Radar Sensors in Automatic Driving Cars

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***Abstract*—The principles and performance of ultrasonic radar sensors, millimeter wave radar sensors and lidar sensors were analyzed and compared in this paper. Horizontal comparison between various types of radar sensors and smart cars in the market was performed, and the importance of multi-sensor fusion systems was interpreted. The development trend of these types of sensors and the prospect of self-driving vehicles are described.**

Keywords-automatic driving; ultrasonic radar sensors; millimeter wave radar sensors; lidar sensors; sensor fusion

I. INTRODUCTION

A. Automatic Driving

The Ministry of Industry and Information Technology of China announced the approval of the national standards for "Classification of Driving Automation", which defined the standards for classification of driving automation systems in China and is expected to be implemented in 2021. This document not only provides a new standard for R&D of automatic driving technologies in China, but marks a new era that China has entered in the field of automatic driving.

Since the 1970s, the autonomous driving technology has been explored by major industrial economies around the world. Its rapid development depicts a promising picture of the future transport sector. However, most automatic driving cars in the market, be it the cars developed by Tesla, Google and other self-driving technology giants or those by Huawei, which seeks cooperation in this field, fail to meet the requirements of "capable of self-driving" or higher standards. This indicates the large room for development of this technology.

B. Radar Sensor

Radar sensors are an indispensable part of automatic driving systems, allowing the car to detect the surrounding environment. The rapid development of sensor technology has made the highly-automated or even fully-automated driving of cars possible in the future. For researchers and manufacturers, radar sensors are undoubtedly one of the core issues in self-driving technology, given that only with a strong sensing capacity can the car provide safe experience for the consumers and take up a share in the market of smart cars.

There are various types of radar sensors, and the most popular type currently is the traditional ultrasonic radar. For example, a Tesla car is equipped with 12 ultrasonic radars [1]. With the development of technology, early ultrasonic radar modules no longer meet the drivers' needs. As a result, the more advanced millimeter wave radar and Lidar have entered the market. On the other hand, TI, NXP and other companies began to develop integrated radar chipsets to save the valuable internal space of cars.

II. WORKING PRINCIPLE

A. Ultrasonic Ranging

Ultrasonic sensors emit mechanical waves with a frequency higher than the audible sound wave range of human ears through the transmitter. After reflection, the waves are received by the receiver. The distance between the car and the object is obtained by calculating the time difference between receiving and sending. Most commonly used frequencies are 40*kHz*, 48*kHz* and 58*kHz*. In general, a higher frequency leads to higher accuracy of the sensor. The sensor features a small diffraction and good directivity, which allows the ultrasonic sensor to propagate the signals in the form of rays. It is mostly used in low-speed driving scenarios such as automatic parking systems and reversing radars. The measuring principle is:

$$L = \frac{c \cdot \Delta t}{2} \tag{1}$$

where c is the propagation speed of sound waves in the air and can be 340*m/s* when the requirement for accuracy is not high; Δt is the time difference between the transmission and reception of the ultrasonic waves. In general, the car is driving slowly, so the impact of the Doppler Effect is negligible.

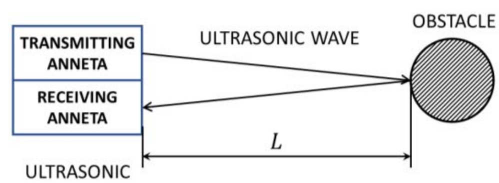

Figure 1. Principle of Ultrasonic Radar

B. Millimeter Wave Radar Sensor

The working frequency of the millimeter wave radar sensor is 30~300*GHz*, that is, the emitted electromagnetic wave is in a millimeter scale. Due to the long wavelength of the millimeter waves, which is between that of far infrared waves and that of the microwaves, it has the characteristics of both waves. The wave is not susceptible to impact from the outside world, so it can adapt to various climate environments; the beam is narrow, the angle resolution is strong, the Doppler Effect is obvious, and the resolution is generally on the decimeter level. The millimeter wave radar can be divided into the pulse mode and frequency modulation continuous wave mode by the

978-1-7281-9928-3/20/$31.00 ©2020 IEEE
DOI 10.1109/ICECTT50890.2020.00061

measurement methods. The pulse method is to use a pulse signal to change the voltage-controlled oscillator in the radar transmitter from low frequency to high frequency instantaneously, and to isolate the reflected wave from the transmitted signal in the receiver. The structure is more complicated than other radar systems and the cost is very high, so FM continuous wave mode ranging is the most widely used method.

