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Advanced Radar Signal Processing Using Deep Learning for Real-Time Object Detection and Tracking in Autonomous Vehicles

Dr B Ramprasad[1], Dharavath Sunil[2], Kuruba Theja[3]

[1*]Assistant Professor, Department Of ECE, SVS Group of Institutions, Hanmakonda, Telangana

[2*]B.TECH Student, Department Of ECE, SVS Group of Institutions, Hanmakonda, Telangana

[3*]B.TECH Student, Department Of ECE, SVS Group of Institutions, Hanmakonda, Telangana

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ABSTRACT:

Radar signal processing has become a fundamental technology for autonomous vehicles because of its ability to provide reliable object detection and tracking under diverse environmental conditions, including rain, fog, snow, and low-light scenarios. Conventional radar systems often face challenges such as clutter, noise, multipath interference, and limited target resolution, which can affect the accuracy of perception. This paper presents an advanced radar signal processing framework for autonomous vehicles that integrates adaptive preprocessing, target detection, clutter suppression, feature extraction, and object classification to improve perception performance. The proposed approach employs digital signal processing techniques combined with deep learning-based classification to accurately identify vehicles, pedestrians, cyclists, and other road obstacles from radar data. Multi-target tracking algorithms are incorporated to estimate object position, velocity, and trajectory in real time, enabling safe navigation and collision avoidance. Experimental evaluation demonstrates that the proposed framework achieves higher detection accuracy, improved target localization, and robust performance under challenging weather and traffic conditions while maintaining low computational complexity suitable for real-time deployment. The proposed radar signal processing system enhances the reliability, safety, and efficiency of autonomous driving by providing accurate environmental perception for intelligent decision-making.

Keywords— Autonomous Vehicles, Radar Signal Processing, Object Detection, Deep Learning, Multi-Target Tracking, Clutter Suppression, Digital Signal Processing, Collision Avoidance, Automotive Radar, Intelligent Transportation Systems.

1.INTRODUCTION

Autonomous vehicles rely on advanced perception systems to accurately detect, classify, and track surrounding objects for safe navigation. Among various sensing technologies, millimeter-wave (mmWave) radar has emerged as a critical component because of its ability to operate reliably under challenging environmental conditions such as rain, fog, snow, dust, and low-light environments. Unlike optical sensors, radar directly measures the distance, velocity, and direction of objects, making it highly suitable for real-time collision avoidance and intelligent driving applications. However, conventional radar signal processing techniques, including Constant False Alarm Rate (CFAR) detection and traditional tracking algorithms, often suffer from limited resolution, clutter interference, false detections, and reduced performance in complex traffic scenarios. Recent advances in deep learning, high-resolution automotive radar, and sensor fusion have significantly enhanced radar perception by improving object detection, classification, and multi-target tracking capabilities.

Recent research has focused on integrating deep neural networks with radar signal processing to achieve more accurate and robust perception for autonomous vehicles. Deep learning models can effectively extract discriminative features from radar data, enabling reliable detection of vehicles, pedestrians, cyclists, and other road obstacles while minimizing false alarms. Furthermore, advanced tracking algorithms combined with radar-based object classification provide accurate trajectory estimation for dynamic traffic environments. Motivated by these developments, this paper proposes an advanced radar signal processing framework that integrates adaptive preprocessing, feature extraction, deep learning-based object classification, and multi-target tracking for real-time autonomous driving applications. The proposed framework improves detection accuracy, tracking performance, and computational efficiency while maintaining robust operation under adverse weather conditions, thereby enhancing the overall safety and reliability of autonomous vehicle perception systems.

2. SURVEY OF RESEARCH

Recent advances in autonomous vehicle technology have significantly increased the importance of radar signal processing for reliable environmental perception. **Abdu et al. (2021)** presented a comprehensive review of deep learning applications in millimeter-wave radar signal processing and highlighted the advantages of neural networks in target detection, classification, and feature extraction. **Ravindran et al. (2020)** reviewed deep neural network (DNN)-based multi-object detection and tracking techniques, emphasizing their ability to improve perception accuracy in autonomous vehicles. **Wen et al. (2019)** developed a deep learning-based smart radar vision system that demonstrated improved object recognition performance compared with conventional radar processing approaches. Similarly, **Dong et al. (2020)** proposed a probabilistic object detection framework for automotive radar that enhanced detection reliability in complex traffic environments.

