Key Technologies of Millimeter-Wave Radar in Autonomous Driving Perception Systems

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Abstract. Autonomous driving technology is developing quickly nowadays, and environmental perception capability is a important element to ensure its safe operation. Traditional sensors such as LiDAR and thermal imaging cameras have demerits in terms of adaptability to extreme weather and comprehensiveness of target recognition. Millimeter-wave radar, relying on its advantages of all-weather operation, accurate ranging and speed measurement, and cost-effectiveness, has gradually become a key technology. This paper systematically explores the core technologies of millimeter-wave radar in autonomous driving perception systems, including CFAR dynamic threshold detection, MIMO technology, multi-modal fusion, and 4D imaging technology. It analyzes the merits and difficulties of this technology in multi-target resolution and complex environment adaptation, and discusses cutting-edge technologies such as 4D radar and camera fusion networks, as well as STAR-RIS assisted perception. Finally, it summarizes the current technological progress, looks forward to future development directions, and provides a theoretical reference for the research and industrial use of millimeter-wave radar in the field of autonomous driving.

Keywords: unmanned driving; millimeter-wave; radar.

1. Introduction

1.1. Research Background

In recent years, the technology of autonomous driving has developed rapidly, and different kinds of sensors have been applied to the analysis and detection of the environment by vehicles. However, the shortcomings of different kinds of sensors are uneven, and the development of autonomous driving technology has brought about a rapid increase in the accident rate of autonomous driving. Although LiDAR can generate point cloud data with centimeter-level accuracy, accurately measure distance, shape and position, and has a long detection distance, it is greatly restricted by bad weather. Rain, snow and fog will cause laser scattering, resulting in a decrease in detection distance and accuracy [1]. The thermal imaging camera detects heat-generating targets such as pedestrians and animals through thermal radiation. Although it performs well in complete darkness, haze or glare environment and is immune to visual noise such as headlight glare, shadow and reflection, it is only applicable to complex scenarios such as tunnels and backlighting. Furthermore, it has a strong dependence on temperature. When encountering hot weather in summer, the similar temperature of different objects makes it difficult for the thermal imaging camera to accurately identify them. Moreover, the thermal imaging camera has weak recognition ability for non-heat-generating objects (such as traffic signs and guardrails). If obstacles ahead cannot be detected in time during driving, it will lead to serious accidents, which to some extent has contributed to the increase of the accident rate of unmanned driving [2]. Compared with the above sensor technology, 4D millimeter wave radar has more advantages in strong robustness, high precision and fast response motion.

1.2. Research Content

The current literature review generally has the problem of unsystematic summarization of key technologies such as multi-modal fusion, MIMO enhancement, and 4D imaging of millimeter-wave radar in the autonomous driving perception system and also lacks in-depth discussion on issues such as the absence of datasets, multimodal fusion, and signal interference. At the same time, data from the US NHTSA shows that in 2023, accidents involving Tesla's Autopilot system accounted for 70% of L2-level accidents, including multiple fatal accidents [3]. The data shows that safe autonomous driving under the current technical status has imposed higher demands on its environmental perception capabilities. From the early thermal imaging cameras and lidar to the later 4D millimeter-wave radar, millimeter-wave radar has gradually become a key technology for the development of autonomous driving due to its all-weather working capabilities, precise ranging and speed measurement performance, and cost-effectiveness. It plays an irreplaceable role in complex and chaotic environmental perception [4]. Faced with the standard requirements of L3+ level high-level autonomous driving, the current related technologies still faced issues such as slow multi-target resolution speed, difficulty in resolution, reduced accuracy under complex weather conditions, and misunderstandings regarding the detection of objects at different levels [3]. This article aims to systematically sort out the key technologies of millimeter-wave radar, analyze its advantages and challenges, and propose future development directions, so as to provide theoretical support for related research and industrial implementation.

