International Journal of Research in Engineering, Science and Management
Volume 7, Issue 2, February 2024
https://www.ijresm.com | ISSN (Online): 2581-5792

Performance Analysis of Automotive RADAR Range Systems for Improved Object Detection and Tracking

Ajay Waghmare[1*], Subramaniam Ganesan[2]
[1]*Ph.D. Student, Department of Electrical and Computer Engineering, Oakland University, Rochester Hills, USA*
[2]*Professor, Department of Electrical and Computer Engineering, Oakland University, Rochester Hills, USA*

***Abstract*: Automotive RADAR (RAdio Detection and Ranging) systems have emerged as a key technology for enabling advanced driver assistance systems (ADAS) and autonomous driving. This paper presents a comprehensive analysis of the performance of automotive RADAR systems for object detection and tracking, with a focus on identifying key factors that impact system performance. The study includes a review of the state-of-the-art RADAR system architectures and signal processing algorithms used in automotive applications, followed by a detailed analysis of system performance under different environmental conditions. We also evaluate the impact of environmental factors such as weather conditions, terrain, and interference from other sources on RADAR system performance. Our findings demonstrate that while RADAR technology offers significant advantages over other sensing modalities, there are still significant challenges that must be addressed to achieve high levels of accuracy and reliability in object detection and tracking. We identify key areas for future research, including the development of advanced signal processing algorithms and the integration of multiple sensing modalities for improved object detection and tracking. Overall, this paper provides a valuable contribution to the field of automotive RADAR systems by presenting a comprehensive analysis of system performance under environmental conditions and identifying key areas for future research and development.**

***Keywords*: Adaptive Cruise Control (ACC), ADAS (Advanced Driver Assistance Systems), Autonomous Driving, Automotive, Blind Spot Detection, Camera, Collision Avoidance, LIDAR (Light Detection and Ranging), Long Range Automotive RADAR, Sensor Fusion.**

1. Automotive RADAR

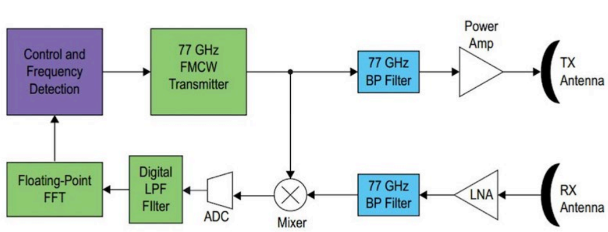

Fig. 1. Basic block diagram of automotive radar system

Figure 1 shows the basic block diagram of automotive radar system. The basic block diagram of an automotive radar system typically consists of the following main components:

Radar Transmitter: The radar transmitter generates and emits radio frequency (RF) signals in the form of electromagnetic waves. These waves travel through the air and interact with objects in the environment.

Antenna: The antenna is responsible for transmitting the RF signals generated by the radar transmitter and receiving the signals that are reflected from the objects in the environment.

RF Frontend: The RF frontend is the initial section of the radar system that processes the received signals from the antenna. It includes components such as amplifiers, filters, and mixers to enhance the received signals and prepare them for further processing.

Signal Processor: The signal processor is a crucial part of the radar system. It processes the received signals and extracts relevant information, such as range, velocity, and angle of detected objects. The signal processor performs tasks like pulse compression, target detection, and signal filtering to improve the accuracy of the measurements.

Digital Signal Processor (DSP): In more advanced radar systems, a digital signal processor is used to handle the complex signal processing algorithms and computations. It can perform tasks like fast Fourier transforms (FFT) for frequency analysis and advanced target tracking algorithms.

Microcontroller/Processor: The microcontroller or processor is the brain of the radar system. It receives the processed radar data from the signal processor or DSP and makes decisions based on that data. It controls the system's behavior, triggers alerts or actions (e.g., automatic braking), and communicates with other vehicle systems.

It's important to note that the actual block diagram of an automotive radar system can vary depending on the complexity and the specific application of the radar technology. Advanced radar systems for autonomous vehicles, for example, may have additional components and sophisticated algorithms to handle complex scenarios and support higher levels of automation.