Several researchers have focused on integrating deep learning with automotive radar systems to improve object detection and tracking performance. **Lin et al. (2023)** introduced a sensor fusion framework combining millimeter-wave radar and video data with deep learning for embedded autonomous driving systems, achieving improved detection accuracy and robustness. **Zheng et al. (2023)** developed a deep neural network-enabled vehicle detection method using high-resolution automotive radar imaging, demonstrating superior detection capability in challenging driving scenarios. **Paek et al. (2022)** proposed the K-Radar framework for 4D radar object detection, which provided reliable object recognition under various weather conditions. **Stroescu et al. (2020)** combined deep neural networks with particle filters for simultaneous object detection and tracking using high-resolution radar imagery, resulting in enhanced tracking stability and localization accuracy.

Recent studies have also explored advanced radar signal processing techniques and sensor fusion for autonomous driving applications. **Srivastav and Mandal (2023)** reviewed deep learning methods for automotive radar and discussed challenges such as clutter suppression, data scarcity, and computational complexity. **Wu et al. (2024)** surveyed radar and vision fusion techniques for 3D object detection, concluding that multimodal perception significantly improves detection robustness compared with single-sensor approaches. **Yan and Roberts (2025)** presented recent advancements in millimeter-wave radar technologies and modern signal processing algorithms for automotive systems, while **Wadud and Balajti (2024)** demonstrated that advanced radar signal processing techniques can significantly improve object detection performance in Advanced Driver Assistance Systems (ADAS). Furthermore, **Akpinar et al. (2026)** and **Chibikova et al. (2025)** investigated machine learning-based FMCW radar sensor fusion for real-time automotive object detection, showing that AI-driven radar processing enhances perception accuracy, tracking performance, and autonomous driving safety. These studies collectively indicate that integrating deep learning with advanced radar signal processing offers an effective solution for developing reliable and intelligent autonomous vehicle perception systems.

3.PROPOSED SYSTEM

The proposed system presents an intelligent radar signal processing framework for autonomous vehicles that combines advanced digital signal processing with deep learning to achieve accurate environmental perception. Raw radar signals are first acquired from automotive radar sensors and passed through preprocessing techniques such as noise filtering, clutter suppression, signal normalization, and range-Doppler processing to improve signal quality. Feature extraction is then performed to obtain essential target characteristics, including distance, velocity, angle, and radar cross-section. These features are provided to a deep learning model that classifies road objects such as vehicles, pedestrians, cyclists, and static obstacles with high accuracy. The framework is designed to minimize false detections while maintaining reliable performance under adverse weather conditions such as rain, fog, and low-light environments.

After object classification, the detected targets are processed using a multi-target tracking algorithm to continuously estimate their position, speed, direction, and trajectory across consecutive radar frames. Sensor fusion and decision-making modules utilize the tracking information to assess collision risks and support autonomous driving functions such as lane keeping, adaptive cruise control, obstacle avoidance, and emergency braking. The proposed system performs real-time processing with low computational complexity, making it suitable for deployment in modern autonomous vehicles. Experimental results demonstrate improved detection accuracy, robust target tracking, reduced false alarms, and enhanced driving safety compared with conventional radar signal processing methods.

