# Poster: Accurate Device Self-Tracking for Robust Millimeter-Wave Imaging on Handheld Smart Devices

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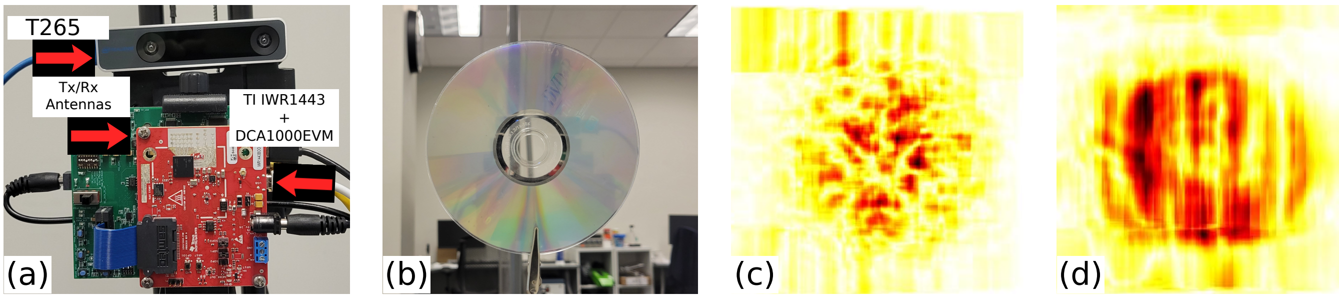


**Figure 1:** *(a)* CompenSAR *integrates a millimeter-wave (mmWave) device and a self-tracking camera to enable handheld mmWave imaging; (b) Optical image; (c–d) Backprojected mmWave images: Before and after pose corrections, respectively.*

## ABSTRACT

Millimeter-wave (mmWave) imaging has been difficult to implement on handheld devices since imaging algorithms rely on millimeter-scale device self-tracking, which existing systems cannot achieve reliably. We propose *CompenSAR*, a handheld system which integrates a mmWave transceiver and a tracking camera, and overcomes the self-tracking limitations to enable handheld mmWave imaging.

## CCS CONCEPTS

• **Hardware** → Sensor devices and platforms; • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools*.

## KEYWORDS

Millimeter-Wave; Synthetic Aperture Radar; Experimental Platform

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## 1 INTRODUCTION

Handheld 5G smart devices have introduced many new opportunities for mobile sensing in augmented reality, indoor navigation, *etc.*, but they cannot perceive objects beyond visual occlusions. Since these devices are equipped with millimeter-wave (mmWave) transceivers, they could be used for mobile through-obstruction mmWave imaging, enabling many applications. (1) *Contactless Inventory Management*: Inventory accounting could be streamlined with a portable device, which non-invasively monitors packages and removes the need for costly repackaging materials. (2) *Disaster Relief*: It could allow first responders to quickly image areas inaccessible to optical sensors. (3) *Mobile Physical Screening*: Traditional airport screening devices require bulky, immobile scanners; a handheld imaging device could reduce congestions while ensuring robust privacy measures.

MmWave imaging is achieved through the Synthetic Aperture Radar (SAR) technique, which uses the motion of a mmWave transceiver to focus reflected signals and generate a through-obstruction image. SAR techniques rely on large motion controllers and device tracking with millimeter-scale accuracy to produce a focused image. But existing self-tracking algorithms for handheld devices are unable to produce sufficiently accurate poses for usable SAR focusing. In this work, we introduce *CompenSAR*, a system capable of correcting pose errors in common vision-based self-tracking devices and realizing handheld SAR imaging. *CompenSAR* improves the device tracking accuracy by synchronizing device components, performing pose estimation based on mmWave reflections, and using the mmWave voxels to align poses and correct large drift error.

## 2 COMPENSAR SYSTEM DESIGN

**MmWave-Based Pose Estimation**: SAR imaging requires precise localization for each mmWave reflection to focus the image. For example, Figure 1(c) shows a mmWave image reconstructed using poses from a self-tracking camera (Figure 1[a]) for the object in Figure 1(b). Clearly, there are no human-perceptible features in the mmWave image due to offsets introduced by the incorrect poses that cause mmWave reflections to destructively combine. *CompenSAR* must correct these poses to improve SAR focusing and enable better


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quality images. To this end, we use reflected signals transmitted and received from multiple mmWave antennas for initial pose estimation. Specifically, we leverage a velocity estimation method [1] to produce locally accurate poses using the known antenna spacing. For two Rx antennas separated by a distance $2p$ receiving the reflections from a single Tx antenna, the velocity along the separation of the two Rx antennas can be found by cross-correlating each $i^{th}$ received frame from Rx1 against each $j^{th}$ surrounding frame from Rx2. The delay $d_i$ is the number of frames between the $i^{th}$ frame and the $j^{th}$ frame at which the maximum correlation occurs. Then, the velocity $V_i$ and position $X_{i+1}$ from initial position $X_i$ is:

$$V_i = \frac{p \cdot f}{d_i}\ ; \quad X_{i+1} = X_i + \frac{V_i}{f} \tag{1}$$

Where $f$ is the frame rate for signal tranception.

