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Research on the Application of Radar Sensor Technology in the Field of Intelligent Vehicles

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Abstract. As a crystallization of industry, automobiles have been responsible for carrying people from point A to point B since their invention. With the continuous advancement of science and technology, automobiles have transcended the category of traditional transportation means and are evolving toward intelligentization. In the process of transforming traditional cars into intelligent vehicles, intelligent equipment is crucial. Radar sensors are an important part of them. However, there are still deficiencies in the optimization of the detection range and accuracy of radar sensors, as well as their anti-interference ability to the environment. By sorting out the literature, this paper introduces the working principle and the applications of three different types of radars (lidar, ultrasonic radar, and millimeter-wave radar).

Keywords: traditional automobiles, intellectualization, intelligent vehicles, radar sensors, research progress of applications

1. Introduction

A radar sensor is an electronic device that detects and identifies information such as the existence, position (distance, angle), and motion state (velocity, acceleration) of target objects by emitting electromagnetic waves (usually radio waves or microwaves) and receiving their reflected echoes. From a technical definition, its core logic is based on the propagation characteristics of electromagnetic waves: the transmitting module inside the sensor generates electromagnetic waves of a specific frequency and radiates them into space. When the electromagnetic waves encounter an obstacle (target object), part of the energy is reflected to form an echo. After the receiving module captures the echo signal, it analyzes and processes the parameters of the transmitted signal and the echo signal (such as frequency, phase, time difference, etc.), and finally extracts the key information of the target.

In recent years, significant progress has been made in research on radar sensors, focusing on improving accuracy and enhancing the level of chip integration. Among these, chip integration is a crucial issue faced by sensors. In the application of intelligent vehicles, considering the performance of the vehicles themselves, developers must balance factors such as the detection distance, detection accuracy of the sensors, as well as their own weight and size. Eventually, radar sensors can only adopt a multi-chip architecture, where each chip is responsible for controlling the execution of action commands of different modules. The scattered distribution of chips increases the volume and

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mass of the modules, which is not conducive to the lightweight design of automobiles. Bosch's SoC radar, launched on July 29, 2025, breaks the traditional architectural layout. It integrates the millimeter-wave radar front-end, four transmit channels, four IQ receive channels, linear frequency-modulated pulse generation logic, a multi-core microcontroller subsystem, and a digital signal processor supporting AI-accelerated inference into a single-package SoC, achieving a leapfrog development from decentralization to integration [1]. Compared with traditional designs, the radar module based on the new SoC has a volume reduction of up to 30%. In modern automotive architectures, this 30% volume reduction is of great significance. It directly translates into greater layout flexibility, enabling the radar module to be more conveniently installed in various parts of the vehicle, thereby achieving a wider coverage range. At the same time, the smaller size is also beneficial for thermal management, allowing the radar system to maintain stable performance during long-term operation, and creating conditions for choosing a more aerodynamic housing, which helps to improve the overall performance of the vehicle. In terms of performance, the new SoC also performs impressively. It supports a series of ADAS functions under the SAE L2+ standard, such as automatic emergency braking, adaptive cruise control, blind spot object detection, and lane change assistance, providing solid technical support for the automatic driving of vehicles.

This paper will summarize the working principles and characteristics of three main types of radar sensors, and outline their practical applications as well as specific research achievements. By integrating relevant literature, this paper analyzes the current application status of radar sensors, and explores the optimization of the detection range, detection accuracy, and environmental anti-interference ability of radar sensors for intelligent vehicles.

2. Classification and working principles of radar sensors

2.1. LiDAR

It is a sensor based on laser ranging technology. Its main working principle is based on time-of-flight (ToF), which calculates the distance to an object by measuring the time from laser emission to its return, enabling distance measurement and environmental perception. There are many types of it: classified by measurement dimension, they include single-line LiDAR and multi-line LiDAR; classified by measurement principle, they include triangulation ranging LiDAR and ToF LiDAR; classified by working mode, they include mechanically rotating LiDAR and solid-state LiDAR.

When a LiDAR is operating, its infrared laser transmitter emits infrared laser. After the infrared laser hits an object and bounces back, it is received by the receiver on the LiDAR. At this point, the LiDAR obtains the time taken for the infrared laser to travel from emission to reception. Combined with the speed of light, it can calculate the distance the laser has traveled. Finally, dividing this distance by two gives the distance between the LiDAR and the obstacle (at this point, the LiDAR only identifies the positional relationship between a single point on the obstacle and itself). Then, the LiDAR rotates and repeats the above steps to obtain information about the positional relationships between all obstacles and itself. Eventually, the data processing unit converts the raw data into 3D point cloud data using processing algorithms.

In actual environments, environmental factors can introduce various types of errors, which affect the measurement results of LiDAR. Taking LiDAR mounted on vehicles as an example, errors can be divided into two categories: systematic errors and random errors.

