Tangential Velocity Measurement with Low-Cost mmWave Radar Assisted with Metasurface

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Abstract

Speed measurement is vital for target motion detection, but low-cost millimeter-wave radars, which are widely used in mobile platforms, lack tangential velocity measurement. This deficiency leads to inaccurate trajectory prediction and even increases collision risks. Existing solutions fail due to these radars' limited antenna aperture. This paper proposes *MultiFusion*, a hardware-software co-designed system. On the software side, it leverages multipath signals and fuses velocity information from both direct and multipath signals to calculate accurate tangential velocity. On the hardware side, it adopts a 77–81 GHz passive reflective metasurface, enabling uniform energy distribution over a wide angular range regardless of incident angle, and ensuring no prior environmental knowledge or in-situ reconfiguration is needed.

CCS Concepts

• **Hardware** → **Wireless devices**; **Sensor applications and deployments**.

Keywords

MmWave Sensing, Tangential Velocity Measurement, Metasurface Technology

1 Introduction

Speed measurement is critical for target motion detection, enabling target trajectory prediction and supporting various applications. Nowadays, low-cost millimeter-wave radars are widely deployed on diverse mobile platforms (e.g., robots, ground vehicles). However, these devices can only obtain radial velocity (target motion toward/away from the radar along the line of sight) and cannot directly measure tangential velocity (target lateral motion relative to the radar's detection axis). Both are vital for target motion detection: without tangential velocity information, real-time accurate trajectory prediction becomes challenging, causing delayed or incorrect judgments and even elevated collision risks.

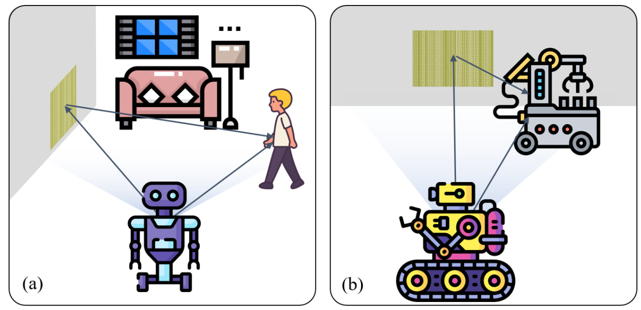

Figure 1: Illustration of the applications of tangential velocity information: (a) avoiding collisions with pedestrians and (b) facilitating cooperation among robots

Existing solutions, including measuring angular rate and interferometric processing [1], are inapplicable to low-cost millimeter-wave radars due to limited antenna aperture. We thus ask: *Can low-cost millimeter-wave radar measure tangential velocity at a resolution comparable to radial velocity?*

This paper presents *MultiFusion*, a low-cost radar-based system answering the question. Via hardware-software co-design, it addresses the following challenges:

Challenge 1: Limited antenna aperture. Reliance solely on low-cost radar technologies is inadequate for achieving this objective, primarily due to the limited antenna aperture inherent in such systems, which restricts angular resolution and fails to provide tangential velocity with sufficient precision.

Software Design: Utilize multipath signals with key information. Millimeter waves typically experience multipath effects during propagation, and our key insight is that multipath signals carry significant information: (i) *spatial characteristics of environmental reflectors*, and (ii) *projected velocity components*. By fusing velocity information from both direct and multipath signals, it allows for solving the full velocity vector, providing tangential velocity with resolution comparable to radial velocity.

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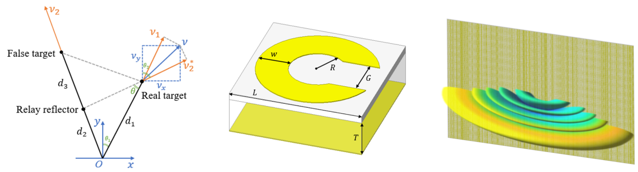


(a) Geometric model (b) Meta-atom structure model (c) Metasurface codebook

Figure 2: The overview and design concepts of *Multi-Fusion*

For unknown environments, we first need to establish the geometric model among reflectors, false targets, and real targets, and obtain velocity component included angles before fusing velocity information. We accomplish these tasks through three mechanisms: *multipath signal identification mechanism*, *approximate matching and angle estimation mechanism*, and *fusing mechanism*—ultimately enabling the accurate tangential velocity calculation with resolution comparable to radial velocity.

Challenge 2: Limitations of natural reflectors. Most of the energy incident on such reflectors undergoes specular reflection, causing weak backscatter signals, which hinders accurate reflector positioning and the establishment of the aforementioned geometric model. Furthermore, for radars at specific incident angles, a large portion of the energy propagates along specular reflection paths, restricting the angular coverage of environmental perception.

Hardware Design: Passive mmWave metasurface. To overcome the limitations of natural reflectors, we need to deploy additional reflectors, which must meet two requirements: (i) *functional requirements*: enhancing backscatter signals and expanding outgoing signal angle coverage regardless of incident angles; (ii) *low-cost deployment*: low manufacturing cost, compact size, and no prior environmental knowledge or in-situ reconfiguration.

We propose a passive reflective metasurface operating within the 77–81 GHz frequency band, which matches the radar's working spectrum. Through the elaboration of the meta-atom geometry and metasurface codebook design, this device meets the above requirements.

