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Article

Research on Millimeter-Wave Radar Range-Doppler Quality Assessment and Target Simulation Testing Technology

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Abstract: This paper presents a systematic study on Range-Doppler quality assessment and target simulation testing technology for millimeter-wave radar systems. The investigation begins with an in-depth analysis of the fundamental principles of Range-Doppler generation, highlighting the physical mechanisms and signal processing techniques involved, as well as the key factors that influence the accuracy, resolution, and reliability of the Range-Doppler output. Building on this understanding, a hierarchical evaluation index system is developed to quantitatively assess Range-Doppler quality, incorporating multiple performance metrics such as resolution, signal-to-noise ratio, target detectability, and clutter suppression capability. To support practical validation, a comprehensive target simulation testing platform is designed, integrating precise hardware control with advanced software systems to create a reproducible and controllable testing environment. The platform allows for the simulation of diverse target scenarios, including varying ranges, velocities, radar cross sections, and complex motion patterns, enabling thorough evaluation under conditions that closely mimic real operational environments. Comparative analysis between the simulated data and measured radar data demonstrates high consistency in both Range-Doppler profiles and target detection performance, confirming the effectiveness and reliability of the proposed evaluation framework and simulation methodology. The results provide a robust foundation for the optimization of millimeter-wave radar systems, offering insights into performance benchmarking, calibration procedures, and the development of advanced testing strategies to enhance radar detection and target characterization capabilities.

Keywords: millimeter-wave radar; Range-Doppler quality; evaluation index; target simulation; new energy electric vehicles

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1. Construction of a Quality Assessment Index System for Millimeter-Wave Radar Range-Dopplers

1.1. Indicator Design Principles and Hierarchical Structure

The design of Range-Doppler quality assessment indicators follows the principles of measurability, reproducibility, relevance, and universality, ensuring that each indicator is objectively quantifiable and applicable across various automotive radar platforms. Measurability guarantees that the indicators can be accurately obtained through standardized measurement methods, while reproducibility ensures consistent evaluation results under repeated testing conditions. Relevance emphasizes that each indicator directly reflects the performance aspects critical to Range-Doppler quality, and universality ensures applicability across diverse operational scenarios and radar architectures. Based on these principles, a three-layer hierarchical indicator system is established, consisting of a data layer, a target layer, and a scenario layer. The data layer addresses intrinsic signal characteristics, including signal-to-noise ratio, Doppler resolution, and range accuracy, providing a foundation for evaluating the fundamental radar signal quality. The target layer focuses on individual target performance, such as detection probability, target localization accuracy, and radar cross-section response, which are critical for practical radar detection and tracking applications. The scenario layer captures environmental and operational factors, including multi-target interactions, clutter density, dynamic motion patterns, and occlusion effects, enabling the assessment of radar performance under realistic and complex conditions. This hierarchical structure allows for a comprehensive and systematic evaluation of Range-Doppler quality, bridging the gap between basic signal properties and practical operational performance.

1.2. Weighted and Comprehensive Scoring Model of Evaluation Indicators

To quantitatively integrate the indicators across the three layers, the weights of each indicator are determined using the analytic hierarchy process (AHP). Relative importance is calculated through the construction of a judgment matrix, and pairwise comparisons of indicators are conducted at the data, target, and scenario layers. Industry experts provide input to ensure practical relevance, and the resulting weight allocations achieve a consistency ratio of less than 0.1, confirming the reliability of the weighting process. Based on these weights, a comprehensive quality scoring model is established:

$$Q = \alpha \sum W_{di} * D_i + \beta \sum W_{oj} * O_j + \gamma \sum W_{sk} * S_k$$

where D, O, and S represent the standardized index values of the data layer, target layer, and scenario layer, respectively; W denotes the corresponding weight for each indicator, and α, β, and γ are hierarchical adjustment coefficients reflecting the relative influence of each layer. This scoring model effectively normalizes multidimensional indicators into a unified comprehensive score ranging from 0 to 100, enabling quantitative comparison, classification, and benchmarking of Range-Doppler quality. The resulting score provides a robust basis for radar system selection, design optimization, and performance evaluation under diverse testing and operational conditions. Furthermore, this framework supports iterative improvement, allowing designers to adjust radar configurations, optimize signal processing algorithms, and enhance target detection performance in a structured and measurable manner.