RADAR (Radio Detection and Ranging) is an essential technology used in automotive systems for various applications, primarily in advanced driver assistance systems

*Corresponding author: ajaywaghmare@oakland.edu

(ADAS) and autonomous driving. It enables vehicles to sense and detect objects in their vicinity, providing crucial data for making informed decisions and enhancing safety on the road.

Here are some key points about RADAR in automotive systems:

Object Detection: RADAR uses radio waves to detect objects in the vehicle's surroundings, such as other vehicles, pedestrians, cyclists, and obstacles. It measures the time it takes for the radio waves to bounce off these objects and return to the RADAR sensor.

Range Measurement: RADAR can estimate the distance between the vehicle and the detected object. This information helps the vehicle's control system understand the proximity of other objects and take appropriate actions.

Velocity Estimation: In addition to range measurement, RADAR can also determine the relative speed of the detected objects. This data is vital for predicting potential collisions and adapting the vehicle's speed accordingly.

Doppler Effect: RADAR utilizes the Doppler effect to measure the velocity of objects. The Doppler effect occurs when there is a frequency shift in the reflected radio waves caused by the motion of the objects relative to the RADAR sensor.

Multiple Radar Sensors: Advanced automotive systems often use multiple RADAR sensors placed at different locations on the vehicle. This configuration provides a more comprehensive view of the environment and improves the accuracy of object detection and tracking.

Fusion with Other Sensors: RADAR data is typically combined with information from other sensors like cameras, lidar, and ultrasonic sensors. This sensor fusion approach enables a more robust perception system, as each sensor complements the strengths and weaknesses of the others.

Adaptive Cruise Control (ACC): RADAR plays a significant role in adaptive cruise control systems. ACC uses RADAR data to maintain a safe following distance from the vehicle ahead by automatically adjusting the vehicle's speed.

Collision Avoidance: RADAR can trigger collision avoidance systems, alerting the driver or initiating automatic braking to prevent or mitigate collisions with obstacles or pedestrians.

Blind Spot Detection: RADAR can be used for blind spot monitoring, helping drivers become aware of vehicles in their blind spots during lane changes.

Autonomous Driving: RADAR is a key sensor in autonomous or self-driving vehicles. It provides crucial real-time data to the vehicle's control system, allowing it to perceive the environment and make decisions for safe navigation.

Overall, RADAR technology in automotive systems has significantly contributed to the development of safer and more capable vehicles by improving situational awareness and enabling advanced driver assistance features.

Automotive radar is a technology that uses radio waves to detect objects and their movements in the surrounding environment of a vehicle. It is an important part of advanced driver assistance systems (ADAS) and autonomous driving technologies. Automotive radar systems typically operate in the microwave frequency range, usually between 24 GHz and 77 GHz. They can be classified as either short-range or long-range radar, depending on their intended use.

Short-range radar (SRR) is used for close-range applications, such as blind spot detection (BSD), Rear Cross Traffic Alert, (RCTA) and parking assistance. Long-range radar (LRR) is used for more distant applications, such as adaptive cruise control and forward collision warning. The automotive radar equation is a mathematical expression that describes the relationship between the radar system parameters and the radar performance in terms of range, resolution, and signal-to-noise ratio (SNR). The equation can be written as:

SNR = (Pt * Gt * Gr * lambda^2 * RCS * sigma)/(4 * pi^3 * R^4 * k * T * B * L)

where:
SNR is the signal-to-noise ratio
Pt is the transmitted power
Gt is the transmit antenna gain
Gr is the receive antenna gain
lambda is the wavelength of the transmitted signal
RCS is the radar cross section of the target
sigma is the scattering coefficient of the target
R is the range to the target
k is Boltzmann's constant
T is the ambient temperature
B is the bandwidth of the transmitted signal
L is the system loss.

The radar equation shows that the SNR is proportional to the transmitted power, antenna gains, wavelength, RCS, and scattering coefficient, and inversely proportional to the fourth power of the range. It also shows that the SNR is affected by the system noise temperature, bandwidth, and losses.

In automotive radar applications, the radar equation is used to determine the performance requirements of the radar system, such as the transmit power, antenna gains, and bandwidth, based on the desired range, resolution, and SNR. It is also used to evaluate the performance of the system under various operating conditions and environmental factors.

To test the Radar in different environmental conditions we need to have a reference system. We use the lab setup to monitor and log the radar with minimum environmental noise. We program the system to simulate the object at 300meters and use it as reference to determine the range accuracy of radar under test.