**Window-Based Pose Correction**: However, the mmWave-based pose estimation method cannot correct errors along the Z (depth) direction, since there is no physical antenna spacing along Z. What's more, most vision-based self-tracking devices have poorer tracking performance along the Z direction that contributes to the most significant image degradation. To this end, *CompenSAR* corrects the Z poses by dividing the sequence of data into overlapping windows with length $C$ and overlap size $L$. For each window $W_n$, the first pose in the window is used as $X_i$ for the mmWave-based pose estimation in the X and Y directions. To overcome the Z antenna spacing limitation and remove the noise within each window, the Z poses are approximated with a line. Now, there are two sets of poses within the overlapping region $L$ sharing the same mmWave reflections that should produce identical mmWave voxels if the poses in $L$ from $W_n$ and $W_{n+1}$ are the same. We use the Time Domain Backprojection Algorithm [2] to produce mmWave voxels within the region $L$ since it directly maps points in the range-compressed signal to a voxel within the beam swath according to distance; so multiple Backprojection scans will produce distinct spatial features. However, if *CompenSAR* produced incorrect poses, *i.e.*, the starting point $X_i$ for each window was displaced from the previous window, or the Z drift exceeded allowable limits, the voxels will not match. Then, to recover the corrected poses, we must perform some transformaton to all poses in $W_{n+1}$ so that the reconstructed voxels from both windows closely correspond. To this end, we use the Normal Distribution Transform [3] to register the 3D voxels with good results. The registration process continues sequentially until all windows have been aligned.

**Data Collection and Post-Processing**: Due to the unavailability of handheld 5G devices that can provide user access to the mmWave reflection profiles, we build a custom setup integrating the TI IWR1443BOOST mmWave radar with the Intel RealSense T265 tracking camera [4]. The IWR1443BOOST has 4 receivers and 3 transmitters and can achieve a depth resolution of 3.75 cm. The T265 features two fish-eye lenses, an IMU, and a specialized vision-processing unit for self-tracking. During data collection, the mmWave device and T265 move together to emulate a synthetic aperture in front of the area of interest. The T265 and the mmWave radar cannot be triggered simultaneously in hardware, and the T265 collects pose at a faster rate than the mmWave radar. Pose correction would unlikely work if each mmWave reflection were associated with an incorrect pose. Thus, we extend our previous approach in [5] to align the reflected mmWave signals from multiple antennas and the poses from T265. After pose corrections, we use the Time Domain Backprojection Algorithm [2] to reconstruct the SAR images.

## 3 PRELIMINARY RESULTS

We evaluate *CompenSAR* by comparing the poses before and after corrections against the ground truths reported by a 2D axis motion controller. The system moves within an 18×18 cm$^2$ grid in front of the object of interest located 30 cm from the aperture plane. With a window length of 1000 and overlap size of 200 frames, *CompenSAR* can reduce the large pose errors and produce better quality shapes (see Figures 1[c] and [d]). Figure 2 shows the CDF of tracking error before and after the pose corrections. Besides, *CompenSAR* improves the median SSIM of the generated images from 0.38 using the raw poses to 0.51 using the corrected poses.

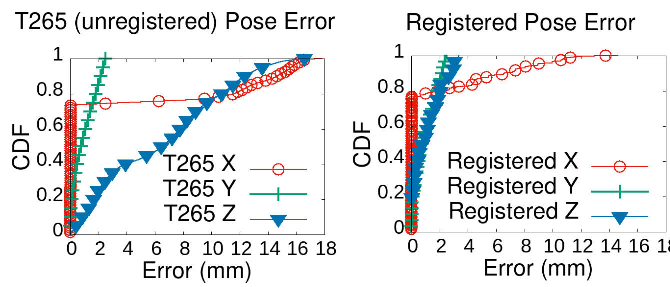


**Figure 2:** *(a) Error in poses reported by Intel RealSense T265; (b) Error in poses with* CompenSAR *corrections.*

## 4 CONCLUSION AND FUTURE WORK

This work introduces *CompenSAR*, a handheld device capable of mmWave imaging without external anchors or bulky infrastructure. *CompenSAR* achieves focusing by correcting poses of the vision-based self-tracking device using the mmWave reflections. In the future, we will perform registration by backprojecting only salient features in the mmWave data (*i.e.*, regions of higher-intensity) to implement a light-weight real-time system on 5G mmWave smartphones. We also plan to explore deep learning techniques to recover high-frequency features in the mmWave image that are fundamentally unavailable in the reflected signals due to the specularity of signals and weak and variable reflectivity of objects.

## ACKNOWLEDGMENTS

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