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EXPERIMENTAL EVALUATION OF VEHICLE MOUNTED MMWAVE SENSOR FOR PARKING SCENARIO

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Abstract : Automotive radars provide numerous benefits to the vehicle. These radars are typically installed in areas such as the vehicle's front, rear, and sides. Furthermore, mm-wave radars are available in a variety of configurations, including long-range radar, ultra-wide band radar, multibeam radar, and laser beam. The short-range applications usually dealt with the mm-wave radar. Parking assistant is one of the major applications that can be developed using mm-wave sensors.

In the proposed work, to evaluate the performance of mm-Wave radar, sensors in the parking scenario, when the vehicle is moving slowly, to park. The ground truth information is available from the phone camera. The nearby parked cars and other obstacles need to be considered to determine the parking slot for the own vehicle from the radar, returns. The machine learning techniques will be used or classifying radar images to detect vacant parking spaces with a 77-GHz radar. An image of a parking scenario is rendered using an FMCW radar, and the image patches corresponding to each parking position are classified independently.

***IndexTerms* - mmwave Sensor,AWR1642,DCA1000,FMCW,Range Resolution, Millimeter Wave Sensor**

I. INTRODUCTION

Millimeter wave (mmWave) is a special class of radar technology that uses short wavelength electromagnetic waves. This is considered a short wavelength in electromagnetic. To process the mmWave signal, the size of the components such as the antennas on the system are small. Short wavelengths provide high accuracy. An mmWave system operating at 76–81 GHz will have the ability to detect movements that are as small as a fraction of a millimeter. This will focus on evaluating the effectiveness of a 77-GHz single-chip mmWave radar sensor, specifically the Texas Instruments **AWR1642**.

mmWave radars transmit signals with a wavelength that is in the millimeter range. This is considered a short wavelength in the electromagnetic spectrum and is one of the advantages of this technology. Indeed, the size of system components such as the antennas required to process mmWave signals is small. Another advantage of short wavelengths is the high accuracy. An mmWave system operating at 76–81 GHz (with a corresponding wavelength of about 4 mm), will have the ability to detect movements that are as small as a fraction of a millimeter. TI devices implement a special class of mmWave technology called frequency modulated continuous wave (**FMCW**). As the name implies, FMCW radars transmit a frequency-modulated signal continuously to measure range as well as angle and velocity. This differs from traditional pulsed-radar systems, which transmit short pulses periodically[1].

II. LITERATURE SURVEY

2.1 J. Wang, S. K. Sharma, R. S. Adve, and P. P. Khargonekar. "Millimeter Wave Radar for Vehicle Sensing Applications".IEEE Transactions on Intelligent Transportation Systems 2017: This paper presents an experimental evaluation of millimeter-wave radar for vehicle sensing applications. The authors conduct extensive experiments to evaluate the performance of the radar in various scenarios, including different weather conditions and traffic densities.

2.2 Al-Habashna, A. El-Saadany, and H. Mouftah Title. "Automotive Radar Sensors for Collision Warning and Autonomous Emergency Braking." IEEE Transactions on Vehicular Technology 2018: This paper evaluates the performance of automotive radar sensors for collision warning and autonomous emergency braking applications. The authors conduct experiments to assess the accuracy and reliability of radar-based systems in detecting obstacles and preventing collisions. These papers should provide you with a good starting point for your research on the experimental evaluation of vehicle-mounted mmwave sensors.

2.3 Harry D. Mafukidze,Amit K. Mishra,Jan Pidanic,Schonken W. P. Francois.Scattering Centers to Point Clouds: A Review of mmWave Radars for Non-Radar-Engineers. IEEE 10th International Conference on Signal Processing Proceedings 2010: Recently, mmWave radars have been gaining popularity, thanks to their low cost, ease of use and high-resolution sensing. In this paper, we provide a review of the mmWave radar data processing frameworks, starting from mathematical foundations to applications. Specifically, we focus on the mmWave radar point cloud as a robust data structure representing compressed signatures for target recognition and classification. We first focus on the generation of the radar point clouds, and the signal processing algorithms designed for their unique characteristics. Then, we illustrate how the radar point clouds are prepared for feature extraction and classification using machine learning and deep learning approaches. Finally, we summarize the state-of-the-art applications, open datasets, developments, and future research directions in this field.

