ABSTRACT

Millimetre-wave (mmWave) radars have emerged as a compelling sensing modality for next-generation cyber-physical systems due to their robustness to illumination variations, resilience against occlusion and clutter, and their intrinsic privacy-preserving characteristics. Operating in the 77-81 GHz bands with Frequency-Modulated Continuous-Wave (FMCW) signalling, modern mmWave radars capture rich micro-Doppler dynamics, fine-grained phase evolution, and geometric reflections, enabling detailed characterization of human motion, vehicular dynamics, and complex spatial interactions. However, despite rapid advances in hardware, several environment-specific challenges continue to constrain the deployment of mmWave radars in real-world settings. These challenges manifest across diverse domains: severe cabin multipath and vibration in automotive environments, high Doppler resolution requirements in indoor micro-activity sensing, sub-Doppler motion ambiguity in ego-motion estimation, and viewpoint-induced distortions in multi-radar cooperative sensing.

This thesis develops a unified set of signal-processing methods, adaptive radar representations, and learning-based perception pipelines to address these challenges across four distinct but complementary sensing scenarios. First, we propose *mmDrive*, an in-cabin radar-based system for passive monitoring of dangerous driving behaviors. Through a combination of jitter-compensated range-Doppler estimation, motion filtering, and fused spatio-temporal deep learning, mmDrive robustly identifies behaviours such as nodding, steering anomaly, picking drops, under road-induced vibration and multipath, using only commodity automotive radars. Second, for room-scale human sensing, we present *MARS*, a framework that systematically characterizes Doppler resolution requirements for micro-activities and in-

troduces adaptive chirp configurations, multi-resolution activity classification, and cross-room generalization, enabling accurate tracking of subtle human motions in cluttered indoor environments.

Third, this thesis addresses the fundamental limitation of Doppler-only radar odometry by introducing *RadarTrack*, a phase-based ego-motion estimation system that leverages phase evolution of static reflectors to recover translational velocity in sub-Doppler regimes. RadarTrack fuses phase-derived velocity with geometric cues from radar point clouds to generate accurate full-trajectory estimates, even at speeds below the radar's intrinsic velocity resolution. Finally, we present *MIRO*, a multi-radar cooperative sensing framework for worker monitoring and occupational safety. MIRO resolves cross-radar identity mismatch arising from viewpoint changes by integrating activity-correlated re-identification with a generative view-adaptation network capable of transforming range-Doppler signatures across different radar perspectives, enabling continuous multi-radar tracking and personalized pollution exposure estimation in harsh industrial environments.

Together, these contributions advance a principled understanding of next-generation mmWave sensing across automotive and human-centric environments by revealing how radar signals evolve under diverse motion scales, environmental conditions, and sensing geometries. Rather than focusing solely on isolated applications, this thesis establishes a cohesive methodological foundation that bridges signal processing, adaptive radar representations, and learning-based perception to enable robust, scalable, and environment-aware mmWave sensing. By addressing fundamental challenges spanning in-cabin monitoring, indoor human activity analysis, ego-motion estimation, and cooperative multi-radar systems, this work positions mmWave radar as a versatile, privacy-preserving, and generalizable sensing modality for intelligent transportation systems, human-centered indoor analytics, robotics, and industrial safety deployments.

Keywords: mmWave radar, FMCW sensing, driver monitoring, micro-activity recognition, radar odometry, phase-based motion estimation, multi-radar re-identification, occupational safety.