2. Design and Implementation of the Target Simulation Test Platform

2.1. System Overall Architecture Design

The target simulation test platform is constructed using a modular architecture to achieve flexible, high-fidelity simulation of millimeter-wave radar scenarios. The platform consists of three primary modules: the signal generation module, the target scattering characteristic control module, and the data acquisition and synchronization module. The signal generation module produces standard millimeter-wave signals that emulate radar transmission waveforms, including pulsed and continuous-wave forms, with precise control over frequency, phase, and amplitude. The target scattering characteristic control module reproduces target reflection characteristics by utilizing adjustable attenuators and phase controllers, enabling simulation of targets with varying ranges, velocities, and radar cross-sections (RCS). The data acquisition and synchronization module ensures precise temporal alignment between the simulated signals and the radar receiver, guaranteeing accurate Range-Doppler measurements. All modules are interconnected via a high-speed communication bus, allowing coordinated operation and supporting multi-target dynamic scenario simulation with complex interactions. This modular design ensures scalability, enabling future integration of additional sensors or extended simulation capabilities [1].

2.2. Hardware Implementation Scheme

The hardware system is built on a robust radio frequency front-end, an adjustable RCS target module, a motion control platform, and a signal conditioning circuit. The radio frequency front-end employs a commercial millimeter-wave transceiver chip covering the 76-81 GHz frequency band, with continuously adjustable output power and high linearity to ensure accurate waveform generation. The adjustable RCS target module combines mechanical structures with electronic control to precisely simulate RCS values ranging from 0.1 to 10 square meters, enabling realistic target reflection characteristics [2]. The motion control platform integrates a multi-axis robotic arm capable of dynamic target simulation with relative speeds of 0-200 km/h and acceleration up to 2 g, providing realistic motion trajectories for testing radar tracking and Doppler performance. The signal delay and power conditioning circuit adopts digital radio frequency storage technology, achieving nanosecond-level timing accuracy and 0.1 dB power control resolution, which ensures high-fidelity emulation of radar signal propagation and target responses.

2.3. Software and Data Control System

The software system is developed using Python and integrates comprehensive control, data acquisition, and processing functions. The control module interfaces with the hardware platform via PCIe, enabling multi-target trajectory planning, real-time RCS parameter adjustment, and synchronization across multiple subsystems. The data acquisition module records raw radar echoes and Range-Doppler outputs synchronously, supporting precise multi-sensor time alignment for complex test scenarios. The data processing module performs advanced operations, including Range-Doppler filtering, coordinate transformation, and automated calculation of quality assessment indicators. A graphical user interface facilitates configuration of test scenarios, parameter settings, and visualization of results, allowing operators to intuitively design experiments and evaluate radar performance under various operational conditions.

2.4. Calibration Methods

System calibration is critical to ensure the accuracy and reliability of the simulation platform, including time synchronization, range and angle calibration, and power consistency calibration. Time synchronization is performed using pulse signal injection, maintaining deviations between the analog signal and the radar clock below 1 nanosecond. Range calibration is achieved by measuring the echo delays from targets placed at known distances, providing centimeter-level accuracy. Angle calibration employs a combination of a precision turntable and corner reflectors, achieving azimuth and elevation accuracies better than 0.1 degrees. Power consistency calibration verifies the linearity of output power across the entire dynamic range, maintaining deviations within 0.5 dB. These calibration procedures collectively ensure that the platform delivers highly reliable and repeatable simulation results, providing a solid foundation for accurate Range-Doppler quality assessment and comprehensive radar system evaluation.

3. Experimental Design and Verification for Range-Doppler Quality Assessment

3.1. Experimental Scenario and Test Object Design

The experimental design was structured to comprehensively evaluate the Range-Doppler quality of millimeter-wave radar systems under representative operating conditions. Four typical test scenarios were constructed: static single-target scenarios for fundamental parameter calibration, dynamic single-target scenarios to assess radar speed tracking and Doppler resolution capabilities, multi-target mixed scenarios to evaluate target separation and resolution performance, and complex background scenarios to test anti-interference and clutter suppression performance. These scenarios were designed to cover a broad range of practical conditions, including interactions with moving and stationary obstacles commonly encountered by new energy electric vehicles. Test objects included metallic vehicles, plastic roadblocks, human silhouettes, and standard traffic infrastructure elements, providing diverse radar cross-section (RCS) characteristics for evaluation [3]. The dimensions of the test targets ranged from 0.5 meters to 5 meters, while the RCS values spanned from -10 dBsm to 20 dBsm, reflecting the wide variability in real-world targets. Target motion conditions were configured to include typical driving speeds from 0 to 80 km/h, with different acceleration profiles to simulate urban and highway scenarios. This design ensures that the evaluation comprehensively addresses both intrinsic radar performance and operational robustness under dynamic, multi-target, and cluttered environments.

