Development of Automotive Millimeter Wave Radars

Masaru Ogawa,
Toyota Central R&D Labs.,

Kazuma Natsume
DENSO Corporation

1. Introduction

In recent years, many safety systems have been implemented in vehicles, such as adaptive cruise control, autonomous emergency braking, and blind spot monitoring. In the future, safety systems are expected to be able to perform the advanced functions necessary for autonomous mobility. To achieve these functions, various sensors are used to accurately perceive the environment around the vehicle. Several types of perception sensors are installed on vehicles, such as radars, cameras, lidars, and sonars. Compared with the other sensors, millimeter wave radars have the following advantages:

- a detection distance of 150 m or more can be easily achieved;
- the relative velocity of the target can be directly detected;
- they are not affected by sunlight;
- their permeability to rain and fog is high.

Owing to these features, millimeter wave radars are now installed on many cars, as they can accurately detect the location and movement of vehicles at a distance. Compared with those for aircraft and ships, automotive radars are required to detect relatively short distances with high accuracy. In addition, many innovations have been introduced to reduce the size and cost of these radars. In this work, the technical development of automotive millimeter wave radars is described, including the technical challenges required for such developments, the difficulties encountered from prototype design to product commercialization, and the future evolution of the technology.

2. Technology of Automotive Radars

2.1 Distance and Relative Velocity Detection

Many methods exist for distance and relative velocity detection; among these, the pulse method and frequency-modulated continuous wave (FMCW) method are widely used. The pulse method transmits pulsed radio waves and measures the time it takes for the reflected waves to return from an object. The FMCW method transmits a radio wave whose frequency varies with time and makes a beat signal by mixing of the transmitted and reflected wave signals (Fig. 1). For example, when the distance from the object is 5 m, the round-trip time of the radio wave is approximately 33 ns. In the pulse method, a fast counter is needed to directly measure this short time. The FMCW method detects the frequency of the beat signal generated using the frequency difference between the transmitted and received signals. Thus, this method is relatively easy to implement.

In the FMCW method, two types of linear frequency modulation signals, namely, a signal with increasing frequency and a signal with decreasing frequency are alternately transmitted. Here, these signals are called rising slope and falling slope, respectively. From the transmitted wave and reflected wave from the object, beat signals of frequencies f_{up} and f_{dn} are obtained at each slope (Fig. 2). The frequencies f_{up} and f_{dn} are the sum or difference between the frequency difference f_r caused by the propagation delay and the frequency shift f_d caused by the Doppler effect (Doppler frequency). Thus, they are expressed as:

$$f_{up} = f_r - f_d, \tag{1}$$

$$f_{dn} = f_r + f_d. \tag{2}$$

Here, f_r and f_d can be calculated from the following two equations:

$$f_r = (f_{dn} + f_{up})/2, \tag{3}$$

$$f_d = (f_{dn} - f_{up})/2. \tag{4}$$

Since f_r is proportional to the distance from the object and f_d is proportional to the relative velocity of the object, with the FMCW method it is possible to measure the distance and the relative velocity simultaneously. In the case that the relative velocity of the object is zero, both f_{up} and f_{dn} become the frequency f_r (they have different signs mathematically).

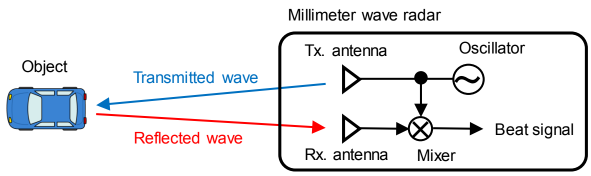

Fig. 1 Basic configuration of the FMCW method.

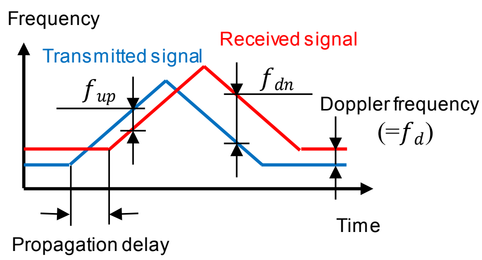

Fig. 2 Frequency of the beat signal that is obtained via the FMCW method.