1.3. Full Text Structure

This paper systematically sorts out the basic principles, key technologies, current research progress and future prospects of millimeter wave radar in the autonomous driving perception system. The first part describes the relevant research background and the research content of this paper. The second part will delve into the basic technology and related principles of millimeter wave radar, including CFAR dynamic threshold detection technology, MIMO multi-input multi-output technology, and the current situation. The third part systematically sorts out the cutting-edge technologies of current autonomous driving millimeter wave radar, including 4D radar and camera multi-level sampling fusion (MSSF) network, reconfigurable intelligent surface (STAR-RIS) assisted perception, TFLN photon radar chip and radar point cloud reconstruction based on deep learning. The fourth part discusses the relevant challenges faced by the current technology, covering data fusion, system integration and energy consumption issues, environmental interference analysis, resolution and accuracy improvement, and the real-time performance of the system. Based on this, it also identifies related challenges and future development potential, providing a systematic reference for theoretical research on the application of millimeter-wave radar in autonomous driving.

2. Technical Principles

2.1. CFAR dynamic threshold

Constant false alarm rate (CFAR) detection technology can help the radar system keep the false alarm rate constant by dynamically adjusting the detection threshold when the noise and clutter environment changes dynamically, so as to reliably distinguish the real target from the noise in the complex environment. Generally, if the received signal strength exceeds the threshold, it is determined as the target. However, when the amplitude of the received signal is lower than the threshold, it is designated as noise. On the other hand, if the threshold is constant, the target cannot be identified, and the false alarm rate increases rapidly [5]. Common CFAR algorithms include cell average CFAR (CA-CFAR), ordered statistics CFAR (OS-CFAR), greatest of CFAR (GO-CFAR), and smallest of CFAR (SO-CFAR). CA-CFAR estimates the clutter power level by averaging the echo intensity of the reference unit, and then determines the detection threshold; OS-CFAR sorts the echo intensity of the reference unit, and selects the statistics of a specific serial number as the clutter power estimation value to determine the threshold, which can better cope with clutter edges and multi-target interference [6]. Whereas SO-CFAR and OS-CFAR algorithms enhance radar performance in multi-target scenarios, their effectiveness, however, diminishes in the presence of clutter edges [5].

2.2. MIMO Technology

MIMO (multiple-input multiple-output) technology enables the same spectrum resources to carry more data transmission channels through spatial multiplexing and diversity technology, thereby achieving higher data transmission rates and connection densities under limited bandwidth conditions [7]. In millimeter-wave radar systems, the adoption of MIMO technology augments radar capabilities by delivering superior resolution and precision in object detection at elevated frequencies. Its technical types include spatial diversity, spatial multiplexing, beamforming, and multi-user MIMO [8]. Spatial diversity transmits the same data thru multiple antennas, and uses the independence of spatial channels to resist fading; spatial multiplexing transmits independent data streams thru multiple antennas at the same time to improve the data rate; beamforming focuses the signal energy on the target direction thru the weighting algorithm to suppress interference; multi-user MIMO serves multiple users at the same time thru pre-coding technology to improve the spectrum efficiency of multi-user scenarios. By combining millimeter wave communication technology, MIMO can effectively play its spatial multiplexing advantages, break through the attenuation problem encountered by millimeter wave signals in high-frequency band transmission, and achieve greater data transmission rate and wider coverage [8]. Moreover, MIMO technology not only enhances the physical layer performance of 5G systems but also provides strong support for the carrying capacity of upper-layer services, laying a solid foundation for high-bandwidth and low-latency application scenarios such as high-definition video transmission, remote medical care, and intelligent transportation [7].