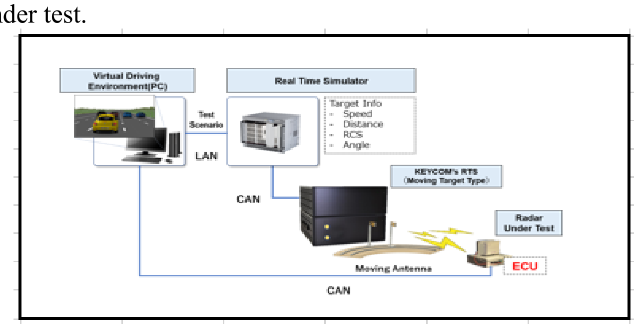

Fig. 2. RADAR target system block diagram

2. RADAR Range Analysis

Figure 2 depicts the block diagram of the Radar Target Simulator (RTS) system, designed for the analysis of RADAR performance in controlled environments. The RTS system consists of a computer program that establishes a connection with an actual RADAR. By employing a simulation script, the RADAR's performance can be thoroughly tested under various conditions. This comprehensive platform enables the validation of crucial RADAR capabilities, including range measurement, velocity estimation, and target detection, facilitating robust development and testing of automotive RADAR technologies.

Fig. 3. Lab system antenna settings

Figure-3 shows the RADAR parameter setting screen of RTS analysis software. Many factors will influence the radar detection range, which cannot be controlled by the designers. Therefore, in a first step we need to work with the basic information available, related to the propagation of the electromagnetic waves and the analog frontend.

$$P_r = \frac{P_t \cdot G_{tx} \cdot G_{rx} \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot R^4} = P_t \cdot G_{tx} \cdot G_{rx} \cdot \frac{\lambda^4}{(4\pi \cdot R)^4} \cdot \frac{4\pi \cdot \sigma}{\lambda^2} \qquad (1)$$

The radar range R is directly linked to the RF performance of the radar MMIC transceiver through its link budget, which in this case is called the radar range equation, which provides the power delivered to the RF receiver frontend Pr as a function of the output power of the transmitter frontend (Pt), the gain of the transmit and receive antennas (Gtx and Grx), the frequency of operation (through the wavelength λ) and the radar cross-section of the target (σ):

The term λ4/(4π·R)4 represents the two-way free-space loss, while (4π·σ)/λ2 accounts for the reflection on the target. The link budget and the different contributions to the radar equation are illustrated in figure 4.

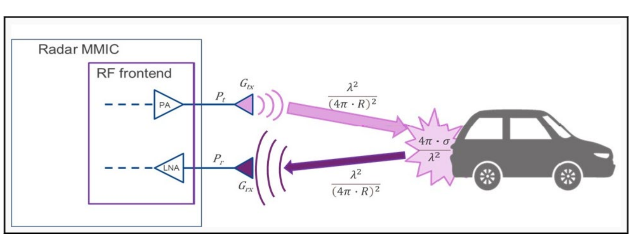

Fig. 4. Basic range calculation by radar

The overall performance of a radar system will be strongly affected by the performance of the analog RF transmit and receive in the radar MMIC transceiver. In the case of the range limitations, two main parameters need to be considered: the output power of the transmitter and the noise of the receiver.

When we test the radar in Sunny day with straight line of sight then we observed the maximum stable range performance with minimum noise reflections at 300meters as shown in Figure 6.

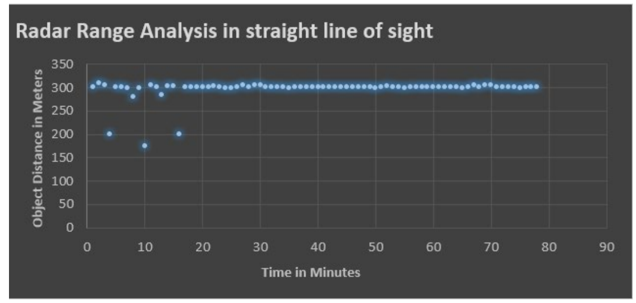

Fig. 5. Range of object in lab environment

3. RADAR Range vs. Snow Weather Condition

RADAR systems use radio waves to detect objects in the surrounding environment, including other vehicles, pedestrians, and obstacles. However, weather conditions such as rain, snow, and fog can affect the performance of RADAR systems, reducing their effectiveness. In particular, precipitation can cause reflections and scattering of the RADAR signal, leading to false positives or missed detections. Fog can also cause signal attenuation, which reduces the range and resolution of the RADAR system. To address these challenges, automotive RADAR systems are designed to account for weather conditions. For example, they may use multiple frequencies and polarizations to reduce the impact of precipitation and improve target detection. They may also use advanced signal processing techniques to filter out noise and interference caused by weather conditions.