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2.2 Beam Scanning

Several different methods of beam scanning are used to detect the direction of an object. Receiving antenna systems are of three types: (i) mechanical scanning (Fig. 3), which is steered by mechanically deflecting the receiving antenna; (ii) lens beam scanning (Fig. 4), which uses lenses to switch multiple receiving antennas at different positions; (iii) electronic scanning (Fig. 5), which synthesizes the signals of multiple receiving antennas by shifting the phases using either hardware or software. Among these, the main advantages of the electronic scanning method consist in the fact that it has no driving mechanism and does not require a lens. However, the performance will be degraded if multiple antennas cannot receive the amplitude and phase accurately. This is a technical challenge for millimeter waves with a wavelength of approximately 4 mm. This work focuses on the possibility of achieving future miniaturization and cost reduction, as well as reliability and quietness, and thus challenges the development of electronic scanning with digital beamforming (DBF), which has not yet been achieved by other companies in the automotive millimeter wave radar field.

In DBF, a time difference exists to reach multiple receiving antennas depending on the angle of arrival θ of the reflected wave. The time difference is measured as the phase difference of the received signal. The angle is detected by adjusting the phase with a phase shifter, so that the amplitude of the combined output is maximized. A relationship exists between the phase difference φ and the angle of arrival θ between adjacent receiving antennas. θ can be calculated according to:

$$\theta = \sin^{-1}(\varphi\lambda/2\pi d). \qquad (5)$$

The signal output from each antenna is digitized via an A/D converter and synthesized using signal processing to detect the angle.

Since there are signs, guardrails, etc., as well as vehicles on the road, multiple objects can exist at approximately the same distance. In equation (5), the calculation is not possible when multiple reflection waves return. However, all the angles can be calculated correctly by measuring the amplitude and phase of each receiving signal with multiple receiving antennas and by solving the simultaneous equations.

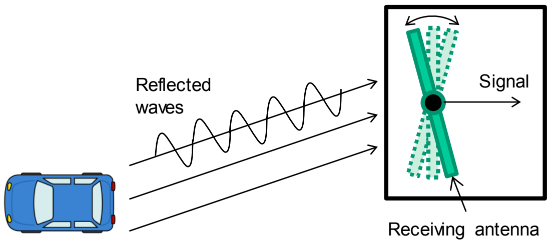


Fig. 3 Mechanical scanning.

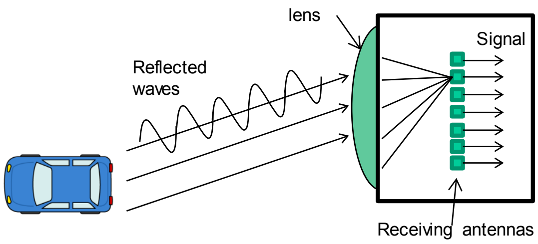


Fig. 4 Lens beam scanning.

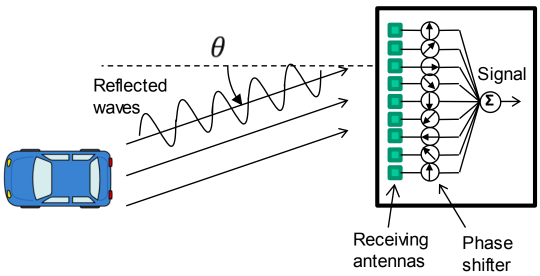


Fig. 5 Electronic scanning (beamforming).

3. Technical Development and Commercialization of Automotive Millimeter Wave Radars

3.1 Prototyping and Improvement of the Radar

We have been developing technologies to realize millimeter wave radars since the 1990s. At that time, DENSO and Toyota Central R&D Labs. (TCRDL) were working on their own prototypes. Fig. 6 shows the external appearance of the millimeter wave radar prototype developed by DENSO. This radar uses a DBF electronic scanning with nine channels of slot arrays arranged horizontally as the receiving antenna. A cylindrical lens is mounted in front of the receiving antenna to focus the beam in the vertical plane. Figure. 7 shows the detection results for the arrival angle using this prototype, with the target placed at angles of −5°, 0°, and +5°. It can be seen that the peak angle and directivity pattern agree well with the simulations, and the expected results were thus obtained.