2 Design Overview

2.1 Software Design

We assume the system operates in an unknown environment with a static radar, and consider 2D scenarios for simplicity.

Multipath Signal Identification Mechanism. Multipath signals inherently carry (i) *spatial characteristics of environmental reflectors*, such that false targets induced by the multipath effect are situated behind real targets or relay reflectors along the line of sight. Besides, if a real target possesses a tangential velocity, the resulting false targets will be dynamically distinct and contain (ii) *projected velocity components*. To distinguish targets from the environment, dynamic point clouds are separated from static ones. To determine whether these dynamically distinct point clouds correspond to multipath signals, we analyze them by checking for the presence of a static point cloud in their foreground.

Approximate Matching and Angle Estimation Mechanism. Considering direct return signals and secondary reflection signals, low-cost millimeter-wave radars suffer from limited angular resolution, which introduces errors in the estimated angles of arrival (AOA) for both real and false targets-for example, the estimated AOAθ_1 of a real target. In contrast, the relative error in range estimation via range FFT is smaller. After approximate matching based on angle and range information in accordance with the law of cosines, we establish the geometric model among reflectors, false targets, and real targets. Then, we achieve more accurate included angle θ estimation using only range information.

Fusing Mechanism. Given both the projection velocities v_1 of the direct and v_2^* of multipath return signals, along with their included angle θ, the full velocity v of the target can be derived in accordance with the following equation:

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} \sin\theta_1 & \cos\theta_1 \\ \sin\theta_2 & \cos\theta_2 \end{bmatrix}^{-1} \begin{bmatrix} v_1 \\ v_2^* \end{bmatrix} \tag{1}$$

where θ_1 and θ_2 are the angles corresponding to the direct and multipath signals, respectively, and relate to θ.

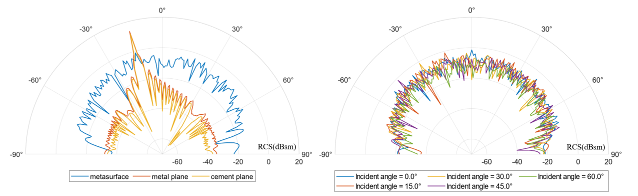
2.2 Hardware Design

Meta-Atom Geometry. A passive metasurface operating within the 77–81 GHz frequency band is proposed herein, wherein each meta-atom comprises a split-ring resonator (SRR) fabricated through hot stamping, a metallic ground plane, and a dielectric layer integrating paper and an air interlayer, which is inspired by Automs [2]. Precisely controlling SRR geometric parameters (radius R, gap G, width W) achieves full 2π phase shift coverage for incident waves. Tuning air interlayer thickness T ensures electromagnetic energy is mainly manipulated by the SRR, minimizing substrate-induced losses. We systematically discretize the design space into 18 distinct meta-atom configurations based on SRRs.

Metasurface Codebook. The codebook of the metasurface is designed to satisfy the following criteria: (i) *uniform energy distribution over a wide angular range*; (ii) *radiation pattern invariant to incident angles*, thus meeting the *functional requirements*.

The meta-atoms on the metasurface impart additional phase shifts $\delta(x, y)$ to the incident wave, and inspired by angular spectrum theory, we envision that if we can achieve the following condition:

$$|A_o(k_x, k_y)| \equiv A_0 \tag{2}$$



(a) Radiation patterns of metasurface vs. natural reflectors (b) Metasurface Radiation Patterns at Diverse Incident Angles

Figure 3: Simulation results of metasurface performance

where $|A_o(k_x, k_y)|$ is the amplitude of the angular spectrum of the outgoing wave, k_x and k_y are related to the propagation direction of the plane wave by $k_x = k \sin\theta \cos\phi$ and $k_y = k \sin\theta \sin\phi$, θ is the polar angle, ϕ the azimuthal angle, of the outgoing wave, and A_0 is a constant, the metasurface could be designed to satisfy the above criteria. In a 2D scenario where $\phi = 0$, we only need to satisfy

$$|A_o(k_x, 0)| \equiv A_0 \tag{3}$$

where $k_x = k \sin\theta$. Given that the angular spectrum $A_o(k_x, k_y)$ can be obtained via the 2D Fourier transform of the outgoing wave $E_o(x, y)$, we use the gradient descent method to minimize the L2-norm objective function to achieve the design target, with the value of A_0 consistent with Parseval's theorem.

Functional Requirements. We conducted simulations using HFSS. Fig.3 (a) shows that, compared with natural reflectors such as metal planes or cement planes with the same size, the metasurface can achieve better (i) *uniform energy distribution over a wide angular range.* Fig.3 (b) further demonstrates that for different incident angles, the metasurface can achieve nearly consistent radiation patterns, satisfying (ii) *radiation pattern invariant to incident angles.*

Low-cost Deployment. The metasurface is fabricated using easily accessible materials, enabling low-cost manufacturing. With a thickness of less than 1mm, it achieves a compact size. The versatility of the metasurface configuration eliminates the need for prior environmental knowledge or in-situ reconfiguration. Ultimately, these advantages collectively enable its *low-cost deployment.*

Acknowledgments

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