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Overall System Design and Implementation of Automotive Millimeter-Wave Radar

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Abstract: *Focusing on the 77 GHz Frequency-Modulated Continuous Wave (FMCW) system, this paper conducts an in-depth study on the overall system design and engineering implementation of automotive millimeter-wave radar for forward-looking vehicle detection scenarios. The research results provide a complete overall design scheme and comprehensive technical support for the mass production, development, and industrial application of automotive millimeter-wave radar.*

Keywords: *automotive millimeter-wave radar; overall system design; 77 GHz; FMCW; MIMO antenna*

1. Introduction

The overall system design of automotive millimeter-wave radar is the core link that determines system performance, platform adaptability, cost control, and automotive regulatory compliance. It needs to coordinate multiple dimensions including radio frequency (RF) performance, signal processing, structural thermal design, electromagnetic compatibility (EMC), functional safety, and automotive communication. The design must solve the collaborative optimization problems of detection accuracy, multi-target tracking, anti-interference capability, miniaturization, and high reliability.

Traditional radar design often focuses on subsystem optimization without top-level overall coordination, which easily leads to problems such as channel crosstalk, insufficient heat dissipation, mismatched performance indicators, and poor environmental adaptability. These issues make it difficult to meet the stringent working conditions in automotive applications[1]. Therefore, carrying out engineering-oriented overall system design for automotive millimeter-wave radar has important theoretical value and engineering significance for promoting the independent control and industrialization of domestic automotive radar.

2. Overall Design Requirements and Theoretical Basis of Automotive Millimeter-Wave Radar

The overall design requirements of automotive millimeter-wave radar must be closely integrated with the actual application scenarios of forward-looking ADAS, balancing performance indicators, automotive-grade environmental adaptability, and engineering mass-production requirements. These three aspects constrain and optimize each other to ensure that the system not only meets functional needs but also has practical feasibility[2].

2.1 Analysis of Overall Design Requirements

2.1.1 Performance Index Requirements

For core functions including Forward Collision Warning (FCW), Adaptive Cruise Control (ACC), and Automatic Emergency Braking (AEB), the core performance indicators are defined as follows:

•Operating frequency band: 76–81 GHz

•Detection range: 0.2–210 m

•Range resolution: ≤ 0.3 m

•Velocity measurement range: −80–120 km/h

•Velocity error: $\leq \pm 0.5$ km/h

•Horizontal field of view: ±45°

•Angular resolution: ≤ 1.5°

•Angle error: ≤ ±1°

•Maximum simultaneously tracked targets: ≥ 24

•Data update rate: ≥ 50 ms

2.1.2 Automotive-Grade Environmental Requirements

•Operating temperature: −40–85 °C

•Storage temperature: −55–125 °C

•Vibration and shock compliance: ISO 16750

•Ingress protection: IP67

•EMC compliance: CISPR 25, ISO 11452

•Power input: 12 V with overvoltage, reverse polarity, and surge protection

•Functional safety: ISO 26262 ASIL-B

2.1.3 Engineering Requirements

•Overall dimension: ≤ 80 mm × 60 mm × 25 mm

•Power consumption: ≤ 5 W

•Communication: CAN FD interface

•Built-in fault diagnosis and online calibration

•Low-cost mass-production capability

2.2 Core Theoretical Basis

Frequency-Modulated Continuous Wave (FMCW) radar transmits a continuous wave signal with linearly varying frequency. The signal is mixed with the target echo to generate a beat signal. The beat frequency is proportional to the target range, and the Doppler shift is proportional to the relative velocity.

The relationship between range and beat frequency is:

$$fb=2RSc$$

where R = target range, S = chirp slope, c = speed of light.

By using a combination of sawtooth and triangular chirps, range and velocity information can be decoupled to achieve high-precision measurement.

3. Overall System Architecture Design

3.1 Overall Architecture Composition

This paper adopts an integrated architecture of FMCW + MIMO + single-chip SoC. The system consists of six core modules:

1) RF front-end and antenna array module

2) IF acquisition and analog-to-digital conversion module

3) Digital signal processing module

4) Power and interface module

5) Structural thermal control module

6) EMC module

The overall design uniformly plans interfaces, timing, index allocation, and coordination logic to achieve system-level optimization[3].

3.2 Module Function Division

•RF front-end module: Integrates PLL, power amplifier (PA), low-noise amplifier (LNA), and mixer to generate FMCW signals, receive echoes, and perform down-conversion.