Figure 5 shows the RADAR range performance in lab under controlled environment.

The range resolution under snow condition is examined in the below Figure 6. We can observe the reflection causing false positive objects and increasing the number of detection by more than double the amount of detection in lab setup.

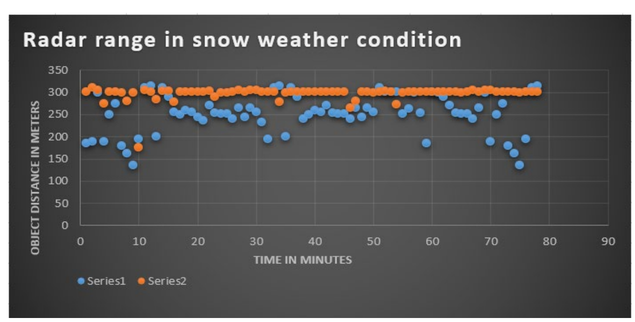

Fig. 6. RADAR range detection in snow environment

In order to eliminate the false detection and to improve the accuracy we can implement the filter in software to eliminate the objects which are caused by the reflection from snow. Objects that don't have the properties of reference object we placed at 300meters can be eliminated by filter to improve the range resolution, but the filter can also eliminate some of the real object because they don't match the exact properties of reference object. In real world scenario this will cause miss detection and cause system failure if not detected by backup system in time. The below Figure 7 shows the output of filter implementation, the below figure also shows the elimination of some good detection that are not match as per the reference we have created causing miss detections.

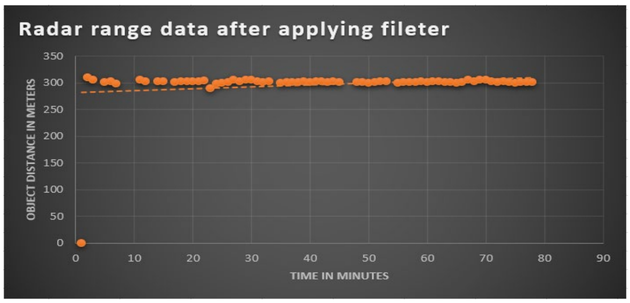

Fig. 7. The output of filter implementation

4. RADAR Variable Range Analysis

To analysis the radar at different ranges we need to perform variable range test, we place the object at pre-defined distance and analysis the output range provided by radar in lab environment and in snow environment.

In the below Figure 8 you can observe the data of lab setup when object is placed at different distance from radar. In the lab setup the radar shows the accurate range of reference object without any false object detection. We will use this data as a reference to compare the real-world data to analysis the effect of snow environment on radar range.

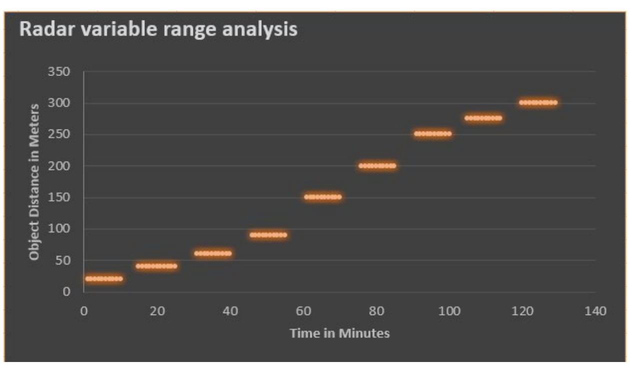

Fig. 8. Radar at distance range from 50Mtr to 300Mtr

In the below Figure 9 you can observe the effect of snow on the radar range detection output. Radar can detect the object at various distance with some false objects caused due to environmental factors. This output can be further filtered to get the more accurate range analysis.