Further, the appearance and configuration of the radar prototype developed by TCRDL are shown in Figs. 8 and 9, respectively [1,2]. To simplify the configuration and reduce the cost, a method for switching between three transmitting antennas and three receiving antennas with a single transmitter and receiver was attempted. By

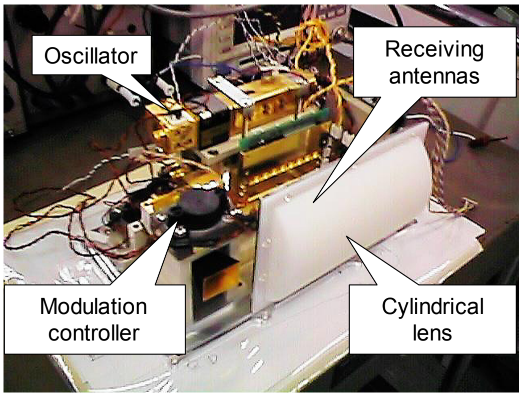
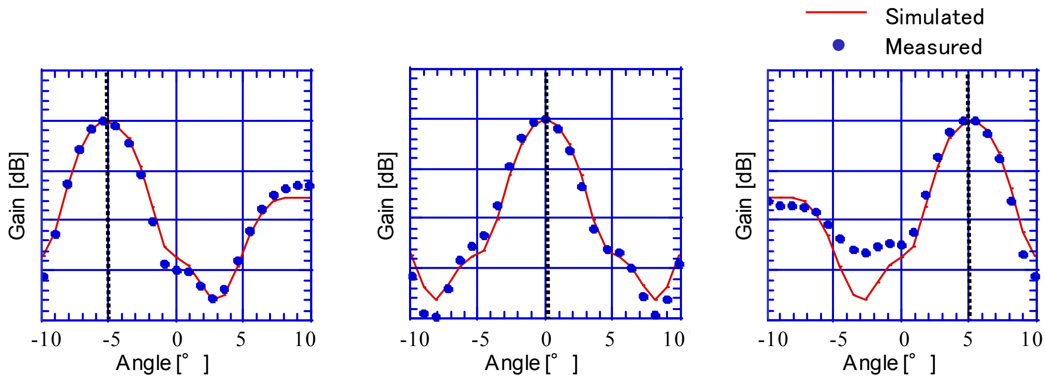


Fig. 6 Radar prototype (DENSO).



(a) Direction of target: −5° (b) Direction of target: 0° (c) Direction of target: +5°

Fig. 7 Detection results of the arrival angle via the prototype.

setting the interval of the transmitting antennas to three times the interval of the receiving antennas and switching the antennas in a time-division manner, nine channels of the signal can be received. This reduces the number of channels and the number of switches by using only two three-channel switches. Both prototypes had dimensions of 20 × 30 cm^2, thus being very large to be installed on a vehicle. However, they enabled us to obtain the basic technology through various tests.

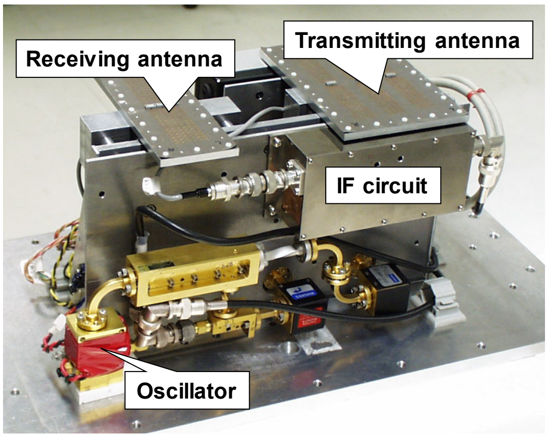


Fig. 8 Radar prototype (TCRDL).