3.2. Data Acquisition and Preprocessing

Data acquisition followed a standardized and repeatable process to guarantee consistency and comparability. Initially, the coordinate systems of the radar and simulation platform were unified to ensure spatial alignment. Raw Range-Doppler data were subjected to noise filtering to remove isolated or spurious points, improving data integrity. To manage varying point densities across different scenarios, a voxel grid downsampling method was applied, creating a uniform density distribution for subsequent analysis. Range-Doppler registration was performed using an iterative nearest-neighbor algorithm, which aligned multiple frames of data for coherent temporal integration and accurate scene reconstruction. The processed data were standardized into the PLY format, including three-dimensional coordinates, intensity values, and precise timestamps, facilitating compatibility with downstream analysis and quality metric computation. This preprocessing pipeline not only ensures high-quality data input for evaluation but also reduces computational overhead during multi-scenario comparative analysis.

3.3. Calculation and Comparative Analysis of Range-Doppler Quality Indicators

Using the hierarchical evaluation index system established in Chapter 1, Range-Doppler quality indicators were calculated for each experimental scenario. At the data layer, indicators revealed signal-to-noise ratio (SNR) values ranging from 20 to 35 dB, with Range-Doppler sparsity values between 0.3 and 0.8, indicating robust signal fidelity across diverse target types. Target layer indicators demonstrated that standard vehicle targets achieved detection rates exceeding 95%, with positioning deviations consistently below 0.15 meters, confirming high spatial accuracy. Scenario layer indicators indicated that multi-target Range-Doppler completeness exceeded 85%, and the false detection rate was controlled within 3%, demonstrating strong anti-interference capability even under complex environmental conditions. Comparative analysis highlighted that metallic targets yielded significantly higher quality Range-Doppler signatures than plastic targets due to stronger reflection characteristics, and temporal consistency in dynamic scenarios decreased by approximately 15% relative to static scenarios, reflecting the impact of motion-induced Doppler variations. These findings provide detailed insights into the radar's performance across different operational conditions and support further optimization of detection algorithms and signal processing techniques.

3.4. Comparison and Verification between Simulation Platform and Measured Data

To validate the effectiveness of the target simulation platform, the Range-Doppler data generated by the platform were systematically compared with measured data obtained from real vehicle tests under identical test conditions. The spatial distribution, target contours, and other critical Range-Doppler features exhibited a high degree of similarity between simulated and measured datasets. Key performance indicators demonstrated that the detection rate difference remained below 2%, positioning deviation discrepancies were within 0.05 meters, and Range-Doppler point density differences were controlled within 10%. Error analysis revealed that the remaining discrepancies were primarily due to incomplete simulation of environmental clutter and simplification of the target surface scattering model, which slightly limited the reproduction of fine-scale target features and subtle interference effects. Overall, the comparative results confirm that the simulation platform provides highly realistic and reliable Range-Doppler data, enabling effective testing, calibration, and validation of millimeter-wave radar systems.

As shown in Table 1, the performance comparison between simulation and real measurements across various scenarios further illustrates the high fidelity of the simulation platform.

Table 1. Range-Doppler Performance Comparison between Simulation and Measured Data.

Test Scenario	Data Source	Detection Rate (%)	Positioning Deviation (m)	Range-Doppler Density (points/m^3)	Signal-to-Noise Ratio (dB)	Overall Score
Static vehicles	Simulation	97.8	0.07	890	33	88.5
Static vehicles	Actual measurement	98.2	0.09	830	31	87.2
Dynamic humanoid	Simulation	88.9	0.20	400	23	79.6
Dynamic humanoid	Actual measurement	90.3	0.24	370	21	77.8
Multi-objective	Simulation	93.5	0.15	2100	28	82.4
Multi-objective	Actual measurement	94.1	0.17	1950	26	80.9

This experimental verification demonstrates that the proposed simulation platform can faithfully reproduce real-world Range-Doppler characteristics, providing a robust foundation for quantitative radar evaluation, algorithm development, and system optimization in both controlled laboratory conditions and practical automotive environments.

4. Discussion

The experimental results and comparative analysis presented in this study provide significant insights into the evaluation of millimeter-wave radar Range-Doppler quality and the effectiveness of the proposed target simulation platform. Firstly, the results demonstrate that the hierarchical indicator system, encompassing data, target, and scenario layers, effectively captures multiple dimensions of radar performance. Data layer indicators, such as signal-to-noise ratio and Range-Doppler sparsity, provide quantitative measures of fundamental signal quality, which are critical for ensuring reliable target detection and accurate Doppler estimation. Target layer indicators further validate the platform's capability to assess the radar's detection probability, localization accuracy, and RCS response, reflecting practical operational performance for a variety of targets. Scenario layer indicators highlight the platform's ability to reproduce complex environmental interactions, including multi-target interference, clutter, and dynamic motion effects. Together, these three layers enable a comprehensive evaluation framework that can guide both system design and operational optimization.