For example, time delay error is a type of systematic error. During the emission and reception of laser pulses, the response time of the device and signal transmission time may lead to time delay errors [2]. Such time delay includes not only the time required for the laser pulse to propagate in the

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air but also involves multiple factors, such as the speed of signal processing by the electronic system, internal calculation delay, and the time for signals to transmit in the circuit. The delay in each link may affect the final measurement result, causing a systematic deviation in the measured distance. After a laser pulse is emitted from the transmitter, it takes a certain amount of time to reach the target and reflect back. In this process, the propagation velocity of pulses in the air is a known parameter; however, due to the internal response time of the device and signal processing latency, the actual measured time may deviate from the theoretical value (either being longer or shorter). This error directly affects the accuracy of distance measurement, and its impact is more significant especially in application scenarios with high precision requirements.

(2) Random errors refer to errors caused by accidental environmental factors, which occur randomly and do not appear consistently. Such errors cannot be completely eliminated through calibration, but their impact can be reduced through statistical analysis (such as taking the average of multiple measurements) or optimized algorithms.

For example, atmospheric refraction error is a type of random error. Lasers are affected by refraction when passing through the atmosphere, and this refraction phenomenon becomes more pronounced especially under conditions of high humidity or haze [2]. In high-humidity environments, water molecules have an enhanced ability to refract lasers, which may cause a slight deviation in the laser path and thus lead to measurement errors. Therefore, atmospheric refraction error is particularly significant under specific climatic conditions, posing a challenge to the measurement accuracy of LiDAR.

2.2. Ultrasonic radar

The working principle of an ultrasonic radar is to emit ultrasonic waves through an ultrasonic transmitting device, and calculate the distance based on the time difference between the transmission and the reception of the ultrasonic waves by the receiver. The commonly used operating frequencies of the probes are 40kHz, 48kHz, and 58kHz. Generally speaking, the higher the frequency, the higher the sensitivity, but the smaller the detection angles in the horizontal and vertical directions. Ultrasonic radars are waterproof and dustproof, and even a small amount of sediment blocking does not affect their performance. With a detection range of 0.1 to 3 meters and high precision, they are very suitable for application in parking assist systems [3].

The reason why ultrasonic waves have not been replaced so far lies in the following advantages:

(1) Low cost. Compared with LiDAR (Light Detection and Ranging) and millimeter-wave radar —both of which typically exhibit four-figure price points—ultrasonic radar, with its two-figure price point, remains irreplaceable in current application scenarios.

(2) Small size. Ultrasonic radars can be hidden in the front and rear bumpers of cars, making them easy to arrange. However, due to their large size, LiDARs can generally only be mounted on the roof, which affects the overall aesthetics.

(3) It can make up for the blind spots of LiDAR. Given that LiDAR systems are typically mounted on vehicle rooftops, the regions beneath or adjacent to the vehicle hood constitute detection blind zones—posing a significant hazard to driving safety. The ultrasonic radars installed on the front and rear bumpers as well as the sides of the car can cover these blind spots.

2.3. Millimeter-wave radar

Millimeter-wave radar operates in the millimeter-wave frequency band, where millimeter waves generally refer to electromagnetic waves in the 30–300 GHz frequency range (with wavelengths of

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1–10 mm). As a vehicle-mounted sensor, millimeter-wave radar has a 30-year history. In the early days, it used compound semiconductors, requiring 7–8 radio frequency (RF) chips to form the transceiver front-end, resulting in a complex structure and high cost. Around 2000, discrete components of the RF front-end were gradually integrated into MMICs (Monolithic Microwave Integrated Circuits) and shifted to gallium arsenide (GaAs) and silicon-germanium (SiGe) processes, reducing the number of chips to 3–4 and lowering the cost. After the introduction of the CMOS solution in 2017, the cost of the RF part (MMIC) decreased significantly, and the processor (MCU/MPU) became the main cost item. Today, CMOS single-chip solutions are gradually emerging. Compared with 20 or 30 years ago, the material cost has dropped by more than 80%, thanks to innovations in semiconductor technology [4].

A millimeter-wave radar generates electromagnetic waves with a specific modulation frequency through a transmitter, which are then sent out via an antenna. When these electromagnetic waves encounter a target object, part of them is reflected back and captured by the receiving antenna. The received reflected electromagnetic waves are mixed with the transmitted ones in a mixer to generate an intermediate frequency signal. The distance between the target and the radar can be calculated by measuring the frequency of the intermediate frequency signal; the relative speed of the target object with respect to the radar can be derived based on the Doppler frequency shift; and the azimuth angle of the target object can be computed using the phase difference between the radar waves reflected by the same target and received by the antenna array.

Millimeter-wave radar operates in the frequency band of 30–300 GHz. It features strong penetration, enabling all-weather and all-meteorological adaptability. Additionally, it boasts advantages such as controllable cost, small size, high response speed, and high precision, and is capable of identifying multiple static and dynamic targets [5].