When the transmitted FM continuous wave is received after being reflected by the object, there will be a time interval. If a car is driving at high speed, due to the Doppler effect, the echo frequency will change, and then the two frequencies are processed by the mixer, and then the current vehicle speed can be obtained [2]. If c is the speed of light, L is the distance from the object, Δt is the time delay, T is the signal FM period, f' is the frequency difference, Δf is the FM bandwidth, v is the current vehicle speed, and f_d is the Doppler frequency shift, F_0 represents the center frequency of the transmitted signal of the FM wave, then the following equations can be obtained:

$$L = \frac{c \cdot \Delta t}{2}$$

$$\Delta t = \frac{T \cdot f\prime}{2\Delta f}$$

$$v = \frac{c \cdot f_d}{2 f_0} \qquad (2)$$

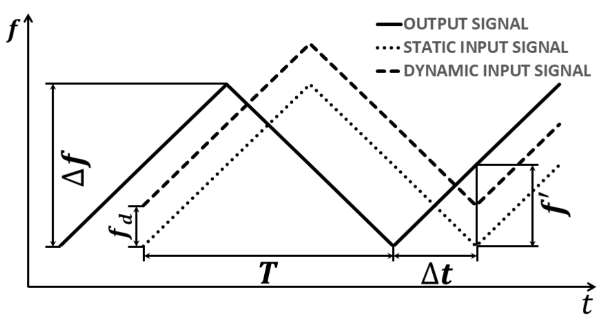

Figure 2. FM Continuous Wave Measurement Principle

When the car is stationary, the echo frequency does not change, thus $f_d = 0$, $v = 0$. When the car starts to move, at the same distance, the distance between the car and the object can be calculated through the same method, and the echo frequency is different. The relative speed can be obtained by calculating the difference f_d.

C. Lidar

Lidar is used to detect the position of the target by emitting a laser beam. The laser light is electromagnetic waves, which are quite different from mechanical waves. Lidar has two modes: two-dimensional scanning and three-dimensional scanning. The measurement principle is to calculate the distance by detecting the time from the laser emission to the reflection by the object. Among them, the part responsible for laser emission has a rotatable mirror. When the mirror poses a certain range of pitch angle after rotation, the effect of three-dimensional scanning is achieved (Fig. 3). Lidar can be divided into three forms depending on the presence or absence of this mechanical rotating part: mechanical lidar (with macroscopic rotation), hybrid solid-state lidar (with both "moving part" and "solid part"), all-solid-state laser Radar (without macroscopic mechanical rotation). The reliability and integration of radar increase with the decrease of the number of radar mechanical structures. Therefore, the mature three-dimensional laser sensor technology should move closer to the all-solid state [3].

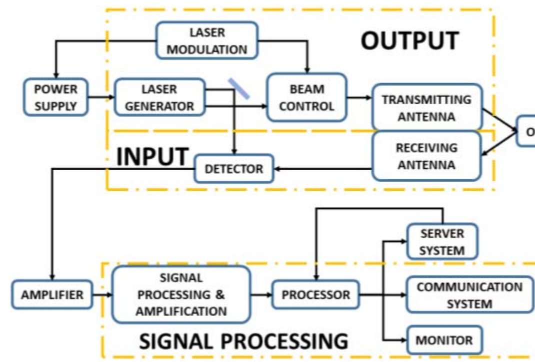

Figure 3. Instructure of Lidar

A two-dimensional Lidar can only scan one plane, its structure is relatively simple, the calculation load and technical difficulty is less than those of the three-dimensional Lidar. However, once the potholes and uneven road surface occur, the data measured by the system will be unreliable. The three-dimensional Lidar can scan the contour edges of the object, and the obtained contour data constitute all the terrain within the detection range of the point cloud reconstruction, and outputs high-resolution data on the geometry, distance, and speed with an accuracy of up to the centimeter level. The resolution achieved by Lidar is higher than that obtained by a millimeter wave radar. However, due to the complicated structures and large load of calculation, Lidar entails high computing power of the computer system [2]. In addition, the Lidar is extremely susceptible to impact of tough weather conditions, and its performance will be greatly reduced when it encounters rain and snow [7].

III. The Status of Vehicle-mounted Radar & Multi-sensor Fusion

A. Market Analysis

Table I lists the basic performance parameters of three types of radar sensors [10]. When there are higher requirements for specific situations, the type and parameters of the radar should be selected.

Statistics released by Yole show that the current market size of Lidar is about 110 million US dollars and that for the millimeter-wave radar is about 10 million US dollars. In 2032, their market size is predicted to reach 7.2 billion and 1.5 billion US dollars, respectively; but the market size of ultrasonic radar may only be 800 million US dollars.

TABLE I. COMPARISON OF PERFORMANCE OF THREE TYPES OF RADAR

	Ultrasonic radar	*Millimeter radar*	*Lidar*
Cost	+	++	+++
Computing capacity requirement	+	++	+++
Resolution	+	++	+++
Visual range	+++	++	+
Adaption of tough conditions	++	+++	/
Capacity of speed distinguishing	++	+++	+

1) Ultrasonic radar

Ultrasonic radar was first used in parking assistance systems to remind the driver of the distance between the car and obstacles in the rear. Now it is gradually used in automatic parking systems and road speed limit recognition tasks. After decades of development, the technical challenges of current ultrasonic sensors have been greatly reduced. Car manufacturers such as Bosch and Valeo have many years' experience of mass production. Improvement over generations has proved that the current ultrasonic radar technology is relatively mature.

