Towards Three-dimensional Millimeter-Wave Radar Imaging of On-the-move Targets

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***Abstract*—This paper presents our preliminary results for a three-dimensional (3D) imaging of an on-the-move target using a MIMO millimeter-wave (mm-wave) radar, which uses 9 transmitters and 12 receivers. The operating frequency of the mm-wave radar is from 70 GHz to 77 GHz. Experimental results show that the images can be created as the target under detection moves in front of the radar system, which is combined with 3D video to show the continuous movement of the target. This preliminary work paves the way towards a mm-wave imaging system that can be used at checkpoints; thus enabling on-the-move detection of potential threats, enhancing passenger's overall experience, and achieving a high scanning throughput.**

I. Introduction

Active near-field Millimeter-wave (mm-wave) imaging has been proposed during the past few decades for personnel screening at the checkpoint. Specifically, high-resolution mm-wave images are used for detecting potential threats at an affordable cost [1]. Current state-of-the-art mm-wave imaging systems for security screening require people to enter and stand in front of the scanning system, which limits the passenger throughput and convenience. Thus, the development of future checkpoints that enable the inspection of moving persons concealing potential threats having high passenger flow is of especial interest [2].

In this paper, we present a multiple-input-multiple-output (MIMO) millimeter-wave radar architecture, which has 9 transmitters and 12 receivers. Next, the three-dimensional (3D) imaging experiment at $70-77$ GHz is used to image a metallic plate of 302×457 mm moving with a speed of 50 mm/s. The reconstruction algorithm including a 2D cross-section averaging method to enhance the image quality is shown. The experimental results are presented next, showing two frames of the imaging video where the profile of the target under test continuously moves in front of the radar. Finally, a conclusion is drawn.

II. MIMO Millimeter-Wave Radar Architecture

The measured data was collected with the $70-77$ GHz Radar Front End (RFE) Model 8300 developed by HXI [3]. The radar configuration used consists of the following elements: 1) Four HXI # 8302 Transmitter (Tx) Modules; 2) Four HXI # 8301 Receiver (Rx) Modules; 3) One HXI # 8303 Local Oscillator Module (LOM); and 4) Eight HXI # HSWM41203 single-pole four-throw (SP4T) 4-way Antenna Switches. The LOM has eight synchronized outputs, and it permits the use of eight Tx/Rx modules working in a fully-coherent multistatic mode of operation. An FPGA-based

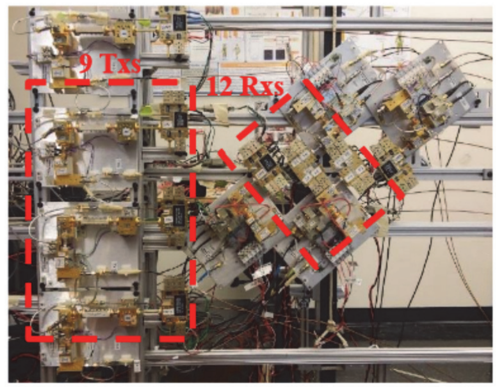

Fig. 1. Front view of the radar configuration with 9 Txs (transmitters) and 12 Rxs (receivers).

switching system based on an Altera Cyclone V DE1-SoC board drives the SP4T switches in parallel; currently 4 of the switches work in transmission mode and the remaining 4 switches work in reception mode. In this paper, the radar collects all data in 11.8 ms; but our FPGA-scanning enables to do this in just 164 μs.

A 2D scanner is placed in front of the radar modules (see Fig. 1) at 0.15 m in the range direction. This is used to capture two separate calibration data sets, which are used to create the sensing matrix in the target region. This process involved the following steps: 1) a sequenced transmission from three static Tx modules, while receiving in a 2D aperture with a moving Rx module; and 2) a sequenced transmission from a single moving Tx module, while receiving in the same 2D aperture with the three static Rx modules. The scanned 2D aperture has a size of in 64 cm in the z-axis (elevation) $\times$ 88 cm in the x-axis (cross-range), spanning the extent of the static Rx/Tx apertures. In order to match the 45° polarization of the receiving modules, the moving transmitter and moving receiver have been equipped with 45° left-hand twist waveguides and tapered waveguides on the apertures. The moving target was co-registered to the acquired radar reconstruction over time with an Xbox One Kinect Sensor.

III. Experiment and Reconstruction Algorithm on Moving Metallic Plate Detection

Fig. 2a shows the geometry used for the 3D imaging experiment of a moving target. The imaging region has a size of 450 mm in x-axis (cross-range), 300 mm in y-axis

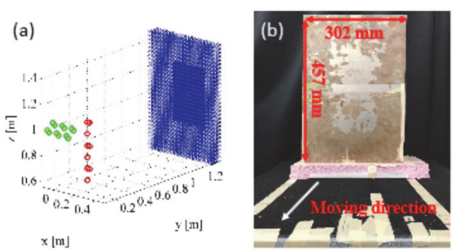

Fig. 2. Target under test is a moving metallic plate with a size of 302 mm × 457 mm. The moving speed of the plate towards the radar transceivers is 50 mm/s.

(depth), and 900 mm in z-axis (elevation). The center of the reconstruction domain is at $[190, 1400, 1010]$ mm. The pixel resolutions are 16 mm, 8 mm, and 30 mm in the x-axis, y-axis, z-axis, respectively. The moving metallic plate in the reconstruction domain has a size of 302 mm × 457 mm. The metallic plate is moving towards the radar transceivers at 50 mm/s –note that speeds over 1 m/s may be achieved by scanning the FPGA in 164 μs. Fig. 2b shows the realistic moving metallic plate.