2.4 Multi-Object Tracking with mmWave Radar: A Review by Andre Pearce,J. Andrew Zhang, Richard Xu and Kai Wu 6 January 2023: This paper aims to provide a critical analysis of the current literature surrounding multi-object tracking and sensing with short-range mmWave radar. There is significant literature available regarding single-object tracking using mmWave radar, demonstrating the maturity of single-object tracking systems. However, innovative research and advancements are also needed in the field of mmWave radar multi-object tracking, specifically with respect to uniquely identifying multiple target tracks across an interrupted field of view. In this article, we aim to provide an overview of the latest progress in multi-target tracking. An attempt to phrase the problem space is made by firstly defining a typical multi-object tracking architecture. We then highlight the areas for potential advancements. These areas include sensor fusion, micro-Doppler feature analysis, specialized and generalized activity recognition, gait, tagging and shape profile. Potential multi-object tracking advancements are reviewed and compared with respect to adaptability, performance, accuracy, and specificity.

2.5 **Sayed Hossein Dokhanchi,Bhavani Shankar Mysore,Kumar Vijay Mishra,Björn Ottersten. A mmWave Automotive Joint Radar-Communications System IEEE Transactions on Aerospace and Electronic Systems (Volume: 55, Issue: 3, June 2019):** This paper propose a millimeter-wave joint radar-communications (JRC) system comprising a bi-static automotive radar and vehicle-to-vehicle communications. And will study the applicability of known phase-modulated-continuous-wave (PMCW) and orthogonal-frequency-division-multiple-access waveforms for bi-static-JRC. In both cases, will design multiplexing strategies to ensure the parameter identifiability, derive JRC statistical bounds and numerically demonstrate superior performance of proposed low-complexity JRC super-resolution algorithms over conventional two-dimensional fast Fourier transform/Multiple Signal Classification.

III. EQUIPMENT

To explore radar-based ADAS applications, we have assembled a lab-scale frequency modulated continuous wave (FMCW) radar test-bed based on Texas Instruments (TI) automotive chipset family. The **AWR1642** radar sensor (Fig.1(a)), developed by Texas Instruments [2], represents a significant advancement in the field of automotive radar technology. With its state-of-the-art features and capabilities, the AWR1642 is at the forefront of enabling advanced driver assistance systems (ADAS) and autonomous driving. The AWR1642 operates in the **76 GHz to 81 GHz** frequency band. This frequency range is ideal for automotive radar applications due to its ability to provide high-resolution sensing. AWR1642 plays a vital role in the development of safer and more reliable ADAS and autonomous driving systems, ultimately contributing to the vision of a future with zero accidents on the road.

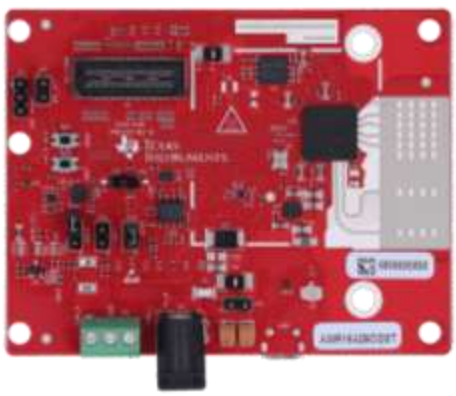

Fig.1(a):AWR1642BOOST [2]

Fig.1(b):DCA1000EVM [2]

The **DCA1000 Evaluation Module (EVM)** (Fig.1(b)) is a sophisticated tool developed by Texas Instruments for evaluating and testing high-speed analog-to-digital converters (ADCs) in radar and other wide-bandwidth applications. As a critical component in radar systems, ADCs are responsible for converting analog signals received from antennas into digital data for further processing, enabling detection, tracking, and imaging of targets.