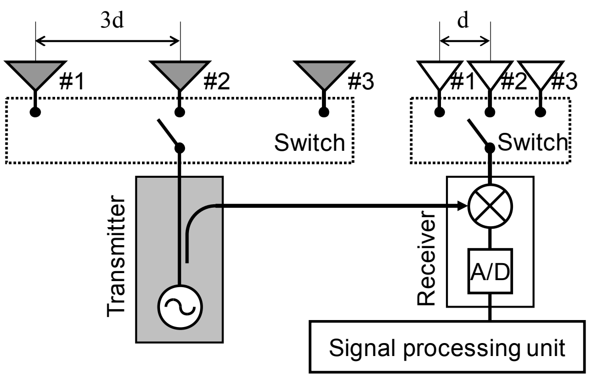


Fig. 9 Configuration of the radar prototype (TCRDL).

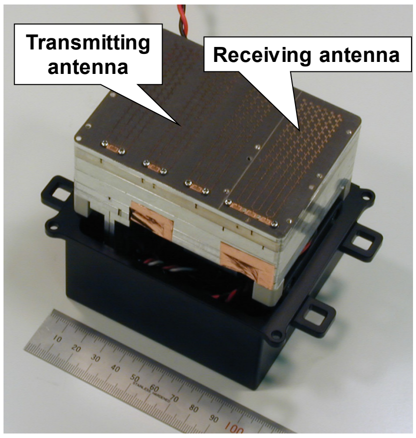


Fig. 10 Radar prototype in ca. 2000.

To further accelerate the research, DENSO and TCRDL decided to bring their technologies together and redesigned the antenna and circuits to realize a smaller radar. This attempt was successful at reducing the width to approximately 10 cm, in ca. 2000 (Fig. 10).

3.2 Important Technology

In DBF, when the phase difference of the received signal between adjacent antennas exceeds 2π, grating lobes are generated. Thus, the object's direction cannot be uniquely determined. To avoid ambiguity, the spacing between the receiving antennas was designed in such a way that the phase difference did not exceed 2π within the field of view (FoV) of the radar. In addition, the sensitivity was suppressed so that the reflected wave arriving from outside the FoV was not received by suppressing the side lobes.

Another challenge is to realize signal processing for stable object detection. The received signal of the radar varies in a complex manner, owing to not only various reflected waves generated by the objects on the road but also the reflections from the road surface and side walls. These depend on the type of object and its aspect angle. In particular, the signal intensity of millimeter wave radars fluctuates greatly because of the short wavelength. The multiple reflections generated simultaneously affect the accuracy of angle detection. Since radio waves are invisible, it is not easy to know the reflection points and each of the reflection intensity. Therefore, a method was established to measure the distribution of reflection intensity from an object with high resolution. This was achieved by measuring the received signal while moving the position of the radar and applying the synthetic aperture technology [3]. An example of the distribution of reflection intensity measured from the rear of a vehicle at different aspect angles is shown in Fig. 11. This method was used to measure vehicles and objects on the road under various conditions. Furthermore, a simulator was constructed to predict the detection results from the data during driving. This simulator was used for radar design and signal processing improvements.

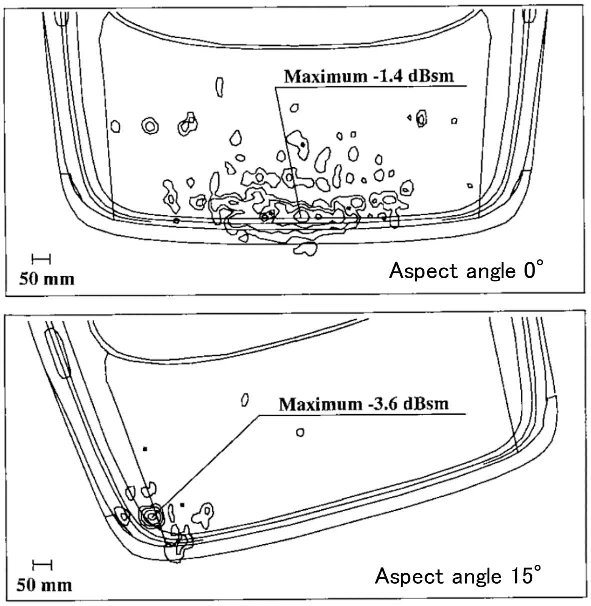


Fig. 11 Distribution of reflection intensity at the rear of the vehicle (top view).