Specifically, millimeter-wave radar has strong penetration through obstacles such as fog and snow, and is less affected by environmental and weather conditions than cameras or LiDAR. Thanks to the stable propagation characteristics of electromagnetic waves in the millimeter-wave band, millimeter-wave radar is not easily interfered by external electromagnetic signals (such as civil radio and mobile phone signals), and thus maintains high detection accuracy and consistency.

3. Applications of radar sensors

3.1. LiDAR

As one of the key sensors in intelligent driving systems, LiDAR's applications in environmental perception are constantly innovating [6]. On May 30, 2025, the HarmonyOS Intelligent Travel flagship vehicle Zunjie S800, jointly launched by Huawei and JAC Motors, was officially released. The intelligent driving perception sensors of this vehicle have become a major highlight, including 3 high-precision solid-state LiDARs (one at the rear and one on each of the left and right sides). These solid-state LiDARs enhance the vehicle's capabilities in three key aspects of environmental perception. Firstly, in terms of negative-direction perception, the rear LiDAR can identify obstacles behind the vehicle (including steps and potholes, etc.) when the vehicle is reversing, promptly assess the collision risk, and bring the vehicle to a stop if necessary. Secondly, in terms of overhead perception, the LiDAR can detect obstacles suspended above the vehicle (such as pipelines). When a vehicle approaches, the system will also conduct a collision risk assessment and maintain a state of readiness to initiate vehicle braking at any time. Thirdly, advancements in the perception of irregular objects address the prior limitation of LiDAR regarding the accuracy of identifying irregularly shaped objects.

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With the improvement of automotive intelligence, especially in L3 and higher-level intelligent driving systems, LiDAR has become a key technology due to its ability to achieve long-distance, high-precision, and real-time 3D environmental modeling. Its characteristic of not being restricted by lighting conditions enables intelligent driving vehicles to accurately identify road conditions, obstacles, and other important traffic signs in various environments [7].

3.2. Ultrasonic radar

Ultrasonic radar is highly popular in the commercial vehicle sector due to its advantages such as small size, low cost, and high precision in short-distance detection. Nowadays, ultrasonic radar is gradually penetrating into other fields of commercial vehicles, such as the anti-pinch system for passenger doors of buses.

Nowadays, buses are becoming increasingly intelligent, with a growing number of electrified devices on board. For instance, passenger doors have evolved from traditional mechanical doors to intelligent electric ones. However, since drivers may make inappropriate judgments about the safety situation near the doors when operating them, and the new electric doors close with greater force, there is a higher possibility of passengers being injured. Therefore, some passenger door anti-pinch systems are now mass-produced and installed on buses.

Taking a specific system as an example, this system includes ultrasonic radars, a controller, a DC-DC power module, an instrument panel, as well as the vehicle's doors and disabled person pedals. There are 2 ultrasonic radars, which are used to detect the passenger door area and the disabled person pedal area respectively. The collected status is converted into electrical signals, which are transmitted to the vehicle controller via data lines. Then, based on the received detection signals, the vehicle controller can issue instructions to the instrument panel to control the status of the doors and disabled person pedals accordingly, and simultaneously display the current working status of the doors and disabled person pedals on the instrument panel [8].

3.3. Millimeter-wave radar

4D millimeter-wave radar is an upgraded version of traditional millimeter-wave radar (3D millimeter-wave radar) and represents a significant leap forward for millimeter-wave radar. The "4D" specifically refers to speed, distance, horizontal angle, and vertical height. 4D millimeter-wave radar adds the detection of vertical height to the capabilities of traditional millimeter-wave radar. Compared with traditional millimeter-wave radar and even other conventional radar products, 4D millimeter-wave radar can break through limitations in aspects such as static target recognition, lateral movement detection, height identification, distinguishing adjacent objects, and detecting hidden vehicles [9].

Compared with traditional millimeter-wave radar, 4D millimeter-wave radar has the advantage of outputting denser point cloud data. Therefore, 4D millimeter-wave radar has a higher recognition degree, can identify target contours more clearly, and can also recognize smaller objects, partially occluded objects, static objects, and laterally moving obstacles [10].

4. Conclusion

This paper introduces the research on the application of radar sensor technology in the field of intelligent vehicles by combining literature. In terms of development history, as early as the 19th century, scientists had already proven the existence of electromagnetic fields, laying the foundation

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for the invention of radar. The world's first radar was born in the 1930s. Nearly a century later, radar sensors have now entered an era of intelligentization and networking. They are gradually integrating with intelligent systems and exerting a pivotal role in the intelligent transformation of human life. However, in practical application scenarios, radar sensors are significantly impacted by environmental factors—this leads to substantial discrepancies between the acquired environmental information and real-world conditions, thereby compromising their detection accuracy. Currently, exploring solutions to optimize the detection accuracy of radar sensors has emerged as a critical research direction in the field of radar sensor technology.

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