In addition to its hardware capabilities, the DCA1000 EVM [3] offers a comprehensive software suite for data acquisition, processing, and analysis. The software provides a user-friendly interface for controlling the EVM, configuring parameters, and visualizing captured data in both time and frequency domains. Moreover, it includes advanced signal processing algorithms and tools for performing tasks such as target detection, range estimation, and Doppler processing, enabling engineers to extract valuable insights and optimize radar performance.

IV. METHODOLOGY

Automotive radar is composed of two TI evaluation boards: **AWR1642 BOOST** and **DCA100 EVM**. AWR1642 high-level architecture as shown in Figure.1, the AWR1642 chipset is an integrated FMCW radar sensor that enables a monolithic implementation of a 2TX, 4RX system with built-in phase lock loop (PLL) and analog to digital converters (ADC) [2]. The RF design makes it capable of operation in the 76-77 or 77-81GHz band with 12.5dBm TX power and 15dB RX noise figure. It also integrates the C674x-based DSP subsystem and ARM R4F-based processor subsystem, which are responsible for radar signal processing and radio configuration control, respectively. DCA1000 EVM is a capture board for streaming the ADC data from AWR1642 board to a local computer over Ethernet. The AWR1642 device is a highly integrated single chip77-GHz radar on-chip device that includes two transmit and four receive chains, a 600-MHz user programmable C674x DSP and a 200-MHz user programmable ARM Cortex-R4F processor. The device comprises of four main subsystems:

