

4D Millimeter Wave MIMO Radar System Design and Its Applications in Home Environments

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Abstract—Millimeter-wave radar has shown strong potential for unobtrusive health monitoring in home environments due to its non-contact, privacy-preserving, and penetrative sensing capability. This report summarizes recent work on 4D MIMO radar system design and its applications in vital sign monitoring and arrhythmia screening. The work includes a high-resolution MIMO radar array design method for subspace-based angle estimation, a 4D vital sign detection technique for multi-posture sleep monitoring, and a knowledge-fusion deep learning framework for premature beat classification. Experimental results demonstrated improved angular resolution, robust overnight heart-rate monitoring across different sleep postures, and accurate classification of normal beats, PAC, and PVC. These studies highlight the potential of millimeter-wave radar for continuous cardiopulmonary monitoring and early cardiac risk screening.

Index Terms—millimeter-wave radar, multiple-input-multiple-output radar, antenna array, vital sign monitoring.

I. INTRODUCTION

CARDIOVASCULAR diseases remain a major global health burden, causing substantial mortality and long-term disability worldwide [1]. Among them, arrhythmias are particularly important because they are often intermittent and difficult to capture during short clinical examinations, making long-term continuous monitoring essential for early detection and intervention.

In recent years, millimeter-wave radar has emerged as a promising unobtrusive sensing modality for home-based cardiopulmonary monitoring, owing to its non-contact, privacy-preserving, and penetrative sensing capability. By detecting subtle chest-surface motions induced by respiration and heartbeat, it enables continuous physiological monitoring without attaching electrodes or requiring active user participation. To advance this vision, three key conditions are required: first, a high-resolution 4D MIMO radar hardware system with optimized waveform and array design; second, robust signal processing and sensing algorithms for reliable vital sign extraction under realistic home conditions; and third, application-oriented intelligent methods for clinically relevant tasks, such as posture-aware monitoring and arrhythmia screening. Guided by these objectives, this project has focused on both radar system design and health-oriented sensing applications.

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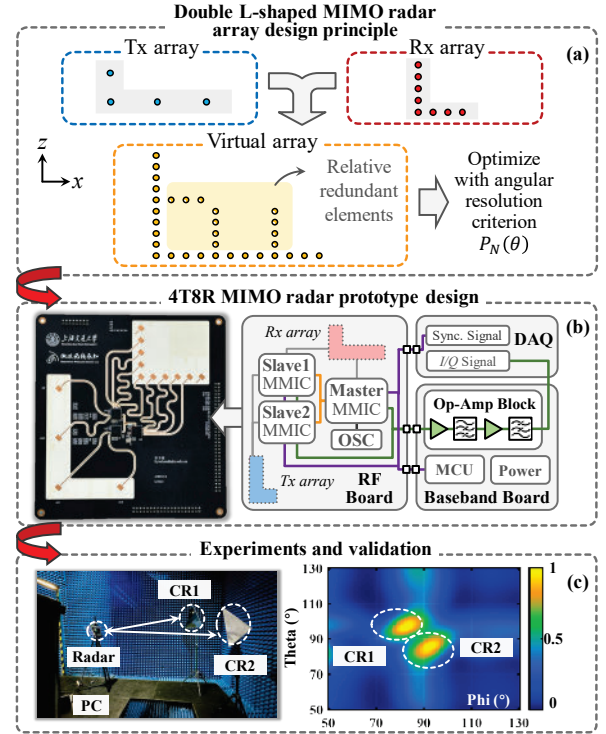


Fig. 1. Overall framework of the double L-shaped MIMO radar array design.

II. HIGH-RESOLUTION MIMO RADAR SYSTEM DESIGN

A high-resolution 4D MIMO radar hardware design method was developed for subspace-based direction-of-arrival (DOA) estimation [2]. Since angular resolution is fundamentally determined by the virtual aperture distribution, different array configurations were analyzed in terms of aperture utilization, angular discriminability, and noise robustness. As shown in Fig.1, an angular resolution discriminant was introduced to quantitatively evaluate 1D and 2D array structures, and the role of redundant elements in virtual aperture formation was further investigated. Based on this analysis, a double L-shaped transmit–receive array configuration was proposed, in which both arrays adopt identical L-shaped layouts to construct a virtual aperture with favorable super-resolution performance in both theta and phi dimensions. A 4T8R MIMO radar prototype was designed and fabricated. Experimental results showed that the developed system achieved angular resolutions of 8.4° and 6.1° in the theta and phi planes, respectively. Indoor multi-target experiments further verified its effectiveness for high-resolution target separation in confined environments, providing a hardware and theoretical foundation for home scenarios sensing applications.