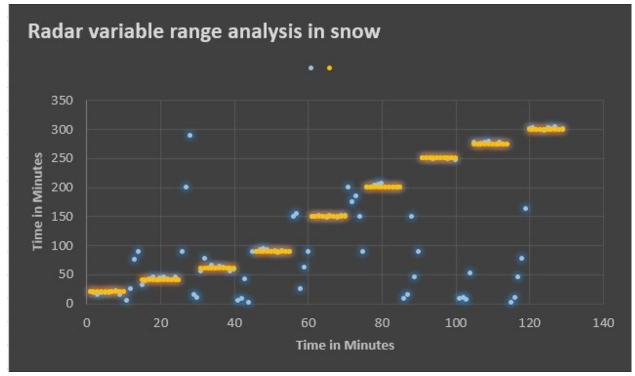

Fig. 9. Variable range in snow

5. Conclusion

Automotive radar at 76.4G Hz frequency is a very powerful system and can detect the target very precisely when it is stationary. While applying the filter to eliminate the false object and ghost object I observed that the filter also blocks some of the real object considering them as a false object. In real scenario it will be considered as a miss detection and can cause a system failure if not detected by any backup system. The Radar system is very accurate in detecting the range of objects but environmental conditions like snow, rain, road condition and terrain can cause failure of the system. A big layer of snow can create a complete blockage to a radar system.

Radar is very accurate in range detection and can be very effective when used as a subsystem with other sensors like Lidar and camera. The sensor data fusion will improve the quality of detection and will eliminate the false detection rate.

6. Proposed Solution

Radar is very accurate in range detection and can be very effective when used as a subsystem with other sensors like Lidar and camera. The sensor data fusion will improve the quality of detection and will eliminate the false detection rate.

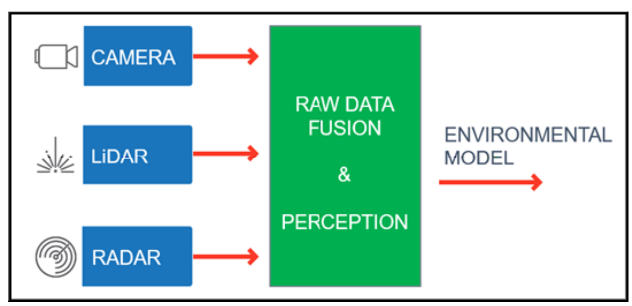

Fig. 11. Sensor fusion block diagram

References

[1] C. H. Wang, O. Altintas, C. D. Ozkaptan and E. Ekici, "Multi-Range Joint Automotive Radar and Communication using Pilot-based OFDM Radar," *2020 IEEE Vehicular Networking Conference (VNC)*, New York, NY, USA, 2020, pp. 1-4.

[2] https://www.eeworldonline.com/the-radar-technology-behind-autonomous-vehicles/

[3] A. Macaveiu, C. Nafornita, A. Isar, A. Campeanu and I. Nafornita, "A method for building the range-Doppler map for multiple automotive radar targets," *2014 11th International Symposium on Electronics and Telecommunications (ISETC)*, Timisoara, Romania, 2014, pp. 1-6

[4] H. Rohling and C. Moller, "Radar waveform for automotive radar systems and applications," *2008 IEEE Radar Conference*, Rome, Italy, 2008, pp. 1-4.

[5] P. Wenig, M. Schoor, O. Gunther, B. Yang and R. Weigel, "System Design of a 77 GHz Automotive Radar Sensor with Super resolution DOA Estimation," *2007 International Symposium on Signals, Systems and Electronics*, Montreal, QC, Canada, 2007, pp. 537-540.

[6] D. Ma, N. Shlezinger, T. Huang, Y. Liu and Y. C. Eldar, "Automotive Dual-Function Radar Communications Systems: An Overview," *2020 IEEE 11th Sensor Array and Multichannel Signal Processing Workshop (SAM)*, Hangzhou, China, 2020, pp. 1-5.

[7] R. Prophet, G. Li, C. Sturm and M. Vossiek, "Semantic Segmentation on Automotive Radar Maps," *2019 IEEE Intelligent Vehicles Symposium (IV)*, Paris, France, 2019, pp. 756-763.