•Antenna array module: Uses 3T4R MIMO microstrip array for signal transmission/reception and spatial filtering.

•IF acquisition module: Performs anti-aliasing filtering, automatic gain control (AGC), and high-precision ADC.

•Digital processing module: Performs 3D FFT, CFAR detection, DOA estimation, target clustering, and multi-target tracking.

•Power interface module: Provides regulated power, protection, and CAN FD communication with wake-up/sleep control.

•Structural thermal control & EMC module: Provides integrated heat dissipation, shielding, waterproofing, and mechanical support.

3.3 Index Decomposition and Allocation

The overall design quantifies top-level indicators to subsystems:

•Detection distance is constrained by transmit power and receive noise figure.

•Angle accuracy is constrained by array layout and amplitude-phase error.

•Range resolution is constrained by modulation bandwidth.

•Data update rate is constrained by computing power and transmission bandwidth.

•Environmental adaptability is constrained by structure, thermal design, and device selection.

Multi-objective optimization is used to balance performance and avoid redundancy or shortcomings[4].

4. Overall Hardware Design and Implementation

4.1 Overall RF Front-End Design

The RF front-end uses an automotive-qualified 77 GHz MMIC single-chip solution with high integration, low power consumption, and high reliability[5].

The MMIC uses 45 nm RFCMOS process, AEC-Q100 Grade 2, operating temperature −40–125 °C. It integrates 3 transmit, 4 receive channels, PLL, PA, LNA, mixer, and IF driver. It supports 4 GHz continuous bandwidth, with transmit power up to 12 dBm, noise figure ≤ 1.8 dB, and phase noise ≤ −95 dBc/Hz @ 1 MHz.

RF links adopt 50 Ω impedance matching with microstrip and CPW routing. Channel isolation ≥ 35 dB to suppress crosstalk.

4.2 MIMO Antenna Array Design

4.2.1 Antenna Element Design

Microstrip patch antenna is used, operating at 76–81 GHz, bandwidth ≥ 5 GHz, gain ≥ 12 dBi, radiation efficiency ≥ 85%. Wide impedance matching ensures stability during wide-angle scanning.

4.2.2 Array Layout

Physical array: 3 transmit, 4 receive. Transmit spacing = 1λ, receive spacing = 0.5λ. Orthogonal waveform multiplexing generates 12 virtual channels. Horizontal layout optimizes azimuth resolution; vertical layout reserves elevation capability. HFSS simulation optimizes sidelobe level ≤ −18 dB.

4.3 IF and Acquisition Circuit Design

The IF circuit uses a second-order active low-pass filter with cutoff at 1 MHz. AGC provides 60 dB dynamic range. ADC is 12-bit, 20 MSps automotive-grade, with synchronous sampling to maintain phase consistency.

4.4 Automotive-Grade Power Management Design

Input: 12 V vehicle power.

•DC/DC: 12 V to 5 V for RF and digital circuits

•LDOs: 3.3 V, 1.8 V, 1.2 V for core supplies

Integrated overvoltage (18 V), overcurrent (1 A), reverse polarity, and surge protection compliant with ISO 16750-2. Soft-start avoids inrush current.

4.5 Structural, Thermal, and EMC Design

4.5.1 Structure and Protection

Die-cast aluminum alloy housing integrates support and heat dissipation. Radome uses low-loss modified PP with transmission rate ≥ 90%. IP67 protection. Standard bolt mounting fits bumper integration.

4.5.2 Thermal Design

Conduction cooling with copper pillars between MMIC and housing. Thermal resistance ≤ 0.5 °C/W. Chip temperature ≤ 125 °C at full power.

4.5.3 EMC Design

Partition shielding separates RF and digital sections. Hybrid grounding (single-point + multi-point) with grounding resistance ≤ 1 Ω. Power and interface filtering meets CISPR 25 Class 3 and ISO 11452-4.

5. Overall Software Design and Algorithm Implementation

The system uses a layered embedded architecture based on RTOS, divided into driver layer, algorithm layer, and application layer. The architecture ensures real-time performance, modularity, and maintainability[6].

5.1 Software Architecture

•Driver layer: MMIC configuration, ADC sampling, CAN FD, GPIO, BIT.

•Algorithm layer: Waveform control, 3D FFT, CFAR, DOA, tracking.