The measured electric fields on the 2D aperture are used to compute the equivalent magnetic currents in transmission $\mathrm{M}_{\mathrm{tx}}^{\mathrm{aper}}$ and in reception $\mathrm{M}_{\mathrm{rx}}^{\mathrm{aper}}$. Then, by using Physical Optics (PO) approximation, the sensing matrix $\mathbf{H}$ can be calculated as:

$$\mathbf{H} = \mathbf{E}_{\mathrm{tx}}^{\mathrm{RoI}}(\mathbf{M}_{\mathrm{tx}}^{\mathrm{aper}}) \cdot \mathbf{E}_{\mathrm{rx}}^{\mathrm{RoI}}(\mathbf{M}_{\mathrm{rx}}^{\mathrm{aper}}) \quad (1)$$

where $\mathbf{E}_{\mathrm{tx}}^{\mathrm{RoI}}$ and $\mathbf{E}_{\mathrm{rx}}^{\mathrm{RoI}}$ are the electric fields, generated by $\mathrm{M}_{\mathrm{tx}}^{\mathrm{aper}}$ and $\mathrm{M}_{\mathrm{rx}}^{\mathrm{aper}}$, respectively, in the region of interest (RoI).

The reconstruction algorithm used in the experiment is based on Tikhonov regularization, which often used in ill-posed inverse scattering problems; and it is given by

$$\mathrm{r} = \left(\mathbf{H}^T\mathbf{H} + \mathbf{\Gamma}^T\mathbf{\Gamma}\right)^{-1}\mathbf{H}^T\mathrm{g} \quad (2)$$

where g is the measured vector having 4320 elements (9 Txs × 12 Rxs ×40 frequencies); r is the reflectivity vector; $\mathbf{\Gamma}$ is the Tikhonov matrix chosen as a multiple of the identity matrix, $\alpha\mathbf{I}$, and α is the regularization parameter.

To further improve the reconstructed image quality, a 2D cross-section averaging is applied to r. The averaging processing for the k_0-th cross-section reconstruction plane corresponding to a fixed depth can be expressed as

$$\mathrm{r}(i_0, j_0) = \frac{1}{N^2} \sum_{i=-N/2}^{N/2} \sum_{j=-N/2}^{N/2} \mathrm{r}(i_0 + i, j_0 + j) \quad (3)$$

where $\mathrm{r}(i_0, k_0, j_0)$ is the reflectivity of the (i_0, j_0)-th pixel on the k_0-th cross-section plane, and N is the length of the 2D averaging processing.

IV. Experimental Results

Due to space limitations, the experimental results only show two frames of the moving target. Nevertheless, the video containing all reconstructed frames shows the target continuously moving in front of the radar system. Fig. 3a and 3b are the experimental reconstructed images of the plate with 16-pixels 2D averaging ($N = 16$) in the cross-section at time $t = 0$ and 4.0 s, respectively. Fig. 3c and 3d are recorded images by the Kinect for reference. As we can see, the profiles of the metallic plate, as well as its locations at different time frames, are well imaged and similar to that of the reference frames generated by the Kinect Sensor, which verifies the effectiveness of our proposed on-the-move 3D imaging.

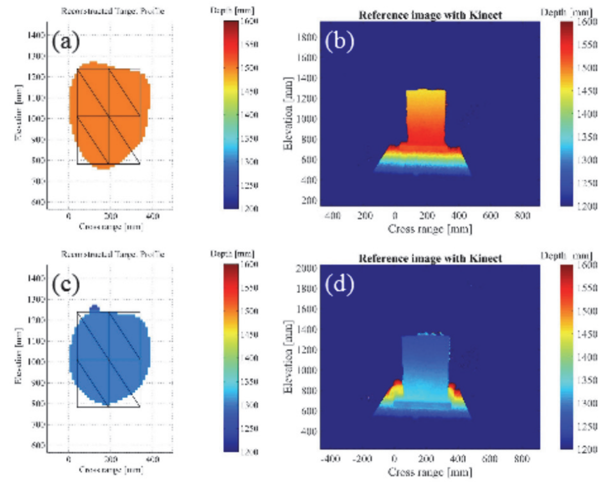

Fig. 3. Experimental results for the moving metallic plate at different time frames. (a) and (b) are the experimental reconstructed images of the plate with 16-pixels 2D averaging in the cross-section at time $t = 0$ and 4.0 second, respectively. (c) and (d) are the acquired depth recorded by the Kinect for reference purposes.

V. Conclusion

This paper presents a MIMO millimeter-wave radar system capable of 3D imaging on-the-move targets. The paper also describes an effective 2D cross-section averaging method to further enhance the imaging performance. Experimental results show that the images can be created as the target under test continuously moves in front of the radar system. This work is motivated by the need to develop new mm-wave imaging systems capable of inspecting moving persons concealing potential threats, producing high throughput, and enhancing the overall experience of the passenger at the checkpoint.

ACKNOWLEDGEMENT

This work has been partially funded by the NSF CAREER program (Award No. 1653671) and the U.S. Department of Homeland Security (Award No. 2013-ST-061-ED0001).

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