Poster: ViSAR: A Mobile Platform for Vision-Integrated Millimeter-Wave Synthetic Aperture Radar

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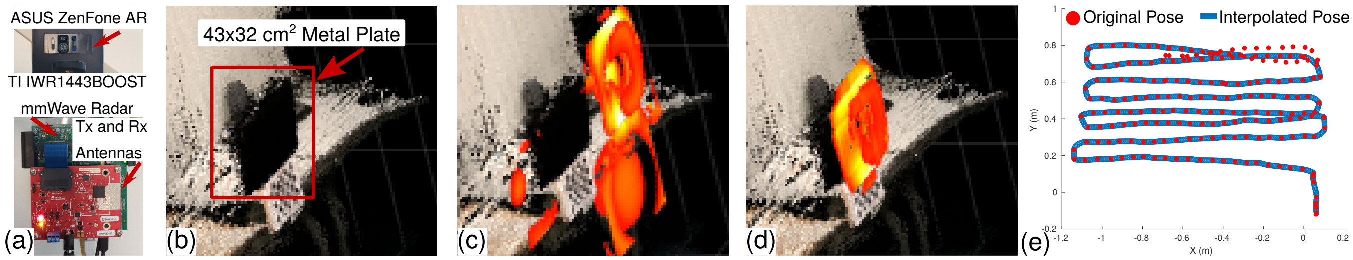

Figure 1: (a) *ViSAR* integrates vision and millimeter-wave (mmWave) radar devices; (b) Visual Point Cloud (PCD) of a metal plate; (c) Backprojected mmWave image of the metal plate (red) overlayed with the PCD without device synchronization; (d) Backprojected mmWave image after synchronization and interpolation; (e) Pose of handheld scanning trajectory before and after interpolation.

ABSTRACT

The ubiquity of millimeter-wave (mmWave) technology could bring through-obstruction imaging to portable, mobile systems. Existing through-obstruction imaging systems rely on Synthetic Aperture Radar (SAR) technique, but emulating the SAR principle on handheld devices has been challenging. We propose *ViSAR*, a portable platform that integrates an optical camera and mmWave radar to emulate the SAR principle and enable through-obstruction 3D imaging. *ViSAR* synchronizes the devices at the software-level and uses the Time Domain Backprojection algorithm to generate vision-augmented mmWave images. We have experimentally evaluated *ViSAR* by imaging several indoor objects.

CCS CONCEPTS

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

KEYWORDS

Millimeter-Wave; Synthetic Aperture Radar; Experimental Platform

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1 INTRODUCTION

The democratization of handheld optical 3D imaging systems capable of localizing, mapping, and motion tracking has laid the groundwork for many ubiquitous sensing applications. But objects occluded by physical barriers cannot be sensed by existing handheld systems. The ubiquity of millimeter-wave (mmWave) technology in 5G-and-beyond mobile devices could bring through-obstruction imaging to portable, ad-hoc settings and enable multiple applications. (1) *Disaster relief*: An emergency response team may quickly and safely identify structures hidden beneath rubble that are not visible to traditional aerial imaging systems. (2) *Inventory management*: Team members could check packaged inventories for damage, measure space utilization, detect missing items, *etc.*, without package intrusion. (3) *Security applications*: Mobile checkpoints could reduce congestion in high-traffic areas while providing comparable security and privacy insurance. (4) *Medical diagnosis*: Hyper-spectral images using different mmWave frequencies and bandwidths could allow at-home users to non-intrusively monitor healing progress post-surgery by imaging beneath the skin at various depths.

Through-obstruction imaging systems rely on Synthetic Aperture Radar (SAR) technique [1] that transmits and receives mmWave wireless signals while scanning the scene. Existing SAR systems typically require precise, controlled motions or expensive motion tracking equipment. Thus, emulating the SAR principle on portable or mobile platforms has been challenging. Existing platforms for through-obstruction imaging such as Walabot [2], ThruWave [3], VuSystems [4], *etc.*, are not portable, use microwave frequency bands, or rely on infrastructure.

In this paper, we propose *ViSAR* (Vision-Integrated Synthetic Aperture Radar), a portable, mobile platform that integrates optical camera and mmWave radar to enable through-obstruction 3D imaging. *ViSAR* leverages off-the-shelf components and includes an ASUS ZenFone AR smartphone [5] and a TI IWR1443BOOST mmWave radar [6]. *ViSAR* synchronizes the components through software and applies the Time Domain Backprojection algorithm [7] to obtain images, even under non-linear handheld motion.

2 *VISAR* SYSTEM DESIGN

Unlike the existing SAR imaging systems that require the radar to follow a strictly linear or grid-like trajectory, *ViSAR* must accommodate irregularities in handheld motions to produce a mmWave image. To this end, we mount the TI IWR1443BOOST board, an FMCW radar operating at 76–81 GHz frequency, and the TI DCA1000EVM capture card [8] onto the ASUS smartphone. Figure 1(a) shows the platform. The mmWave radar operates under 4 GHz channel bandwidth and has a depth resolution of 3.75 cm. The smartphone is capable of 3D mapping and self-positioning in an indoor environment [9]. We use RTAB-Map [10], an RGB-D SLAM software, to collect the visual point cloud (PCD) as well as the device's self-pose during the synthetic aperture motion.