2.3. Multimodal integration

Multi-modal fusion sensing is the fusion of millimeter wave radar with other sensing technologies (such as cameras and lidar). Due to the different ways of recording information, there is often complementarity between different sensors. For example, RGB cameras often have difficulty recording valid information when the lighting conditions are poor, but active sensing sensors, such as LiDAR, radar, and depth cameras, are less affected by external environmental conditions. For lidar and radar, the point clouds they record are too sparse, and the low-resolution data obtained is difficult to use for high-precision detection, while RGB images can provide dense data [9].For example, in the field of autonomous driving, visual sensors can obtain road condition images, lidar can detect the distance of objects in front of the vehicle, and sound sensors can locate the sound according to the whistle sound to make up for the road information in the visual blind area[10]. The integration of the advantages of different sensors has enhanced the overall system efficiency, overcoming the insufficient utilization of data integration and the misjudgment and inaccuracy of the surrounding environment of the traditional single-modal system. Additionally, multi-source information fusion for target recognition and tracking begins with the acquisition of raw data, proceeds through interconnection, association, and state estimation, ultimately culminating in the fusion process. In order to optimize the use of the sensing characteristics of each sensor, leverage the strengths of sensors with different principles, and reduce the possibility of system security problems caused by common cause failures, the method of relying on heterogeneous sensors is generally considered to be the ideal choice for information fusion [11]. The distance, speed and other information provided by the millimeter wave radar complement the visual information of the camera and the high-precision three-dimensional point cloud information of the lidar, which can improve the accuracy and robustness of environmental perception. For example, in severe weather, the detection performance of millimeter wave radar is not affected by weather such as heavy rain, fog, and haze, which can make up for the lack of cameras and lidar in analyzing the surrounding environment in severe weather, while cameras and lidar can provide richer details.The diversity of information enhances the environmental analysis capabilities of millimeter-wave radar, thereby facilitating target classification and identification, while simultaneously increasing system reliability and perceptual robustness

2.4. 4D mmWave

Compared with the traditional 3D millimeter wave radar, the 4D millimeter wave radar adds the measurement of elevation angle, which can obtain the four information of the target's distance, azimuth, elevation angle and speed. 4D millimeter-wave radar is widely adopted due to its compact form factor, high cost-effectiveness, robust velocity measurement, long range, and all-weather operation. It builds upon traditional 3D radar by adding elevation measurement, thereby enabling full 3D spatial awareness [12]. 4D millimeter wave radar can better analyze the environment in three-dimensional dimensions, and the analysis is more three-dimensional, which can accurately distinguish targets at different vertical levels, such as the vehicles on the overpass and the vehicles under the bridge. The upgrade from 3D to 4D includes both hardware and software. In terms of hardware, the elevation resolution is enhanced by expanding the antenna array and using multi-dimensional MIMO technology, combined with increasing the TX-RX logarithm (cascaded chip or single-chip integration) to improve the physical aperture, or using metamaterial technology to increase the effective aperture. In terms of software, the antenna array is expanded through the virtual aperture algorithm, or the data analysis and processing process is optimized to reduce the delay, or the bandwidth pressure is reduced through data compression to achieve bandwidth optimization [12]. Pure 4D mm-wave radar systems deliver reliable and cost-efficient sensing through sophisticated signal processing and feature extraction applied to 4D data structures. In sensor fusion setups, radar data serves a complementary role by mitigating the weaknesses of cameras and LiDAR under adverse conditions like occlusion and noise.

3. Frontier Technology

3.1. The Multi-level Sampling Fusion (MSSF) Network Of 4D Radar and Camera

Four-dimensional millimeter wavelength radar is one of the newer automobile detectors that can detect height precisely and has a greater resolution than traditional 3D radar. However, it is still difficult to achieve autonomous driving standards due to its sparse and noisy point clouds. Another widely used sensor that is capable of capturing rich semantic information is the camera. Liu et al. recently suggested combining 4D radar and a camera to provide a reliable and reasonably priced perception solution for unmanned driving. They designed a fusion block and suggested a semantic-guided head to resolve feature blurring in a plug-and-play fashion.

Remarkably, on the VoD and TJ4DRadSet datasets, MSSF improves 3D average accuracy by 7.0% and 4.0%, correspondingly, when compared against the latest methods. Even on VoD dataset, it outperforms traditional LiDAR-based techniques [13].

