Demo Abstract: Platypus: Sub-mm Micro-Displacement Sensing with Passive Millimeter-wave Tags As "*Phase Carriers*"

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ABSTRACT

We demonstrate Platypus, a sub-millimeter micro-displacement sensing system presented in [3]. Micro-displacement measurement is a crucial task in industrial systems such as structural health monitoring, where millimeter-level displacement of specific points on the structure or machinery parts can jeopardize the integrity of the structure and potentially leading to catastrophic damage or collapse. Platypus enables sub-millimeter level sensing accuracy by using mmWave backscatter tags and their reflection as *phase carriers* to shift the phase changes due to tiny displacements to clean frequency bins for precise tracking. It then reconstructs the tag phase changes with sub-millimeter level accuracy even from extended ranges (over 100m) or in non-line-of-sight (NLoS) situations where the tag is blocked by other objects. Here, we demonstrate Platypus's performance by attaching a Platypus tag to a stepper motor-driven motion-stage and demonstrating the micro-displacement detection in real time, and the system robustness against multipath and occlusions.

1 INTRODUCTION

Measuring and tracking *micro-displacements* of multiple points in space from long ranges has important applications in several contexts ranging from structural health monitoring and environmental sensing to industrial robotics and automation. These displacements can serve as an early detection mechanism for internal failures or excessive strain on the structure. Prior arts which use either traditional sensors (accelerometer, LVDT, RFID, etc), vision-based systems, or advanced surveying platforms, suffers from limited accuracy or prohibitive costs. More recent solutions based on radars partially address these challenges, but their accuracy drastically drops in dynamic environments with moving objects. The main challenge is that the phase changes caused by such micro-displacements can be easily masked by the noise in the signal because of the quasi-static nature of micro-displacements.

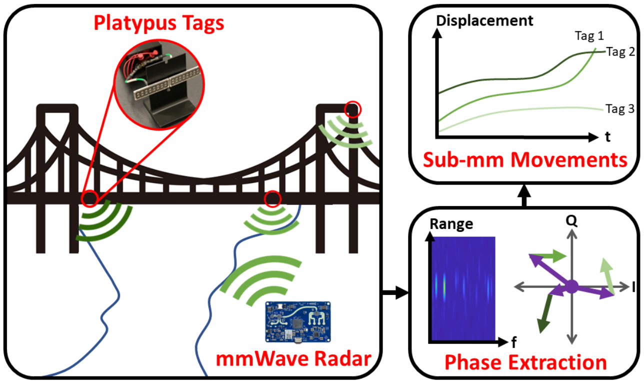

Figure 1: Platypus's Overview: 1) Backscatter tags are attached to the structure of interest and the radar is mounted at a reference point away; 2) Tags are detected by their unique signatures and phase changes caused by micro-displacements are refined; 3) Extracted sub-millimeter displacements are used for structure health monitoring.

In this paper, we focus on *enabling unstructured micro-displacement estimation using commodity mmWave radars*. Similar to carrier waves in telecommunication that share wireless mediums via frequency division multiplexing, we demonstrate that by simply attaching passive modulating tags at the targets of interest, we can drastically improve the resolution and accuracy of micro-displacement measurements in dynamic environments. Specifically, we can use tag modulation frequencies as *phase carriers* to shift the phase changes due to the targets' micro-displacements apart from each other and other background reflectors. This results in a multi-point micro-displacement sensing system with sub-millimeter accuracy even from long ranges (i.e. up to 100 meters). Uniquely, we make no assumptions on the trajectory or shape of this displacement, unlike prior work in vibration [2] or 1D displacement sensing [4]. Platypus achieves this through three main components:

Tag Modulation as "Phase Carrier": An FMCW radar sends out multiple chirps in one measurement frame. A tag attached to the point of interest receives the radar signals and performs on-off keying modulation across frames [5] by switching between reflecting or terminating the RF signal. This appears as a square function applied on top of the tag reflection in range-FFT profile across