1. The RF/analog subsystem 2. The radio processor subsystem 3. The DSP subsystem 4. The master subsystem.

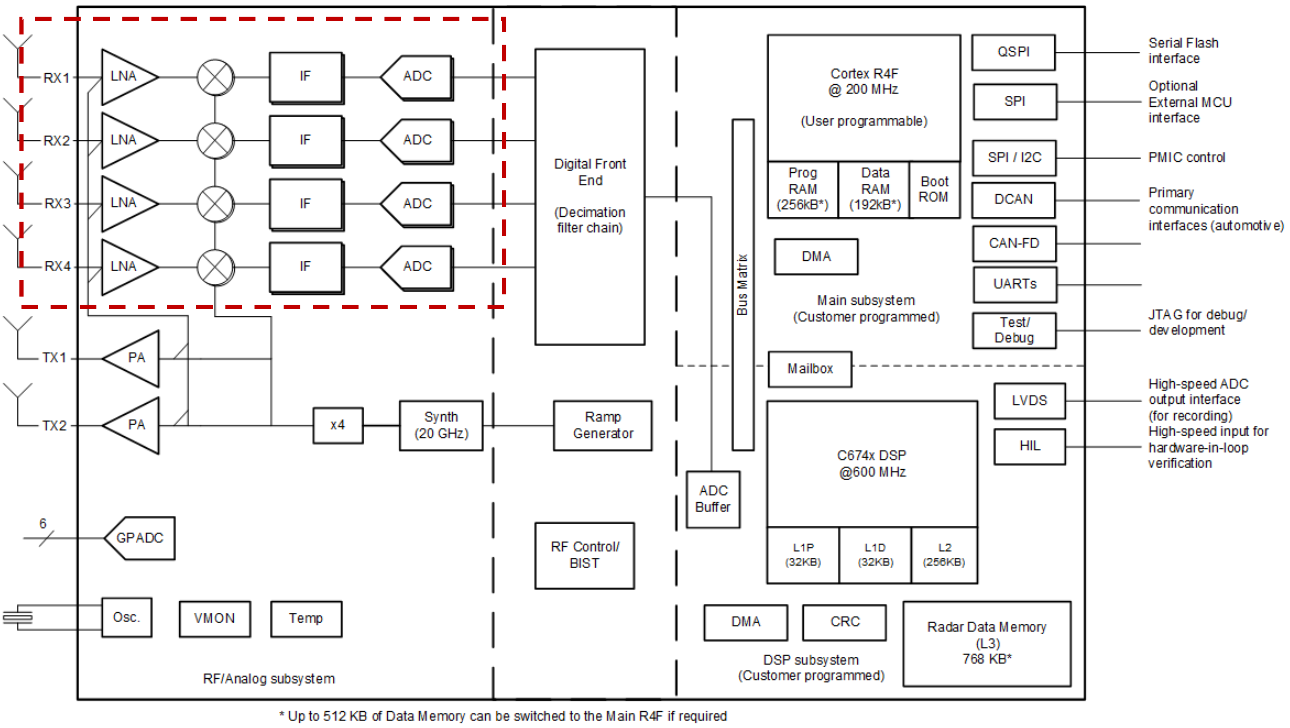

Fig.2: TI AWR1642 chip diagram, where the red dash rectangle highlights the receiver chain [2]

There are 2 transmitters and 4 receivers which provide better angular resolution and provide better velocity resolution. The AWR1642 radar sensor has better range resolution. Due to the RF bandwidth of 76–81 GHz of the sensor, the chirps are highly linear, ramping up of the chirps is faster up to 100MHz/Micro sec and on-chip BIST functionality that allows the module to test itself. With DSP integration, the AWR1642 sensor allows implementation of improved detection algorithms and high-resolution angle estimation.

V. CONFIGURATION PARAMETERS & EXPERIMENTAL SETUP

5.1 Configuration Parameters

A radar dataset for various objects have been collected for multiple scenarios - parking lot, campus road, city road, freeway by a vehicle mounted platform that is driven (see Fig. 3(b)). Significant effort was placed in collecting data for situations where cameras are largely ineffective, i.e. under challenging light conditions. The radar configurations used for the data collection are shown in Table I below. The Configuration Parameters of AWR1642 Evaluation Module are shown in Table II below.

TABLE-I
CONFIGURATIONS OF FMCW SIGNAL AND TEST-BED

Parameter	Configuration
Start Frequency	77 GHz
Sweep Bandwidth	670 MHz
Sweep slope	21 MHz/us
Frame rate	30 fps
Sampling frequency	4000 ksps
Number of chirps in one frame	255
Number of samples of one chirp	128
Number of transmitters, receivers	2, 4

TABLE-II
CONFIGURATION PARAMETERS OF AWR1642 EVM

S.No	Parameter	Value
1	Start Frequency	77GHz
2	Frequency Slope	65.998 MHz/μs
3	Idle Time	100μs
4	ADC Start Time	6μs
5	ADC Samples	256
6	Ramp End Time	60μs
7	No of Chirp Loops	128
8	No of Frames	100
9	Number of transmitters, receivers	2, 4
10	Number of Frames	10
11	Frame Periodicity	100 ms
12	ADC sampling frequency(ksps)	5000

5.2 Experimental Setup

The AWR1642EVM module and DCA1000 EVM needs to be connected as shown in Fig.3(a) below.

Fig.3(a): FMCW radar test-bed (red board: AWR1642 BOOST; green board: DCA1000 EVM)

Fig.3(b): Vehicle mounted platform for dataset collection

The **AWR1642EVM** module and **DCA1000 EVM** are two key components in radar-based sensing systems, facilitating the collection and processing of radar data for vehicle automation applications. The experimental setup for vehicle automation using the AWR1642EVM module and DCA1000 EVM typically involves several steps:

- **Hardware Configuration**: The AWR1642EVM module and DCA1000 EVM are connected according to the specified interface requirements. This usually involves connecting the output of the AWR1642EVM module to the input of the DCA1000 EVM using appropriate cables and connectors. Additionally, power and data connections are established to ensure proper operation of both modules. The EVM also hosts a device to assist with onboard emulation and UART emulation [4] over a USB link with the PC.
- **Software Setup**: The necessary software tools and drivers for configuring and controlling the AWR1642EVM module and DCA1000 EVM are installed on a host computer. This includes device drivers, graphical user interfaces (GUIs), and development environments provided by Texas Instruments. These tools allow engineers to configure the radar parameters, capture radar data, and perform real-time analysis of the collected data.
- **Calibration and Alignment**: Before conducting experiments, the radar system must be calibrated and aligned to ensure accurate and reliable performance. This involves calibrating the radar sensor to compensate for any hardware imperfections and aligning the sensor's field of view with the vehicle's orientation. Calibration and alignment procedures are typically performed using specialized software tools provided by the radar sensor manufacturer. The relative

