# PhD Forum Abstract: Pushing the limits of high resolution sensing with single-chip mmWave radar

Akarsh Prabhakara
Carnegie Mellon University

Despite being widely used in today's portable, small form-factor devices like phones, visible light camera and lidar sensing quality degrades with occlusions. In contrast, Radio Frequency (RF) signals pass through occlusions and have enabled through-occlusion sensing in critical contexts like radar scanners at airports seeing through clothes. However, these traditional RF sensing setups are too bulky for small form-factor phone-like devices. Our central vision is to build towards a small form-factor RF sensor that can enable high quality perception even in several occluded settings such as a firefighter navigating a smoky environment.

Millimeter waves (mmWave) have very short RF wavelengths and are best suited for miniaturizing RF system elements such as antennas to achieve a compact form factor. Recent integration of mmWave multi-antenna and associated RF circuitry in a single-chip form factor is a key enabler in envisioning RF sensing on small form factor devices. However, Fig. 1 qualitatively illustrates the low resolution sensing of single-chip, small form factor mmWave sensing setups. For context, state-of-the-art single-chip radars have only 8 antennas packed in a ~2 cm form factor. 8 element antenna array has an angular sensing resolution of 15°. This is orders of magnitude worser than mechanical lidars which are 0.1° (also shown in Fig. 1) and cameras which are about 0.01°. Thus, the mmWave sensing outputs are coarser than lidar/camera and lack any structural resemblance with physical objects. This limits them to coarse grained applications. Rather than increasing form factor for better resolution, we address this trade-off by asking the following question - *"From a single-chip, small form factor mmWave setup, how can we obtain high resolution sensing?"*.

Past approaches look at sensor fusion approaches using camera or lidar with radar [2]. This can be challenging in occluded environments where cameras and lidars fail. Synthetic Aperture Radar (SAR) based approaches [7] involve moving the radar in a structured fashion on a motored motion stage. While this helps in emulating a large multi antenna array and thus improves the resolution, to obtain the same resolution as a lidar or camera, a motion stage would need to move 1 m and 10 m respectively. This makes the whole sensing setup non-compact and large form factor.

Here, we introduce five different techniques that generate high resolution sensing data from low resolution radar data, whilst maintaining a small form factor. Each of these techniques emerge from envisioning sensing application operating points that are unique in terms of radar and object dynamics (see Fig, 2). Operating

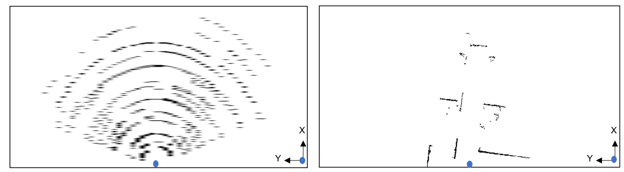


**Figure 1: Single-chip mmWave radar clearly has a much lower angular resolution than state-of-the-art lidar. ● marks the origin. The images show the same scene (10x20 meters) as perceived by each sensor.**

points specify constraints on dynamics for example, requiring the radar/object to be static, or to move in a structured manner or to move extremely slowly, or to move in any (potentially arbitrary) manner. With each operating point that we investigate, we relax constraints on radar-object dynamics moving closer to general purpose high resolution sensing from a small form factor radar. We demonstrate the capabilities of these techniques on applications chosen from the following radar-object dynamics operating points.

**Osprey [4]:** We first consider the operating point where radar remains static and a specific object-to-be-sensed moves in a structured manner. As an example of this class, we consider the application of tire wear monitoring. This application demands the ability to measure fine (millimeter level) changes in the thickness of rubber on a tire amidst road debris such as snow, sawdust, and mud. Seeing through debris motivates the need for RF sensing. Clearly, a 15° angular resolution, from a single-chip mmWave radar mounted in the tire well is too coarse to tell apart surface and groove from each other. Our key insight is to leverage the natural structured rotation of the tire and perform an inverse synthetic aperture (SAR) imaging to obtain high angular resolution image from just a small form factor radar. However, accumulation of road debris leads to ambiguity between debris and groove. We overcome this by embedding metallic strips in the groove in a coded pattern to detect the groove robustly even amdist debris. The general principle of using inverse SAR for small form factor, high resolution sensing can be extended to other contexts by identifying applications with structured object motion.