3.3 Commercialization of Automotive Millimeter Wave Radars

After continuing to study prototypes, in 2003 DENSO finally commercialized the world's first automotive millimeter wave radar with electronic scanning using DBF. The appearance of the commercialized radar and its specifications are shown Fig. 12 and Table 1, respectively. A high-sensitivity triplate-type slot antenna was used. The antenna, the millimeter wave module, and the signal processing board are stacked on top of each other to reach an overall thickness of 60 mm. The beat signal is acquired in a time-division manner, while switching between multiple receiving antennas, is digitized via an A/D converter, and is finally imported into the signal processor (Fig. 13). The flowchart of the signal processing is shown in Fig. 14. The beat signals

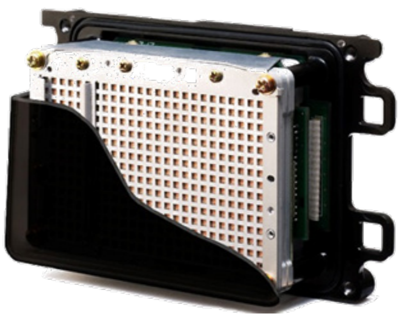


Fig. 12 Commercialized millimeter wave radar.

Table 1 Specifications of the radar (2003).

Parameter	Value
Maximum Distance	150 m
Relative Velocity	-200 ～ 100 km/h
Azimuth Angle Range	-10° ～ 10°
Processing Cycle Time	100 ms
Operating Frequency	76 ～ 77 GHz
Modulation Principle	FMCW
Beam Scanning	Electronic Scanning (DBF)
Average Output Power	2 mW

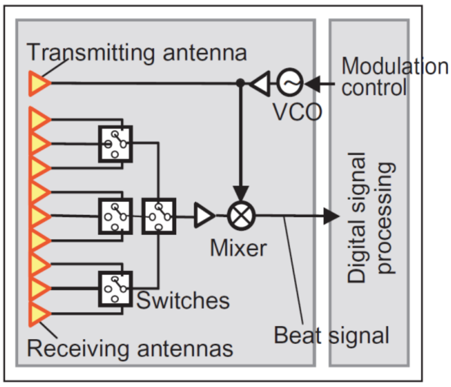


Fig. 13 Block diagram of the radar [4].

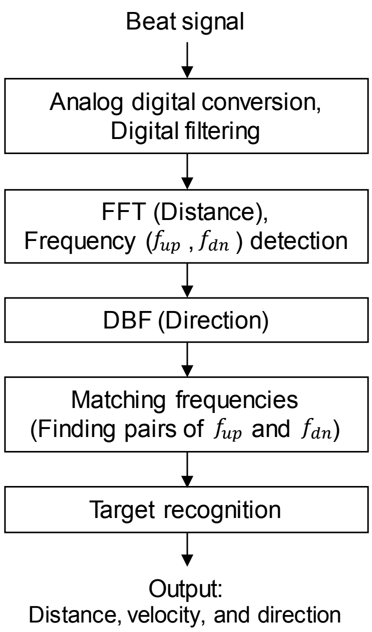


Fig. 14 Signal processing flowchart.

are obtained via multiple receiving antennas. The frequency of the beat signal is detected via Fourier transformations. In addition, beamforming is used to realize electronic scanning and calculate the angle of arrival. This radar calculates the distance, relative velocity, and direction of an object based on the information of the frequency of the beat signal and the angle. A PCS (Pre-Crash Safety) system using this radar has been developed by Toyota Motor Corporation. This was also a world's first.

4. Evolution of Automotive Millimeter Wave Radars

Research and development of the radar technology has continued even after the first commercialization of radar systems.

4.1 Improvement of the Angle Detection Method [4]

Although DBF is capable of high-speed calculation, its low resolution renders it difficult to distinguish between multiple objects in close proximity. To overcome this shortcoming, the well-known high-resolution signal processing technique, MUSIC [5], was applied. Fig. 15 compares the results of MUSIC detection and DBF detection of vehicles traveling beside guardrails. The result shows that, even in situations where it is difficult for DBF to distinguish between vehicle and guardrail, MUSIC can detect them separately. Although reducing the time required to perform complex calculations has been a technical challenge, this has been here achieved by not only improving the performance of the processing unit, but also by replacing complex number operations with real number operations. These technologies were awarded the "Arch T. Colwell Merit Award" by the Society of Automotive Engineers (SAE) in 2006 (Fig. 16).