positioning of vehicles has been estimated using mmWave radar in [5]. Vehicle detection in advanced driving assistant systems using automotive radar with range–azimuth–Doppler dimensions is studied in [6].

- **Data Collection and Analysis**: Once the radar system is calibrated and aligned, data collection experiments can be conducted in various driving scenarios. The radar sensor continuously transmits and receives radar signals, detecting and tracking surrounding objects such as vehicles, pedestrians, and obstacles. The raw radar data is captured by the DCA1000 EVM and streamed to the host computer for real-time analysis. Engineers can use this data to evaluate the performance of object detection and tracking algorithms, assess the system's sensitivity to different environmental conditions, and identify areas for improvement.
- **Performance Evaluation**: After collecting sufficient data, the performance of the vehicle automation system is evaluated based on predefined metrics and criteria. This may involve comparing the detected objects against ground truth annotations, assessing the system's ability to accurately predict object trajectories, and analysing the system's robustness under challenging conditions such as poor weather or low visibility.

VI. Measurement Theory

6.1 Range Measurement

As shown in Fig.4, an FMCW radar transmits a sequence of chirp signals (called a frame) and then mixes the receive echo with the local reference (transmitted signal) to yield a resulting beat signal at a frequency fb = S2d/c in the intermediate frequency (IF) band (shown in Fig. 3), where S is the slope of chirp signal, d is the distance to the object, and c is speed of light. To estimate the beat frequency, it is common to use a fast Fourier transform (Range FFT) to convert the time domain IF signal into the frequency domain, and the resulting spectrum has separate peaks for resolved objects. The resolution of FFT-based range estimation is determined by the swept RF bandwidth B of the FMCW system [7], given by the well-known result Rres = c/2B.

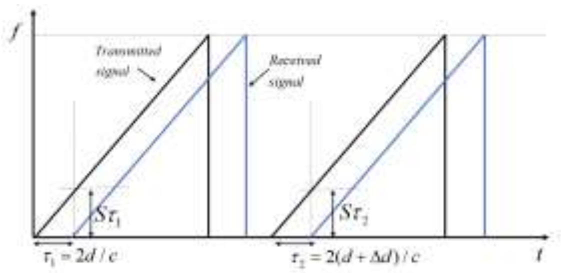

Fig.4: Range and Velocity Measurement

6.2 Velocity Measurement

The object motion Δd (shown in Fig.4) relative to the radar causes a beat frequency shift Δfb = 2SΔd/c on the receive signal as well as a phase shift $\Delta\varphi v = 2\pi fc\ 2\Delta d/c = 4\pi vTc/\lambda$, where fc is the center frequency, v is the object velocity, Tc is the chirp duration, and λ is the wavelength. Compared to the beat frequency shift, the phase shift of mmWave signal is more sensitive to the object movement. Hence, it is common to execute a fast Fourier transform (Velocity FFT) across the chirps to estimate the phase shift and then transform it to velocity. The velocity resolution of this method is given by: Vres = λ/2Tf = λ/2LTc [1], where L is the number of chirps in one frame, and Tf is the frame period.

6.3 Range Resolution

Range Resolution refers to the ability to resolve two closely spaced objects. The two objects are so close that they show up as a single peak in the frequency spectrum as shown in Fig.5(a). The two objects can be resolved by increasing the length of the IF signal as shown in Fig.5(b). Note that this also proportionally increases the bandwidth. Thus intuitively: Greater the Bandwidth => better the resolution. The Range Resolution dres depends only on the Bandwidth swept by the chirp dres = c/2B.