Synchronizing the Radar and the Smartphone: To successfully generate a mmWave image, the position of the radar for each measured reflected signal must be known. RTAB-Map estimates the device's self-poses at irregular intervals, while the radar collects reflected signals from the target scene at a constant interval. Due to various software-level delays, it is hard to trigger the radar and the smartphone at the same time. Thus, *ViSAR* must post-process the data to achieve a software-level synchronization.

At the beginning of each scan, *ViSAR* is kept stationary for a short period while it measures the vision and radar data. Since the consecutive radar frames will be *similar* to each other during this stationary period, we can identify the radar's local timestamp of movement by correlating each frame with the first radar frame. Similarly, we can identify the smartphone's local starting timestamp by identifying the self-pose change. Since the radar and the smartphone begin moving at the same time, we can calibrate the local timestamps and obtain the synchronized start of radar frames and self-poses. Since there are far fewer self-poses than radar sample points as a result of RTAB-Map's irregular sampling, we interpolate the self-poses to match the sampling rate of the radar; in practice, the piecewise cubic interpolation method yields good results.

Generating Images from Time Domain Backprojection: Once the data has been correctly synchronized and interpolated, we use the Time Domain Backprojection algorithm to form the SAR image, since it responds well to highly non-linear trajectories [7]. For example, Figure 1(e) shows a trajectory that a user has produced by free-hand movement, where the points are not uniform and do not follow a rigid grid-like pattern. Backprojection also generates the 3D mmWave image in the same coordinate system as the vision PCD, allowing the image to be directly overlayed onto the PCD without any additional translation or processing. The Backprojection algorithm can be written as [7]:

$$C(v) = \sum_{n=1}^{N} S(n, \Delta R(n,v)) \cdot exp\left(\frac{-j4\pi\Delta R(n,v)}{\lambda}\right); \quad \forall v \in V \qquad (1)$$

where N is the total number of radar frames, V is the set of image voxels, $S(n, \Delta R(n,v))$ is the complex-valued interpolated, range-compressed signal at a distance from frame n to voxel v, and λ is the wavelength of the mmWave signal. The Backprojection algorithm outputs a complex-valued datacube, C, of the target scene. To obtain the 3D mmWave image, we use the absolute value of the datacube as the voxel intensity. Finally, the mmWave image is directly merged with the vision PCD to produce a through-obstruction image.

3 PRELIMINARY RESULTS

We evaluate *ViSAR* by imaging different indoor objects and show the imaging results for a 43×32 cm^2 metal plate (Figure 1[b]) at a 1 meter distance from the scanning area. Figure 1(e) shows the example scanning trajectory by a user, with data that was collected for 200 seconds, with a 25 second stationary period in the beginning. Figure 1(c) shows the imaging result when the radar and vision data are not synchronized: Clearly, the resultant image appears distorted and aliased from its true physical location. Figure 1(d) shows the Backprojection result with software synchronization between radar and vision data: The object now appears at the correct location and the dimensions match with expectations. We further test *ViSAR* for its ability to image through obstructions, such as fabric, by covering the same metal plate with a cotton sweater (Figure 2[a]). The resultant SAR image overlapped with the PCD (Figure 2[b]) shows the presence and correct location of the metal plate.

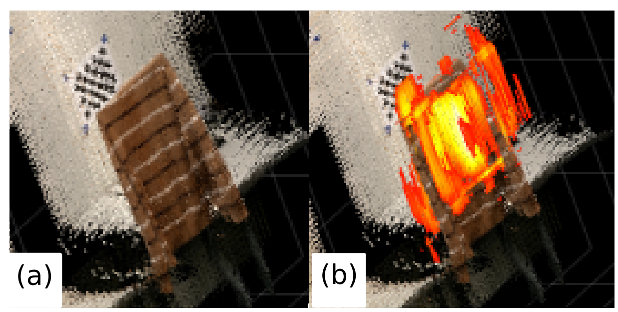

Figure 2: (a) PCD of the metal plate hidden within a cotton sweater; (b) *ViSAR* reveals the position of the metal plate.

4 CONCLUSION AND FUTURE DIRECTIONS

In this paper, we design and prototype *ViSAR*, a mobile device that integrates a vision system with mmWave radar to emulate the SAR principle and enable through-obstruction imaging. *ViSAR* achieves a software synchronization between the vision and the radar components and applies the Time Domain Backprojection algorithm to generate 3D mmWave images. In the future, we propose to extend *ViSAR* to reconstruct higher resolution images using SAR autofocus algorithms and compressed sensing frameworks. Furthermore, we plan to enable hyper-spectral mmWave imaging in *ViSAR* by integrating multi-frequency and wide-bandwidth radars. Since the Backprojection algorithm is parallelizable and can be accelerated by a GPU, we will implement and evaluate a fast Backprojection reconstruction to form 3D mmWave image in real-time.

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