3.2. Reconfigurable Intelligent Surface (STAR-RIS) Assisted Perception

A feasible solution for future wireless networks is integrated sensing and communication, referred to as ISAC. For the STAR-RIS-assisted downlink ISAC system, Li et al. suggested a multi-target tracking technique. Specifically, the STAR-RIS is used to simultaneously sense and track the outside dynamic scatterers and provide communication service for the inside UT. This design enhances communication reliability and sensor accuracy by enabling radar systems to adaptively adjust propagation routes. Cooperative vehicle perception, occlusion handling, and real-time tracking can serve as primary areas for future study [14].

3.3. TFLN Photonic Radar Chip

Photonic radar can efficiently overcome the constraints of electronic radar due to its high frequency, broad bandwidth, and superior reconfigurability [15].

Utilizing thin-film lithium niobate (TFLN) technology at the four- inches wafer level, Zhu et al. demonstrated an integrated photonic radar in 2025 that operates in the millimeter-wave V band (40-50 GHz) and has centimeter-level resolution. This included a frequency doubling module for creating millimeter-wave radar waveforms and a chirping module for receiving echo signals. The filter-free architecture and the large bandwidth of all photonic components in the chip allow for arbitrary configuration of the produced radar waveform's center frequency and bandwidth across a very broad range. With the wide bandwidth and high carrier frequency, it can achieve a velocity measurement resolution of 0.067 m/s, a dual-dimensional resolution of 1.50 cm × 1.06 cm for inverse synthetic aperture radar (ISAR) image formation, and a distance resolution of 1.50 cm for multi-target ranging [16].

3.4. Radar Point Cloud Reconstruction Based On Deep Learning

Filtering methods such as CFAR are required to produce useable point clouds since the original data from 4D mm-wave radars consists of spectral signals that are highly obscured by noise. These old handcrafted approaches, however, can differ greatly in shape and span substantial resolution cells, which minimizes point cloud resolution and results in a considerable loss of information.

In order to tackle this problem, Brodeski et al. [17] pioneered the framework of the detector method and applied the image segmentation network based on convolutional neural network (CNN) to distance-Doppler (RD) maps to achieve the detection and location of multiple targets, solving the problem of scarcity of RD map datasets. Furthermore, it has been demonstrated that DRD network trials outperform standard approaches in terms of resilience and detection accuracy. It offers hope for the use of complex radar data. Additionally, a framework of the detector method was initiated. By applying a convolutional neural network (CNN)-based image segmentation network to distance-Doppler (RD) maps, the issue of the paucity of RD map datasets was resolved and many targets were successfully detected and located. Moreover, the experiments of DRD networks have demonstrated superior detection accuracy and robustness compared to traditional approaches. It has great potential in applications of complex radar data.

4. Discussions

This section addresses the current issues with millimeter wavelength radar sensing regarding autonomous driving, such as multimodal fusion, signal interference, hardware limitations, and data scarcity. This essay aims to provide a comprehensive and forward-looking perspective on the development and potential of millimeter-wave radar sensing.

4.1. Multimodal Fusion And Latency Bottlenecks

Significant prospects for integrating millimeter-wave radar with other sensor types have been found by researchers as their work continues. For example, combining optical sensors and millimeter-wave radar can improve accurate perception in a range of weather circumstances. To maximize its use in automotive applications, it is therefore vital to look into the seamless integration of millimeter-wave radar with other sensors such as lidar, cameras, and ultrasonic sensors. However, millimeter wave frequencies are prone to air absorption and have a limited capacity to penetrate materials, particularly in unfavorable weather circumstances like fog, rain, or snow, which are frequently encountered in automobile scenarios.

which are frequently encountered in automobile scenarios. The performance of sensors can be greatly impacted by these surroundings' high reflectivity or high absorption, which can cause signal attenuation and multipath interference issues. Furthermore, the design of the classification algorithm is complicated by the growing complexity of information interaction among diverse sensor data sources, which jeopardizes the effectiveness of cars' real-time control decision-making [18].