Range resolution [1] is the ability to distinguish between two or more objects. When two objects move closer, at some point, a radar system will no longer be able to distinguish them as separate objects. Fourier transform theory states that you can increase the resolution by increasing the length of the IF signal. To increase the length of the IF signal, the bandwidth must also be increased proportionally. An increased length IF signal results in an IF spectrum with two separate peaks.

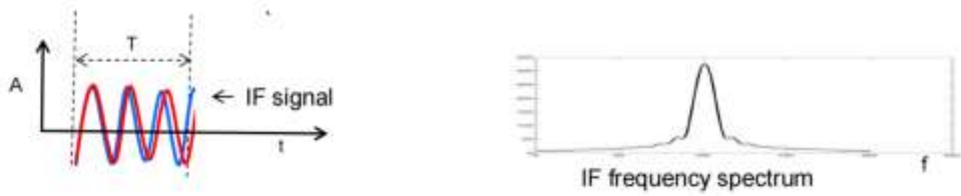

Fig.5(a): Two objects are so close that they show up as a single peak.

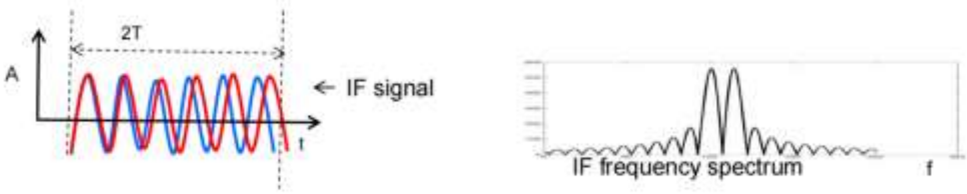

Fig.5(b): Two objects can be resolved by increasing the length of the IF signal.

VII. Results & Discussions

Fig.3(a) & 3(b) represents the Experimental Setup from which both the evaluation modules AWR1642 and DCA1000 are to be connected and Experimental setup provide a means to validate the accuracy and reliability of radar sensor measurements. The Doppler range map is generated for the dataset calculated showing the Relative power undertaking Range and velocity parameters as shown in Fig.6(a) below. Most of the graph is blue, indicating low relative power according to the color scale. An oval shape outlined in red around range 100 m at approximately -5 m/s velocity could indicate an area of interest or anomaly. The color gradient bar on the right shows relative power in decibels (dB), with dark blue representing low power and red indicating high power.

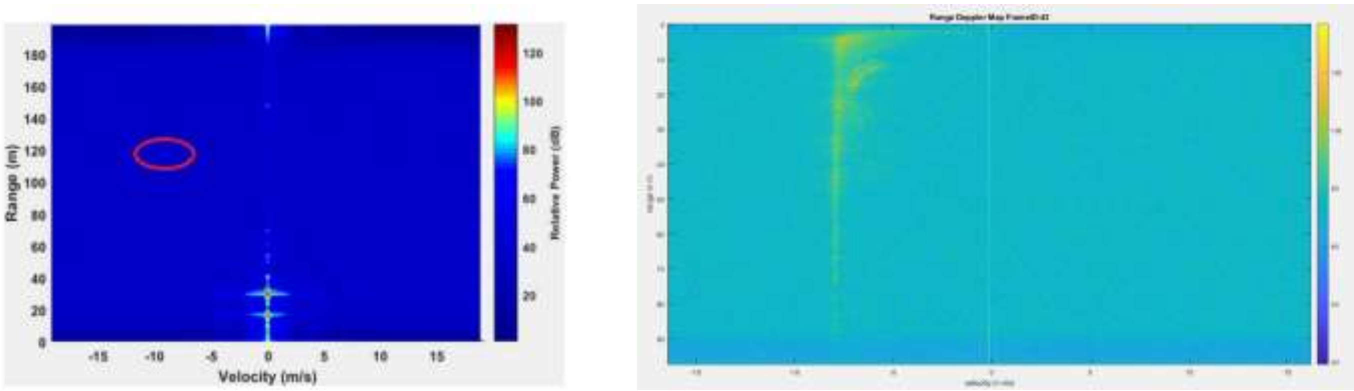

Fig.6(a): Doppler range maps showing the Range and Velocity measurements.