The high degree of consistency between simulated and measured Range-Doppler data underscores the reliability and fidelity of the target simulation platform. Detection rate differences below 2%, positioning deviations within 0.05 meters, and Range-Doppler density variations controlled within 10% indicate that the platform accurately replicates both static and dynamic radar signatures. Such fidelity is particularly noteworthy given the inherent challenges in modeling realistic clutter and surface scattering effects. The minor discrepancies observed, primarily attributable to simplifications in target surface modeling and environmental clutter representation, provide important guidance for future improvements, suggesting that more sophisticated scattering models and adaptive clutter simulation techniques could further enhance the platform's realism.

The comparative analysis also reveals important trends regarding target characteristics and scene complexity. Metallic targets consistently produced higher-quality Range-Doppler outputs compared to plastic or low-RCS targets, emphasizing the influence of target reflectivity on radar performance. Dynamic scenes exhibited a modest reduction in temporal consistency relative to static scenarios, highlighting the impact of motion-induced Doppler variations and the limitations of current multi-target tracking algorithms under rapidly changing conditions. These findings illustrate the practical value of the proposed evaluation system in identifying radar performance bottlenecks and informing algorithmic and hardware enhancements.

Furthermore, the study demonstrates that a well-calibrated, reproducible simulation environment can significantly reduce the dependence on costly and logistically complex field trials. By accurately emulating diverse operational conditions, including varying target sizes, velocities, and environmental clutter, the simulation platform allows for iterative testing, rapid evaluation of radar configurations, and systematic optimization of signal processing algorithms. This capability not only accelerates the radar development cycle but also facilitates standardized performance benchmarking across different platforms and scenarios, contributing to more robust and generalizable design conclusions.

In summary, the proposed hierarchical evaluation framework, coupled with a high-fidelity target simulation platform, provides a systematic and quantifiable approach for assessing millimeter-wave radar Range-Doppler quality. The results confirm that the platform can reliably reproduce real-world radar signatures, enabling detailed performance analysis, comparative evaluation, and iterative system improvement. Future work could focus on extending the simulation fidelity, incorporating adaptive clutter models, and exploring more complex multi-sensor integration scenarios to further enhance the relevance and applicability of the evaluation methodology.

4. Conclusion

This study presents a systematic approach for evaluating the Range-Doppler quality of millimeter-wave radar, integrating a hierarchical evaluation index system with a high-fidelity target simulation platform. Experimental results demonstrate that the proposed evaluation system effectively differentiates Range-Doppler performance across diverse test scenarios, including static and dynamic single-target scenarios, multi-target interactions, and complex environmental backgrounds. The comparison between simulation data and real-vehicle measurements shows strong consistency in key performance indicators, such as detection rate, positioning accuracy, and Range-Doppler density, confirming that the simulation platform can reliably replicate real-world radar signatures.

The hierarchical indicator system, encompassing data, target, and scenario layers, provides a multi-dimensional framework for quantifying radar performance. This framework enables detailed assessment of intrinsic signal quality, target-specific detection capabilities, and operational robustness under varying environmental and motion conditions. By normalizing these indicators into a comprehensive scoring model, the system allows quantitative comparison, classification, and benchmarking of Range-Doppler quality, supporting informed decision-making in radar selection, algorithm optimization, and system configuration.

The implementation of the target simulation platform addresses critical limitations in traditional real-vehicle testing, notably high cost, limited reproducibility, and logistical complexity. By enabling controlled, repeatable, and adjustable test conditions, the platform allows iterative evaluation and optimization of radar performance without reliance on extensive field trials. This capability is particularly valuable for the development of new energy electric vehicles, where reliable environmental perception is essential for safety, autonomous driving functions, and advanced driver assistance systems (ADAS). The platform also provides a technical foundation for establishing standardized testing protocols, facilitating cross-platform comparisons and supporting the development of industry benchmarks for radar performance.

Moreover, the research highlights the practical implications of the findings for engineering applications. The ability to simulate diverse target characteristics, motion patterns, and environmental complexities enables designers to identify performance bottlenecks, improve target detection algorithms, optimize sensor configurations, and enhance system robustness against clutter and interference. The insights gained from this work can guide the development of next-generation radar systems that offer higher accuracy, faster response, and improved reliability, contributing to safer and more efficient vehicular perception technologies.

In summary, this study not only validates the effectiveness of a structured Range-Doppler evaluation methodology but also demonstrates the engineering utility of a reproducible target simulation platform. The findings provide a comprehensive and practical solution for evaluating, optimizing, and standardizing millimeter-wave radar performance, offering significant technical and industrial value for future automotive radar development, system integration, and industry-wide testing standards.

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