide detection in range, velocity, under different environment, besides other two major sensors, camera and Lidar which contribute the perception capability of driving environment. Camera, as the sensor which provides human like perception capability, has already been widely used in lots of application regarding environment sensing in both indoor and outdoor due to its strength on obtaining the semantic information and azimuth information like human eyes. Whereas the shortages of camera, e.g. sensitive to the light condition, variation of weather, hard to extract depth information for obstacle object especially, etc, are also obverse. Lidar[62], as the other promising sensor shows great potential on range exploration, azimuth and elevation resolution improvement, and semantic understanding, is used for variant applications, e.g. ego vehicle localization, mapping, and target tracking[90] for demo project, by providing accurate 3D information using opto-mechanical, electromechanical, micro-electromechanical systems (MEMS), or solid-state scanning[91]. However the cost is the main bottleneck for making Lidar widely acceptable for the ADAS and AD system. Perception by using camera and Lidar have been heavily investigated and there are several survey papers published recently, gave insightful and complete overview of depth estimation, semantic segmentation, 2D/3D object detection and tracking by using mono and stereo camera[1, 2, 63, 92, 93], Lidar[3, 94], and fusion of camera and Lidar[4, 70, 95, 96]. However, classification, semantic segmentation, object detection and target tracking by using automotive radar, and fusion of camera and automotive radar, haven't yet been studied systematically, though they already drew lots of attentions recently, e.g.[9, 11, 12, 36, 25, 19, 44], due that automotive radar could provide "all day" perception capability under almost arbitrary driving environment with relative low cost. In this paper, we provide complementary resource to fill the gap in survey of perception for ADAS and AD by using automotive radar.

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The paper follows the structure as below:

1) Automotive Radar Signal Processing Introduction: We will describe basic 3D FFT to generate 3D data cube(range, Doppler, azimuth). Alternative algorithm MUSIC[34] and ESPRIT[35] for improving resolution of range and azimuth. Other signal processing technologies to provide high resolution azimuth in automotive radar, e.g. improved two stage MUSIC[67] which estimate ToAs and AoAs successively, improved one stage MUSIC[68, 69] which ToAs and AoAs jointly. Generate detection points from 3D data cube by using CFAR[33]. 4D image radar technologies(range, azimuth, elevation, Doppler). And some other statistical signal processing based methods or deep learning based methods to improve the resolution of automotive radar.

2) Data Representation for Automotive Radar: We will describe range Doppler map, micro-Doppler, range azimuth heat map, range azimuth Doppler 3D cube, detection points.

3) Single Object Classification by using Automotive Radar: We will describe how to do pure classification for only one object per frame/scene, how to generate corresponding training data, how to label/annotate data.

4) Semantic Segmentation by using Automotive Radar: We will describe how to do semantic segmentation for multiple objects per frame/scene, although it is not the major task by using automotive radar and it is quite similar to multiple objects detection by using automotive radar, how to generate corresponding training data, how to label/annotate data.

5) Multiple Objects Detection by using Automotive Radar: We will describe how to do object detection for multiple objects per frame/scene: from "clustering + classification by using different format of automotive radar data" to "instance segmentation(2D bounding box regression) with classification together using deep learning based object detector", how to generate corresponding training data, how to label/annotate data.

6) Multiple Objects Detection by using Automotive Radar and Camera (Early Stage Fusion): We will describe, firstly, how to find out the intrinsic matrix, K, and extrinsic calibration matrix, T, between camera and automotive radar(The calibration of automotive radar and camera). Then we show how to do object detection for multiple objects per frame/scene: 1. From early time exploration before the deep learning technology raised to nowadays, the most straightforward idea is: e.g. automotive radar just provide the ROI proposal in more accurate way to help to speed up object detection in front view(range view/image field) by camera, especially when employed two stage object detector for front view image. 2. The most popular choice: "instance segmentation(2D bounding box regression) with classification together using deep learning based object detector" with fusion of automotive radar and camera data in either front view(range view) or BEV, by using one stage detecotor, SSD, YOLOv3, RetinaNet, etc. 3. Camera, in the other way round, as the ROI provider, to provide frustum in space for cropping the suitable space, in order to guide the PointNet family network to extract the features from suitable automotive radar detection points directly. 4. Camera follows the idea of "pseudo Lidar", to generate "pseudo point cloud", then fuse with automotive radar data which could provide useful information regarding RCS and velocity with more accurate range information as complement, on top of the fruitful extracted feature from pseduo point cloud. Lastly, we also describe how to generate corresponding training data, how to label/annotate data.