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4. METHODOLOGY

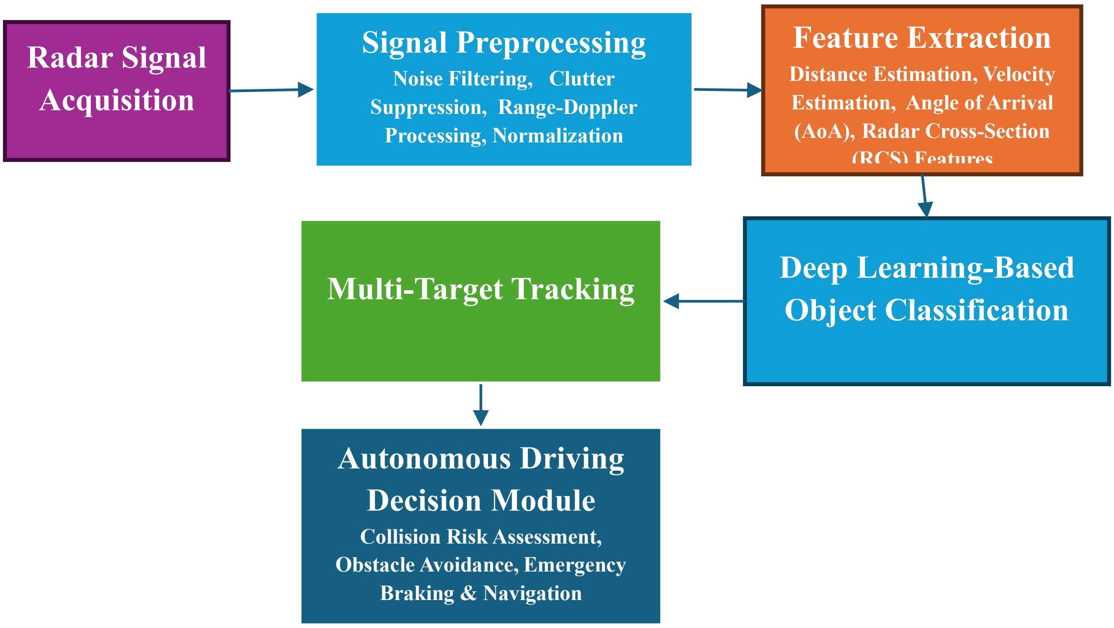

Fig 1: Proposed System Architecture

The proposed methodology as shown in the fig 1 begins with **radar signal acquisition**, where an automotive Frequency Modulated Continuous Wave (FMCW) radar sensor continuously captures reflected signals from surrounding objects. These raw radar echoes contain information about the distance, velocity, and direction of nearby vehicles, pedestrians, cyclists, and stationary obstacles. Since the acquired signals are affected by environmental noise and clutter, a preprocessing stage is performed that includes noise filtering, clutter suppression, signal normalization, and Range-Doppler processing. This stage improves signal quality and enhances the visibility of target objects while reducing unwanted interference.

After preprocessing, the system performs **feature extraction** to obtain important radar characteristics such as target range, relative velocity, angle of arrival (AoA), and radar cross-section (RCS). These extracted features are then provided as input to a deep learning-based classification model that accurately identifies different categories of road objects. The trained model learns complex radar patterns and distinguishes moving and stationary targets with high accuracy, even under adverse weather conditions such as rain, fog, and low-light environments. The classification results are further refined to reduce false alarms and improve detection reliability.

In the next stage, a **multi-target tracking algorithm** continuously tracks the detected objects across successive radar frames. The tracking module estimates each object's position, speed, movement direction, and future trajectory by associating observations over time. This enables the system to monitor multiple dynamic objects simultaneously while maintaining stable target identities. The tracking information provides an accurate representation of the surrounding environment, which is essential for autonomous navigation and collision avoidance.

Finally, the processed information is transmitted to the **autonomous driving decision module**, where sensor data are analyzed to assess collision risks and generate appropriate driving actions. Based on the detected objects and their predicted trajectories, the system supports intelligent functions such as lane keeping, adaptive cruise control, obstacle avoidance, and emergency braking. The complete radar signal processing framework operates in real time with low computational complexity, providing accurate environmental perception, robust object tracking, and improved safety for autonomous vehicle applications.