In addition to velocity, the Doppler range map also provides information about the distance or range of detected objects from the radar sensor. By analyzing the time delay between transmitted and received radar signals, the radar system can estimate the range to detected objects.

An advantage of mmWave radar sensors is their wide field of view. Fig.6(b) illustrates the limited field of view of ultrasonic sensors. Even with more ultrasonic sensors placed around the car than radar sensors (typically as many as 12), there are still gaps in detection. mmWave radar's field of view covers a wider range that enables 360-degree coverage capability around the vehicle while using fewer sensors than an ultrasonic sensor implementation.

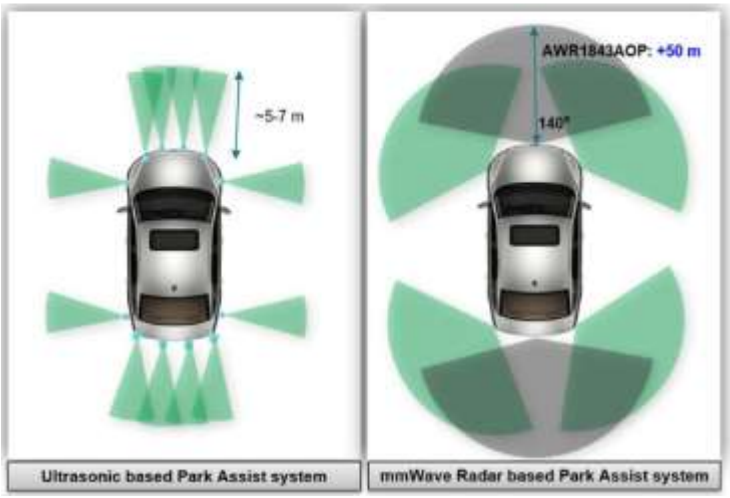

Fig.6(b): Comparison of Range and Field of View for Ultrasonic vs mmWave Radar Systems.

VIII. CONCLUSION

mmWave radar sensors have significant advantages compared to other sensors, making them an ideal solution for a vast number of applications. This article discussed the key performance parameters as well as the interpretation of radar measurements for mmWave radar sensors. The most recent mmWave radar advances and cutting-edge mmWave radars were thoroughly reviewed. The use of mmWave radar sensors was discussed in a variety of applications, such as automotive, industrial, robotics and automation, medical, security, and surveillance fields, as well as others. This information is valuable for autonomous driving systems, where a comprehensive understanding of the surrounding environment is necessary for safe and reliable navigation. mmWave radar can detect objects from farther away than other sensing technologies such ultrasonic sensors. Instead of emitting a sound wave, radar sensors create radio waves: the longest wavelengths in the electromagnetic spectrum. These radio waves bounce off objects in their path to determine distance by calculating changes in frequency.

The future of mmWave radar technology seems promising, with plenty of room for growth and expansion. Here, we present some major trends and developments to keep an eye on in future years. mmWave radars are projected to play a critical role in advanced driver-assistance systems (ADASs) and driverless vehicles in automotive applications. In the future, the increased integration of mmWave radar sensors in automobiles is likely to improve safety, enable autonomous driving, and improve situational awareness in a variety of weather conditions. mmWave radars have the potential to transform industrial applications, such as non-destructive testing, quality control, and process automation. Future advancements may result in smaller, more adaptable, and cost-effective industrial mmWave radar systems.

Abbreviations:

The following abbreviations are used in this manuscript:

FMCW	Frequency Modulated Continuous Wave
ADC	Analog-To-Digital Converter
DSP	Digital Signal Processor
FFT	Fast Fourier Transform
ADAS	Advanced Driver Assistance System
IF	Intermediate Frequency
EVM	Evaluation Module
RF	Radio Frequency

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