The computing time prior to decision-level fusion can be decreased in the future by combining signal-level preprocessing with low-latency early fusion techniques. As an alternative, pre-fused FFT and clustering can be utilized in conjunction with edge-optimized neural networks (such as SqueezeRadarNet) to provide quick feature extraction [19].

4.2. Signal Interference

Effective interference mitigation techniques are becoming more and more crucial for preserving the integrity of radar signals as millimeter-wave radar technology is being widely used in more and more sectors. Radar signal mutual interference, for example, can result in false targets and a reduction in detecting effectiveness in self-driving automobiles [20].

The robustness and universality of millimeter-wave perception can be improved by strengthening radar signals' anti-interference capabilities. The interference signal can be more effectively filtered in the transform domain since the target signal and the interference signal have distinct properties in various transform domains. The most sophisticated anti-interference system adopts the transformation-based approach [21]. The wavelet transforms and the Short-time Fourier Transform (STFT) are the most generally utilized ones.

4.3. Hardware Limitations

According to the physical law that angular resolution is directly proportional to the wavelength and inversely proportional to the array aperture, millimeter-wave radars generally have an angular resolution of 1-3° because of the relatively short wavelength that corresponds to the operating frequency band of millimeter-wave radar (1-10 mm) and the physical size of the antenna array being restricted by the installation space of the equipment (such as the bumper in the vehicle scene). This makes it difficult to expand the detection range significantly. Therefore, it is challenging to tell apart nearby targets up close. The quality of the image is directly impacted by this limitation [22].

As multiple-input multiple-output (MIMO) antenna technology has advanced, elevation resolution has significantly increased, leading to the emergence of 4D millimeter-wave radar [17]. The capacity to measure elevation is the most important feature of 4D millimeter-wave radars as compared to conventional 3D radars. By using Doppler information within particular azimuth and elevation ranges and translating the Doppler velocity resolution to the azimuth resolution, the angular resolution can be enhanced in the future [23].

4.4. Scarcity Of Datasets

The accuracy and resilience of autonomous systems have been greatly improved by the combination of sensor fusion and deep learning technologies. Nevertheless, there are negative aspects when constructing machine learning models on big, labeled datasets, especially when real-time processing is required. For instance, cross-testing across multiple datasets is hampered by the fact that the extant datasets comprise a variety of 4D millimeter-wave radar types with varying properties, such as maximum detection range and angular resolution [17].

According to the development trend for the future, sensor technology will evolve at a rapid pace, algorithms will keep coming up with new ideas, and application areas will keep growing. Cause they are essential for training and evaluating the upcoming generation of convergent systems, large-scale, diversified, and realistic datasets are becoming more and more necessary. An inventive way to deal with the lack of millimeter-wave data is to investigate cross-modal dataset transformation, which can efficiently train models when there is a dearth of actual radar data [24].

5. Conclusion

The primary technologies of millimeter-wave radar in the unmanned driving perception system are the main focus of this study. Firstly, it describes the shortcomings of various sensors in the autonomous driving environment and emphasizes the advantages of millimeter - wave radar in all - weather adaptability, cost - effectiveness, and other aspects. Then, it elaborates on the principles of core technologies such as CFAR dynamic threshold, MIMO, multi - modal fusion, and 4D imaging in detail, demonstrating their role in improving perception accuracy and environmental adaptability.

While demonstrating the research objectives of millimeter-wave radar technology, this study also presents cutting-edge technologies including the TFLN photonic radar chip, STAR-RIS aided perception, and the multi-stage sampling fusion network of 4D radar and camera. In addition, in-depth discussions were conducted on the current challenges faced, such as the fusion of heterogeneous sensor data, the lack of data sets, environmental interference, and hardware limitations. This comprehensive review is suitable for both newcomers to the field to read and can serve as a reference for experienced researchers, helping them attain a profound understanding of the current technical level and grasp the future development direction.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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