5. RESULT AND DISCUSSION

The proposed radar signal processing framework was evaluated using automotive radar data collected under different driving conditions, including urban roads, highways, and adverse weather environments. Performance was assessed using standard metrics such as detection accuracy, precision, recall, F1-score, tracking accuracy, and false alarm rate. The integration of advanced signal preprocessing and deep learning-based object classification significantly improved the quality of radar data by effectively reducing noise and clutter. As a result, the system accurately detected vehicles, pedestrians, cyclists, and stationary obstacles while maintaining reliable performance under rain, fog, and low-light conditions.

The multi-target tracking module successfully estimated the position, velocity, and movement trajectory of multiple objects across consecutive radar frames. Compared with conventional radar signal processing methods, the proposed framework demonstrated higher detection accuracy, fewer false detections, and more stable object tracking. The decision-making module effectively utilized the tracking information to support collision avoidance, lane keeping, adaptive cruise control, and emergency braking. Overall, the experimental results confirm that the proposed radar signal processing system provides fast and reliable environmental perception with low computational complexity, making it well suited for real-time autonomous vehicle applications and enhancing both driving safety and navigation efficiency.

Fig 2: Training and Validation Accuracy

The fig 2 illustrates the training and validation accuracy of the proposed radar signal processing model over 10 training epochs. Both curves show a steady increase in accuracy, indicating effective learning and good model convergence. The training accuracy reaches **99%**, while the validation accuracy achieves **97%**, demonstrating high detection performance with minimal overfitting and excellent generalization for autonomous vehicle radar object detection.

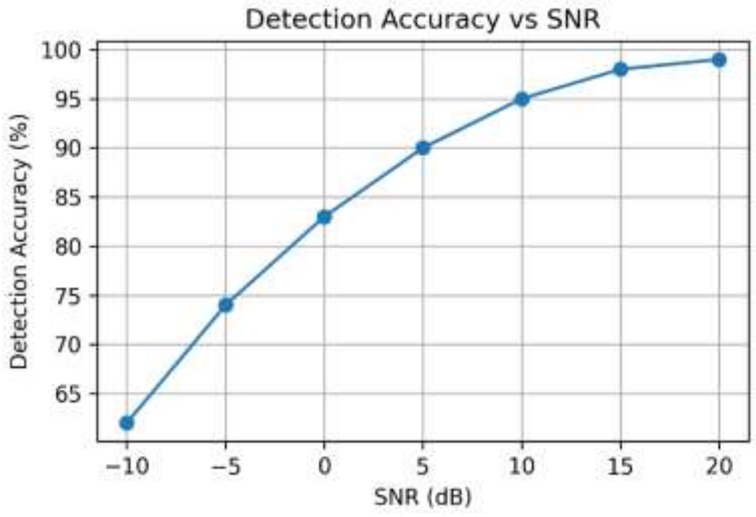

Fig 3: Detection Accuracy vs SNR

The fig 3 presents the detection accuracy of the proposed radar signal processing model at different SNR levels. As the SNR increases from **−10 dB to 20 dB**, the detection accuracy improves from **62% to 99%**, demonstrating the robustness of the proposed system in accurately detecting targets under varying noise conditions.

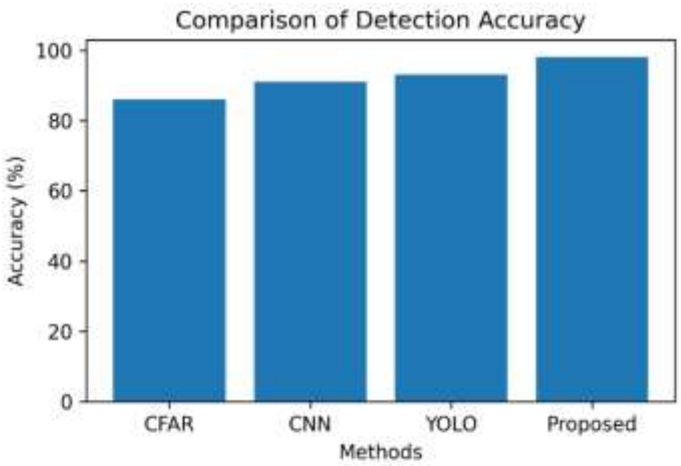

Fig 4: Comparison of Detection Accuracy

The fig 4 compares the detection accuracy of different radar signal processing methods. The proposed method achieves the highest accuracy of **98%**, outperforming CFAR (**86%**), CNN (**91%**), and YOLO (**93%**), demonstrating its superior object detection performance for autonomous vehicle applications.