7) Beyond Objects Detection I: Target Tracking by using Automotive Radar Only or Camera Only: We will briefly explains: How the extended target tracking problem is caused by using mmWave automotive radar only and how to tackle the extended target tracking by using automotive radar only. Visual(Point) target tracking by using camera in image field. Point target tracking + shape estimation by using camera projection to BEV only.

8) Beyond Objects Detection II: Target Tracking by using Automotive Radar and Camera: How(and why) extended target tracking problem could be transferred to point target tracking by using fused detected object from Early Stage Fusion of automotive radar and camera. Extended target tracking(or by using "point target tracking + shape estimation" to approximate real extended target tracking problem) by using detection from both automotive radar and camera(Detection Level Fusion). Point target tracking by using track from both automotive radar and camera(Track Level Fusion). Besides explain the tracking technologies themselves, we also describe how to generate corresponding ground truth data for tracking purpose, and possible criteria used for performance examination.

9) Beyond Objects Detection III: Fusion of Classification Results from Automotive Radar and Camera: It will also include "multi-classification type decision strategies" by using fuzzy logic and DS(Dempster-Shafer)-theory for handling contradictory classification result in tracking level fusion.

10) Object Detection, Target Tracking and Others as Entire Architecture for Perception in ADAS and AD: We will overview the already proposed structure of object detection + target tracking by using automotive radar only and using automotive radar plus camera(here should list and analyze the papers show the architecture of object detection plus tracking). Besides, we will also give a short introduction to other modules in perception system in ADAS and AD, e.g. lane detection(by using camera or automotive radar), traffic sign and traffic light recognition(mainly using camera), etc.

11) Open Challenges and Further Research Direction: 1. How to better fuse camera in pseudo Lidar format with automotive radar data? 2. How to generate "super resolution" automotive radar data(even comparable with Lidar point cloud) by using low resolution automotive radar data(and possibly with camera)? 3. How multi-scale features, especially features from distant objects could be better extracted and fused? One possible answer is, incorporating attention mechanism, e.g. spatial-wise, convolutional kernel(receptive field)-wise, etc, to focus on distant objects detection in one frame fused data from automotive radar and camera. Another possible method is, using distance dependent dilated convolution filter or deformable convolution filter for multi-scale objects whose shapes and sizes are changeable based on different distances. The distance information could be provided by automotive radar in reliable way. 4. How to provide more reliable object detection results to support target tracking, e.g. incorporating uncertainty representation into object detection by using automotive radar and/or camera?

II. Automotive Radar Signal Processing Introduction

III. Data Representation for Automotive Radar

micro-Doppler, together with learning algorithm, has been widely used in several application like hand gesture recognition[27], person identification[28], human-robot classification[29], sensing and recognition of human walking[64, 65] or other activities[30, 31, 32]. Recently, using micro-Doppler[56, 57] generated from raw data measured by automotive radar for object classification, has also been investigated.

IV. Single Object Classification by using Automotive Radar

The research of classification of vulnerable road users(VRUs), e.g. pedestrian[49, 50], by using automotive radar, started from 2011.

V. Multiple Objects Detection and Semantic Segmentation by using Automotive Radar

VI. Multiple Objects Detection by using Automotive Radar and Camera (Early Stage Fusion)

Multi-sensor fusion[66], as the key technology used in autonomous driving system, has several ways of implementation. Early stage fusion for object detection purpose, is one useful option, which could be used to obtain more perception information by extracting features from level data provided by complementary sensors, with high demand in computation.

VII. Beyond Objects Detection I: Target Tracking by using Automotive Radar Only or Camera Only

VIII. Beyond Objects Detection II: Target Tracking by using Automotive Radar and Camera

IX. Beyond Objects Detection III: Fusion of Classification Results from Automotive Radar and Camera

X. Object Detection, Target Tracking and Others as Entire Architecture for Perception in ADAS and AD

XI. Open Challenges and Further Research Direction

XII. Conclusion and Further Work

Appendix A
Proof of the Equation

Appendix one text goes here.

Appendix B

Appendix two text goes here.

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