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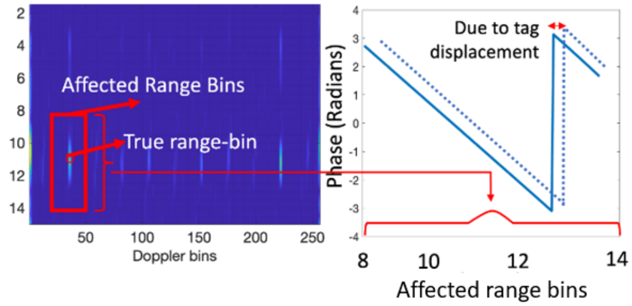
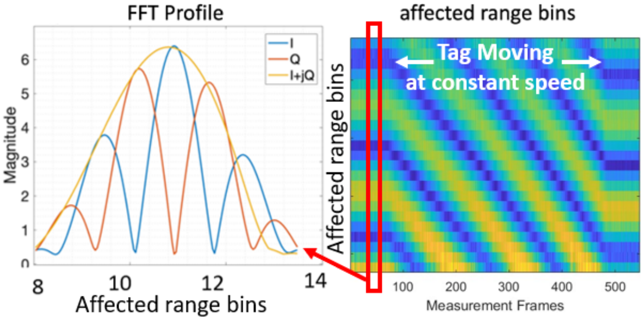


(a) Range-Doppler (RD) FFT Profile

(b) Phase of RD across affected range bins



(c) IQ Signal Strength across range bins

(d) I Signal strength across frames (time)

Figure 2: Platypus exploits the tag signature in Doppler FFT across all affected range bins, model the phase change across affected range bins, and uses IQ processing to achieve granular phase shift estimations.

chirps. Therefore, by taking a second FFT across chirps, a robust sinc function signature appears (Fig. 2(a)). The tag signature has peaks in both positive and negative Doppler bins, and spans across multiple range bins. These peaks carry the phase information of the tag, along with the change in phase from the micro-displacement by FFT properties. Platypus focuses on refining the phase information by leveraging this unique signature of tag modulation.

IQ Domain Processing: The previous step shifts the tag reflection to clean Doppler frequency bins that allows us to eliminate phase noises due to background movements. To extract the phase changes, Platypus pulls In-phase (real) and Quadrature (imaginary) components of the tag's modulation signal from the Doppler-FFT using the conjugate symmetry and linearity properties of FFTs. The I and Q components are combined to create an initial phase estimation.

Exploiting Neighboring Range Bins: To further counter the noise, Platypus leverages a well-known phenomenon in FFT: the reflection of an object not only creates a peak at the true range bin in the Range-FFT Profile but also stretches across neighboring range bins [1]. Platypus exploits two key features from the main peaks of the tag's sinc signature in Fig. 2(a): (1) The phase shifts due to the tag micro-displacements will be combined with a linear phase change across the range bins due to the different underlying beat frequencies (Fig. 2(b)); and (2) the peaks in the signature can be broken into its I and Q components, which are modelled as damped (co)sinusoidal functions that are more sensitive to phase shifts than the combined magnitude (Fig. 2(c)). Fig. 2(d) shows the obvious phase shifts of the I signal under a constant 2mm/s displacement speed. By correlating the I and Q signals with the modelled dampened (co)sinusoidal functions, we robustly extract the phase and therefore the micro-displacement.

Figure 3: Demo setup.

2 DEMO SETUP

We implemented Platypus using a commercial mmWave radar, Analog Devices TinyRad, operating at 24GHz with 250MHz of bandwidth, 8dBm maximum power output, and 1MHz sampling rate. The tag prototype uses an ADRF5027 RF switch powered by an ATmega328P micro-controller. Two off-the-shelf micro-strip patch antennas arrays are connected to RFC and RF1 ports of the RF switch, and a 50Ω load is connected to RF2 to terminate the signal. The tag is attached to the stepper motor-driven motion-stage with 0.01mm nominal accuracy (Fig. 3) and creates different micro-displacement pattern. We will demonstrate Platypus in three aspects:

Micro-displacement Live Detection: We generate random micro-displacements with varying velocities and amplitudes using the motion-stage. The data is collected and processed by Platypus's pipeline. This demonstrates Platypus's capability in accurately estimating tag micro-displacements without any assumption on the shape or direction of displacements.

Multi-path Robustness: We create constant/changing multi-path background around the tag by setting up additional reflectors or moving in the same range bins as the tag's while collecting the data. The tag's modulation frequency component is used to reconstruct the tag phase, while all other noise falls into other frequency bins.

NLOS Robustness: We create occlusions of different materials between the radar and the tag to stress test Platypus performance in harsher settings. mmWave signals penetrates partially through other materials such as plastic, paper, and wood. We put occlusions directly in front of the tag to block all possible multipaths, and demonstrate the detection of micro-displacement.

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