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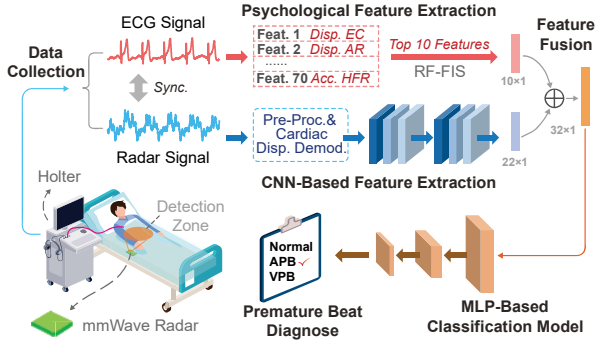


Fig. 2. Overview of the proposed knowledge-fusion deep learning framework for premature beat classification based on radar and ECG signals.

III. MULTI-POSTURE VITAL SIGN MONITORING IN SLEEP SCENARIOS

A 4D vital sign detection method was proposed for unobtrusive cardiopulmonary monitoring in sleep scenarios, where posture variation is a major challenge. By jointly exploiting the angular sensing capability of MIMO radar and the range discrimination capability of FMCW radar, the method enables simultaneous 3D spatial localization and 1D temporal tracking of physiological motion [3]. Compared with conventional beamforming-based approaches, the proposed method more accurately localizes the cardiac motion source and improves the extraction of subtle heart-induced chest movements under different sleeping postures. A custom-designed 2T4R FMCW MIMO radar prototype was developed for experimental validation, and overnight tests were conducted under supine, lateral, and prone postures. Experimental results showed that the proposed method could reliably locate the heart region across different sleep positions, with an effective overnight heart-rate detection time exceeding 92% and an average heart-rate error of 1.5 bpm. These results demonstrate the feasibility of posture-robust, medical-grade heart-rate monitoring using millimeter-wave radar in realistic home sleep environments.

IV. RADAR-BASED ARRHYTHMIA DETECTION

A knowledge-fusion deep learning framework was developed for arrhythmia-oriented analysis of millimeter-wave radar signals, with particular focus on premature beat classification [4]. As shown in Fig2, the objective of this work was to move radar sensing beyond conventional vital sign estimation toward clinically meaningful screening and early diagnosis. To this end, radar waveform features and clinically informed knowledge features were jointly incorporated into a unified classification framework. A CNN-based neural network was employed to extract discriminative representations from radar signals, while auxiliary knowledge-driven features derived from synchronized ECG signals were introduced to enhance the model's ability to capture rhythm-related characteristics and improve interpretability. Based on this framework, a custom-designed 60 GHz FMCW radar prototype was used in clinical trials, and a dataset containing 2,000 signal segments from 250 subjects was established for evaluation. The results are shown in Fig.3 and Fig. 4. The proposed method achieved an overall classification accuracy

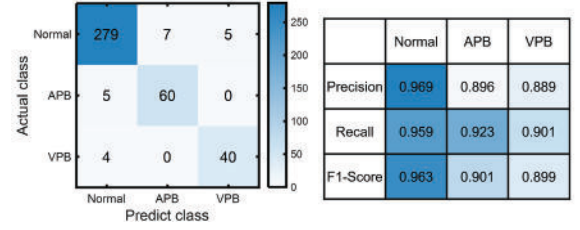


Fig. 3. Confusion matrix and classification accuracy on the test set

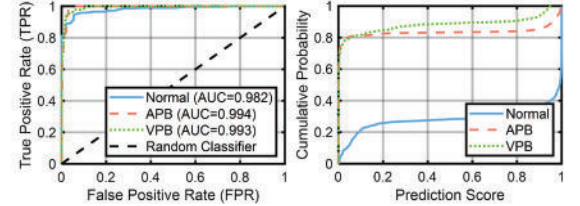


Fig. 4. Performance evaluation of the classification model: (a) ROC curves and (b) CDF curves for each class.

94.75% and an F1-score of 0.924 in distinguishing normal beats, premature atrial contractions (PAC), and premature ventricular contractions (PVC). The results demonstrate that non-contact millimeter-wave radar, when combined with knowledge-guided deep learning, can effectively identify clinically relevant premature beat types and may provide a promising technical route for long-term home-based arrhythmia screening and early warning.

V. CAREER PLAN AND MTT FELLOWSHIP IMPACT

I plan to continue my academic career, focusing on high-resolution millimeter-wave MIMO radar systems and their applications in health monitoring. With the developments in radar technology, more detailed physiological waveforms related to cardiac activity and chronic cardiovascular diseases may become accessible, creating new opportunities for continuous monitoring and early warning of cardiovascular risks. For a young researcher, receiving the IEEE MTT Graduate Fellowship is a great encouragement. It has supported my radar fabrication and experimental research, and has further strengthened my confidence in continuing in this field. It has also helped me engage more deeply with the MTT society through conferences and activities such as IEEE APCAP and IEEE APMC.

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