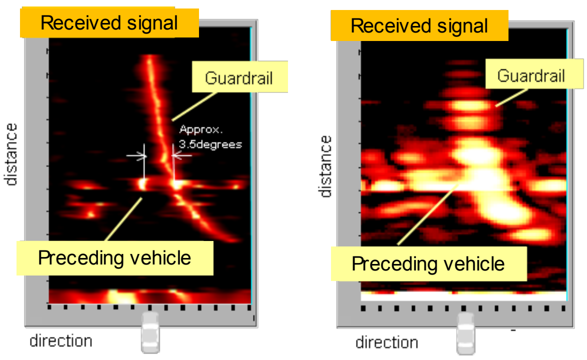


Fig. 15 High-resolution detection using MUSIC.

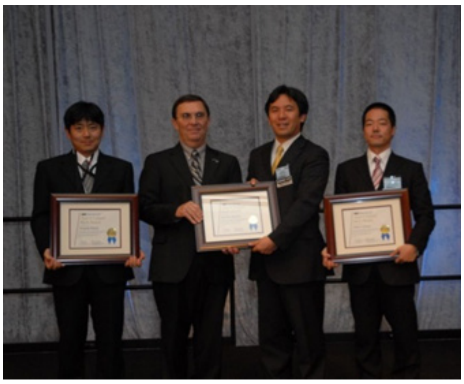


Fig. 16 Award ceremony
(Author: Natsume, third from left).

4.2 Improved Distance and Relative Velocity Detection

As described above, the FMCW method calculates the distance and relative velocity of the object from the frequencies of the beat signals obtained in the rising and falling slopes. Therefore, when multiple objects are present and multiple beat signals are detected, if the distance and relative velocity are calculated from the frequencies of the beat signals generated by different objects, this will result in a false detection. Although it is possible to reduce false detections by improving the detection algorithm, a distance and relative velocity detection method has been realized using a pulse compression method. In this approach, one of the rising and falling slopes is repeated at high speed to fundamentally eliminate this false detection (Fig. 17). The distance is detected from the frequency of the beat signal, whereas the relative speed is detected from the time variation of the phases of multiple beat signals. The frequency of multiple beat signals is almost the same if they can be observed in a short period; thus, they cannot be mistaken for the beat signals of different objects. This technology was achieved by improving the performance of RF devices and signal processing equipment.

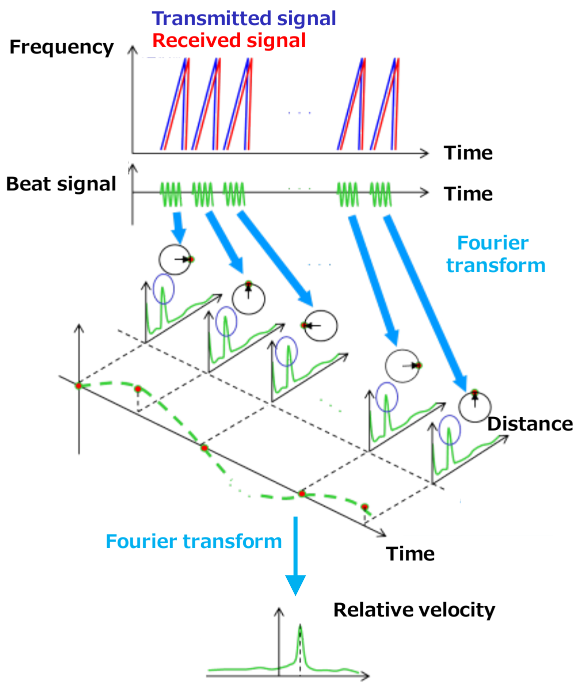


Fig. 17 Pulse compression method.

5. Conclusions

In this article, we have introduced the technical development of automotive millimeter wave radars, including the technical challenges required for such developments, the difficulties encountered from prototype design to product commercialization, and the future evolution of the technology. The needs for safety and comfort are expected to continue to increase in the future. We will continue to contribute to the realization of safe and comfortable mobility through the application of millimeter wave radars and other radio wave products.

6. References

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