**Millimetro [6]:** We next consider the operating point where radar moves but not in a structured manner and it is sensing certain *key objects* that are static. As an example of this class, we consider a radar-enabled car moving on a road sensing critical road side infrastructure in foggy or rainy scenarios that are adverse for camera and lidar. For this, we need a way of identifying and localizing road side infrastructure (like stop signs) from really *long distances* of 100 meters to give the car enough reaction time. A 15° angular resolution is too coarse, and with longer distances localization accuracy only becomes worser. Our key observation is that we are only


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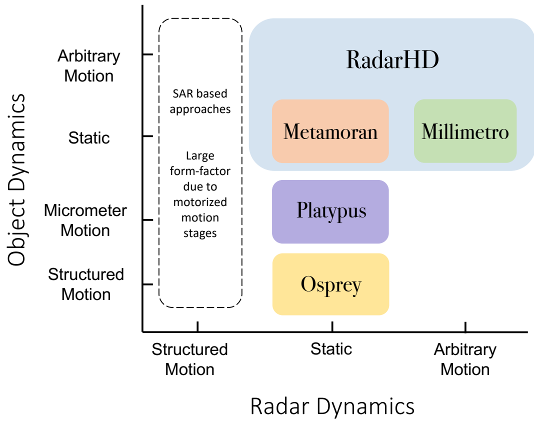


**Figure 2: We tackle the problem of obtaining high resolution sensing from a single-chip, small form factor mmWave radar. Past solutions [7] synthesize large aperture using motorized motion stages which lead to bulky setups. We develop five systems (Osprey, Millimetro, Platypus, Metamoran, RadarHD), with just a small radar form factor, that solve applications with varying degrees of radar and object dynamics.**

interested in identifying and locating *sparse, key objects*. As a result of this, we don't need to sense the whole world at high resolution but just these key objects. Our solution is a first-of-its-kind, low power backscatter tag designed to be mounted on key objects at even 100m ranges and a custom signal processing pipeline at the radar to detect only these tags at high resolution. Traditionally, radar systems are viewed as a simple broadcast and receive system. But our solution introduces a new paradigm of instrumenting tags in the environment that alter the received reflections in specific, desirable manner aiding detection and accurate localization.

**Platypus [1]:** We next consider the operating point where radar is static and objects are moving in a non-structured and extremely slow manner. We consider the example of measuring tiny displacement of Millimetro tags mounted on bridges and other infrastructure that require constant monitoring to avoid catastrophes. The order of magnitude of tag displacements is in a few micrometers which makes it significantly more challenging than the previous use case of Millimetro for localizing road side infrastructure. Our key idea here is to redesign the radar-side signal processing to map tiny micro displacements from the tag to corresponding phase displacements. Owing to the small wavelengths of mmWave frequencies, monitoring phase displacements leads to sub wavelength (sub millimeter) object tracking. Our entire system tackles other problems in tracking phase displacements that show up in practice when radar and tag are deployed at long ranges of 100 meters.

**Metamoran [5]:** A very challenging operating point is when both radar and object-to-be-sensed are static. This situation happens when you want to deploy a 3D surveillance system to enforce strict perimeters. Such as a surveillance sensor monitoring cars parked in a construction zone. One can achieve a 3D imaging solution using just cameras, but that requires deploying cameras from multiple vantage points. We instead propose a single vantage point radar-camera fusion setup that can be easily mounted anywhere to enforce 3D perimeter restrictions on even static objects. A single radar alone will suffer from resolution problems and does not have the capability to identify parked cars accurately. Our key idea is to leverage information from cameras which are good at angular resolution and exploit depth from radar to create a superior sensor. We develop techniques that can tackle this fusion overcoming challenges due to long ranges between sensor setup and object. While this solution works great in conditions favourable to camera, as camera performance degrades, our solution also gets impacted.

**Future Work:** Having considered a wide range of application scenarios, a natural question to ask is can we have a universal, general purpose high resolution sensing solution that can tackle arbitrary radar/object motion, make no assumption on *sparse, key objects* and even deal with conditions that are not favorable to camera/lidar.

To this end, we consider an important application that truly pushes the requirements towards general purpose sensing. Our goal is to enable fire fighting robots with high resolution perception dealing with occlusions from thick dense smoke that renders camera and lidar useless. This high resolution perception could help the robot perform search and rescue operations in scenarios where all other sensors fail. The robot can remain static or move freely in a dense, feature rich indoor environment. The goal of the perception is to obtain an accurate understanding of the indoor environment such as halls in a building, people running away from fire etc. mmWave radars mounted on the robot can see past the smoke but a single-chip radar's resolution would be too coarse for the robot map out indoor features such as walls, desks, etc. To tackle this problem without any assumptions that helped us in previous applications [4], [6], [1], [5], we draw inspiration from machine learning super resolution on images and videos. Our key idea is to train deep learning networks to mimic the output of a high resolution sensor such as lidar, given low resolution radar as input. Our initial solution, RadarHD [3], shows promise for this superior-sensor (lidar) guided radar super resolution and replaces the superior sensor in adverse conditions. Our solution currently can generate high resolution 2D perception of static environments. In the future our goal is to develop this into a full fledged, general purpose super resolution solution. This would involve building new machine learning pipelines custom designed for radar data to output 3D as opposed to 2D, deal with dynamic environments such as people moving and generalize to new environments easily.

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