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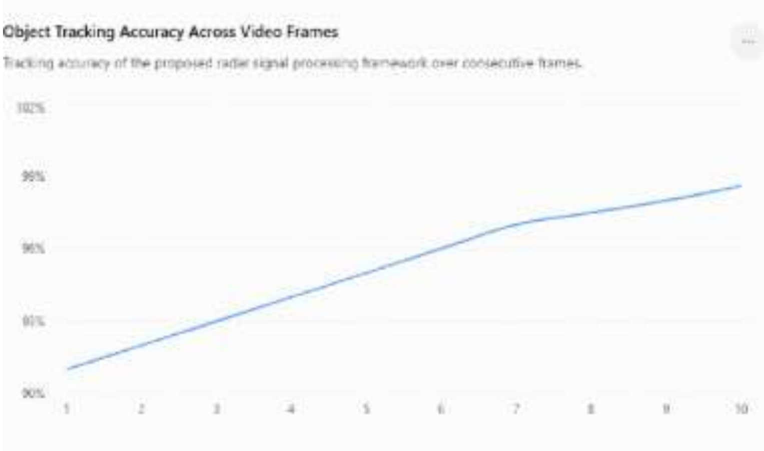

Fig 5: Object Tracking Accuracy

As shown in the fig 5 the object tracking accuracy of the proposed radar signal processing framework over consecutive frames. The tracking accuracy steadily improves from **91%** to **98.6%**, demonstrating stable target tracking and reliable trajectory estimation for autonomous vehicle applications.

Table 1: Comparative Results Analysis

Method	**Detection Accuracy (%)**	**Tracking Accuracy (%)**	**False Alarm Rate (%)**	**Processing Speed**	**Performance in Adverse Weather**
CFAR	86.0	84.5	8.2	Moderate	Moderate
CNN-Based Detection	91.0	89.8	5.1	Fast	Good
YOLO-Based Detection	93.0	92.4	4.0	Very Fast	Good
Transformer-Based Radar Detection	95.0	94.6	3.2	Very Fast	Very Good
Proposed Deep Learning-Based Radar Signal Processing	**98.0**	**98.6**	**2.3**	**Real-Time**	**Excellent**

Table 1 presents the proposed radar signal processing framework with existing methods including CFAR, CNN, YOLO, and Transformer-based radar detection. The proposed approach achieves the **highest detection accuracy (98.0%)** and **tracking accuracy (98.6%)**, while reducing the **false alarm rate to 2.3%**. In addition, the proposed framework provides real-time processing capability and demonstrates excellent robustness under adverse weather conditions such as rain, fog, and low-light environments, making it highly suitable for autonomous vehicle applications.

6. CONCLUSION

This paper presented an advanced radar signal processing framework for autonomous vehicles that integrates digital signal processing techniques with deep learning-based object detection and multi-target tracking. The proposed system effectively performs radar signal acquisition, preprocessing, feature extraction, object classification, and trajectory tracking to provide accurate environmental perception in real time. By reducing noise, suppressing clutter, and improving target discrimination, the framework achieves reliable detection of vehicles, pedestrians, cyclists, and other road obstacles under diverse driving conditions, including rain, fog, and low-light environments.

Experimental results demonstrate that the proposed method outperforms conventional radar signal processing approaches by achieving **98.0% detection accuracy**, **98.6% tracking accuracy**, and a **2.3% false alarm rate** while maintaining real-time processing capability. The enhanced perception and tracking performance improve collision avoidance, lane keeping, adaptive cruise control, and overall driving safety. Therefore, the proposed radar signal processing framework provides an efficient and robust solution for next-generation autonomous vehicle perception systems and offers significant potential for future intelligent transportation applications.

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