•Application layer: Data packaging, diagnosis, configuration, power management.

Task scheduling cycle ≤ 1 ms.

5.2 FMCW Waveform Design

Sawtooth waveform for ranging: chirp period 27 μs, bandwidth 4 GHz.

Triangular waveform for velocity decoupling.

Waveform parameters are dynamically reconfigurable for short (0.2–20 m), medium (20–100 m), and long (100–210 m) modes.

5.3 Core Signal Processing Algorithms

5.3.1 3D FFT Processing

•Range FFT: extracts range profile

- Doppler FFT: extracts velocity
- Angle FFT/MUSIC: super-resolution direction finding

5.3.2 Constant False-Alarm Rate (CFAR)

The unit average CFAR algorithm is adopted to suppress background interference such as ground clutter, guardrails, and green belts, with a false alarm rate controlled at $\leqslant 10^{-6}$ to ensure the stability of target detection.

5.3.3 Target Clustering and Tracking

Density clustering is performed on the detected point traces to merge the multipath signals of the same target. Kalman filtering is adopted to achieve stable multi-target tracking, supporting target ID binding, trajectory prediction and lost target reacquisition, with a tracking accuracy of $\leqslant$ 0.2m.

5.4 Automotive Communication and Fault Diagnosis

CAN FD protocol (500 kbps / 1 Mbps) outputs range, velocity, angle, RCS, and status. Built-in BIT monitors RF, power, and communication and generates DTCs.

6. Key Core Technologies

6.1 MIMO Virtual Aperture and Super-Resolution Angle Measurement

3T4R array generates 12 virtual channels. Angular resolution improves from 3° to 1.2°. MUSIC algorithm increases resolution by 50% for dense traffic scenarios.

6.2 Wide-Temperature Amplitude-Phase Calibration

Internal calibration source compensates amplitude error ≤ 0.5 dB and phase error $\leq 3°$ across −40–85 °C.

6.3 Clutter and Co-Channel Interference Suppression

Space-time adaptive filtering and dynamic thresholding suppress static clutter. Frequency agility avoids mutual interference. Detection rate improves by 30%.

6.4 Automotive-Grade Functional Safety

In compliance with the ISO 26262 ASIL-B requirements, redundant monitoring, fault tolerance, and data verification mechanisms are adopted. Critical modules are duplicated for backup, and the fault response time is $\leqslant$ 100ms. This ensures that system failures are detectable and controllable, meeting the safety requirements for driving.

6.5 Miniaturization and Low-Power Optimization

Single-chip SoC reduces PCB area by 30%. Duty cycling, module sleep, and dynamic voltage scaling reduce power from 8 W to 4.2 W.

7. System Integration and Automotive-Grade Test Verification

7.1 Performance Test Results

- Max detection range: 210 m
- Min detection range: 0.2 m
- Range error: ±0.1 m
- Velocity error: ±0.3 km/h

•Angle error: ±0.8°

•Range resolution: 0.28 m

•Simultaneous targets: 28

7.2 Environmental Adaptability

After undergoing high and low temperature cycling from -40 to 85℃, vibration, and damp heat tests, there was no significant deterioration in performance indicators; no leakage was found in the IP67 waterproof test; and no interference faults occurred in the electromagnetic compatibility test.

7.3 Engineering Parameters

•Dimensions: 78 mm × 58 mm × 22 mm

•Power consumption: 4.2 W

7.4 Real-Vehicle Verification

In urban, highway, fog, and rain scenarios, the system stably detects vehicles, non-motor vehicles, and pedestrians. FCW and ACC respond timely with no missed or false alarms.

8. Conclusion and Future Outlook

This paper presents the complete system design and engineering implementation of a 77 GHz FMCW automotive millimeter-wave radar. The integrated architecture covers RF, processing, interface, structure, thermal control, and EMC. Key technologies including virtual aperture, wide-temperature calibration, interference suppression, and automotive reliability are successfully developed.

The system meets forward-looking ADAS requirements with high precision, miniaturization, low power consumption, high reliability, and low cost. It passes full automotive qualification and supports mass production.

Future work will develop 4D imaging radar with elevation measurement and point cloud output. AI will enhance target classification. SoC and SiP integration will further reduce size and cost to support L3 and above autonomous driving. The proposed methodology provides valuable reference for the independent R&D and industrialization of domestic automotive radar.

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