2) Millimeter-wave radar

TABLE II. COMPARISON OF SOME MODELS OF MILLIMETER-WAVE RADAR

Model	*Visual range*			*Resolution* （m）	*Angle resolution*	*Price* ($)
	Type	*Distance*	*Angle*			
Continental ARS308	Long	200m	±5°	2	1°	2-4 K
	Medium	60m	±17°	0.4	0.1°	
Delphi ESR	Long	175m	±10°	0.5	0.5°	4-7 K
	Medium	60m	±45°	0.25	0.1°	

The currently used millimeter-wave radars are mainly short-range (24*GHz*), medium-range (76-77*GHz*), and long-range (77*GHz*) radars. Most of its markets are occupied by companies such as Bosch, Delphi, Trina Motor Group, Continental, Valeo, etc. The model parameters of some millimeter wave radars are shown in Table II.

3) Lidar

In the current market, Velodyne leads the world in terms of R&D of the Lidar technology. With HDL series 64-line, 32-line, and 16-line Lidar models, it has entered into partnership with 25 manufacturers including Baidu, Ford, Volvo, Google in autonomous driving projects. In addition, the German Continental Group, Infineon, the United States Tetravue, Sick, the Canadian Leddartech and other companies are taking a leading role in the world in terms of Lidar technology. Table III presents the performance parameters of several types of Lidar.

B. Problems and Challenges

So far, the radar sensor technology has already neared perfection and has been widely used as an independent part in various low-level driving assistance systems. For example, in adaptive cruise control (ACC) systems, the millimeter-wave radar can track and monitor obstacles in multiple lanes; Lidar can scan blind areas near the car and provide assistance in situations such as automatic parking and complex roads.

However, due to the differences in the principle and structure among radar sensors, radar can only play a significant role in specific scenarios. The main problems are as follows:

- Under strong interference, such as by strong light, noise, electromagnetic wave interference, bad weather in rain and snow, and complex roads and buildings, the accuracy and stability of radar need to be improved.
- When a car is driving at high speed or a nearby car is approaching [6], it is difficult to obtain the motion parameters (relative speed, relative acceleration, relative motion trajectory, etc.) of the targets nearby, and the safety during driving cannot be ensured.
- More advanced sensors are needed to respond to various emergencies and effectively determine the threat levels of road obstacles.
- In order to ensure the safety of the radar sensor perception system, the supporting software system needs to be improved [5] so that the data obtained by the radar can be processed efficiently and generate more rapid and reliable software.

C. Multi-sensor Fusion Technology

Because radar sensor systems need to overcome the impact of environmental changes, and a single type of sensor cannot meet this demand, a variety of sensors are required to cooperate to meet the reliability and stability of some complex

TABLE III. COMPARISON OF SOME MODELS OF LIDAR

Model	*Line*(s)	*Visual range*			*Distance resolution*	*Angle resolution*		*Price*($)
		distance	*Horizontal*	*Vertical*		*Horizontal*	*Vertical*	
HDL Velodyne	64	120m	360°	26.8°	<2cm	0.09°	0.4°	7 K
	32	70m	360°	40°	<2cm	0.16°	1.33°	3 K
LMS511	1	26-80m	190°	/	1m	0.25°	/	0.3 K

environments. Facts have proved that the multi-sensor fusion technology is a necessary way to achieve a higher level of autonomous driving. The current high-end smart cars are also equipped with a variety of visual sensors to help the system detect the surrounding environment. The methods for the multi-sensor fusion technology today include Kalman filter method, Bayesian criterion method, artificial neural network method, fuzzy set theory method, etc.

For example, using the aggregate view object detection (AVOD) network to realize fusion of images scanned by the Lidar and high-definition camera, more accurate information of the target can be obtained. The software can also be optimized through algorithms to enhance the reliability of the contact between sensors and the capacity to quickly recover after interference, thus avoiding serious errors caused by the system's failure to detect the wrong data detected by the sensor [11].

In addition to the camera, GPS, IMU, and GNSS can be used together to identify the motions and surrounding environment of the car for more accurate results.

IV. Prospects

The multi-sensor fusion technology has been more and more widely used, and it has overcome the difficulties of many single sensors, but the single-type radar sensor technology has not yet reached a maturity and has much room for further development, be it the ultrasonic sensor that is cost-efficient, technically unchallenging and widely adopted, or the millimeter wave radar and laser radar that are technically challenging but still have wide adoption. In [4], the millimeter wave radar that could only scan a two-dimensional plane was improved so that the transceiver could scan the environment with multiple input and multiple output (MIMO), and an imaging effect similar to that of three-dimensional Lidar was obtained. Also, the accuracy, stability, integration, and computing power of radar sensor systems need to be improved in order to generate smart cars that can achieve fully autonomous driving in the future.

In the future, the car will no longer be a mere means of transportation, but will become a part of the IoT of computers, smart phones, and smart furniture, etc., serving as a smart terminal that facilitates people’s life.

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