Signal Processing, Optimization, and Multi-Modal Fusion for Next-Generation Automotive FMCW Radar Systems

Keywords: FMCW radar signal processing, super-resolution, range–Doppler coupling, interference suppression, integrated sensing and communication, optimal time partitioning, direction of arrival, multi-modal sensor fusion.

Abstract: Sensors form the backbone of intelligent and autonomous vehicles, enabling accurate perception and environmental understanding under diverse operating conditions for safe navigation. Among the various sensing modalities used in modern vehicles, frequency modulated continuous wave (FMCW) radar has emerged as a key component in advanced driver assistance systems (ADAS) due to its capability to estimate target range, velocity, and angle. Moreover, their operation is robust under adverse weather and poor illumination conditions. Nevertheless, FMCW radar systems remain constrained by range–Doppler coupling, limited angular resolution, mutual interference, and the competing requirements between sensing and communication resources in integrated sensing and communication (ISAC) operation. Furthermore, integration of radar with complementary sensors such as lidar and camera can considerably enhance overall perception and environmental understanding.

This dissertation advances automotive radar along three major thrust areas: (i) radar signal processing for super-resolution and interference mitigation, (ii) ISAC optimization and collaborative radar systems, and (iii) radar-aided multi-modal sensor fusion for enhanced perception in autonomous driving systems, to address the critical challenges associated with FMCW radar-based autonomous/intelligent driving systems aimed at improving sensing accuracy, robustness, and resource efficiency. At the signal processing level, this dissertation develops advanced super-resolution and interference suppression frameworks to overcome the fundamental challenges inherent to FMCW radars used in automotive applications. Specifically, a reweighted decoupled atomic norm minimization (RMAN) method for joint range–velocity estimation in the presence of range-Doppler coupling and a signal decomposition-based method named VAFER to mitigate interference through variational mode decomposition, Fourier synchrosqueezed transform, and energy–entropy–based thresholding. Furthermore, a Hough transform and time–frequency ridge (HTFR) approach is proposed for the geometric separation of interference and target components in the time–frequency domain. At the system level, this dissertation studies the prospect of designing an optimal time-partitioning (OTP) scheme for vehicle-to-vehicle ISAC and proposes a distributed MIMO-FMCW radar system (DMFRS) for angular super-resolution through coordinate transformation-based fusion and sparse Bayesian learning. The final part of this dissertation explores radar-aided multi-modal frameworks that integrate data from radar, lidar, and camera sensors for robust perception and human-like end-to-end driving systems. We introduce multi-modal attention-based networks (MMA-Net and PyramidCMA) that integrate radar, lidar, and camera data for robust perception and end-to-end driving.

The proposed analytical frameworks in the dissertation are mathematically simulated and evaluated against state-of-the-art methods, demonstrating clear improvements in sensing accuracy, interference suppression, and perception performance. Overall, the proposed frameworks collectively advance FMCW radar systems across signal processing, system-level optimization, and multi-modal perception, contributing to the development of reliable, resource-efficient, and intelligent autonomous driving systems.