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

Jacqueline M Schellberg; Sanjib Sur

Department of Computer Science and Engineering; University of South Carolina, Columbia, USA schellbj@email.sc.edu; sur@cse.sc.edu



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 millimeterscale 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 \rightarrow Sensor devices and platforms; • Human-centered computing \rightarrow Ubiquitous and mobile computing systems and tools.

KEYWORDS

Millimeter-Wave; Synthetic Aperture Radar; Experimental Platform

ACM Reference Format:

Jacqueline M Schellberg; Sanjib Sur, Department of Computer Science and Engineering; University of South Carolina, Columbia, USA, schellbj@email.sc.edu; sur@cse.sc.edu. 2022. Poster: Accurate Device Self-Tracking for Robust Millimeter-Wave Imaging on Handheld Smart Devices. In *The 20th Annual International Conference on Mobile Systems, Applications and Services (MobiSys '22), June 25-July 1, 2022, Portland, OR, USA.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3498361.3538775

1 INTRODUCTION

Handheld 5G smart devices have introduced many new opportunities for mobile sensing in augmented reality, indoor navigation, *etc.*, but

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for third-party components of this work must be honored. For all other uses, contact the owner/author(s).

MobiSys '22, June 25-July 1, 2022, Portland, OR, USA © 2022 Copyright held by the owner/author(s). ACM ISBN 978-1-4503-9185-6/22/06. https://doi.org/10.1145/3498361.3538775 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

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:

$$V_i = \frac{p \cdot f}{d_i} ; \quad X_{i+1} = X_i + \frac{V_i}{f}$$
(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 cm² 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

We sincerely thank the reviewers for their comments. This work is partially supported by the NSF under grants CAREER-2144505, MRI-2018966, and CNS-1910853.

REFERENCES

- Qian, et al., "3D Point Cloud Generation with Millimeter-Wave Radar," ACM IMWUT, vol. 4, no. 4, 2020.
- [2] Zaugg, et al., "Generalized Frequency Scaling and Backprojection for LFM-CW SAR Processing," *IEEE TGRS*, vol. 53, no. 7, 2015.
- [3] Biber, et al., "The normal distributions transform: A new approach to laser scan matching," in *IEEE/RSJ IROS*, 2003.
- [4] "Intel RealSense Tracking Camera T265." [Online]. Available: https://www.intelrealsense.com/tracking-camera-t265/
- [5] J. M. Schellberg and S. Sur, "ViSAR: A Mobile Platform for Vision-Integrated Millimeter-Wave Synthetic Aperture Radar," in ACM UbiComp, 2021.