

High-resolution Automated Millimeter Wave Imaging System

Shiwei Hu¹, Shaoqing Hu¹, Xin Rao², Xiaodong Chen², Nila Nilavalan¹

¹Dept. of Electrical and Electronic Engineering

Brunel University of London

Uxbridge, United Kingdom

²School of Electronic Information

Hangzhou University of Electronic Science and Technology

Hangzhou, China

Abstract- Millimetre-wave imaging has promising applications in security screening, non-destructive testing and medical diagnostics due to its high resolution, non-ionising radiation and ability to penetrate optically opaque materials. However, the use of conventional high-resolution systems based on synthetic aperture radar (SAR) usually requires the use of mechanical scanning devices or tracking equipment for coherent aperture synthesis. In this paper, we propose a millimetre wave imaging system consisting of a FMCW (frequency modulated continuous wave) radar module, a programmable electromechanical XY scanning platform and dedicated control software. The system automatically acquires the echo data on a preset scanning grid, and then reconstructs the image by distance FFT and spatial frequency domain phase compensation. Experimental validation of the method for metal detection shows that the method can clearly distinguish target features and accurately locate the depth.

I. INTRODUCTION

Millimeter-wave (mmWave) radar typically operates in the frequency range of 30 to 300 GHz, corresponding to wavelengths from 1 to 10 mm. Due to its relatively short wavelengths, mmWave radar systems offer high-resolution imaging capabilities, safe non-ionizing radiation, and the ability to penetrate various optically opaque materials, including clothing, plastics, and wood [1]. These advantages enable mmWave radar to effectively measure the reflectivity characteristics of different objects or individuals, making it particularly suitable for applications such as security screening, non-destructive testing, and medical diagnostics. For instance, mmWave imaging technology has demonstrated significant potential in detecting concealed objects beneath clothing, providing clear advantages in safety, detection capability, and operational flexibility compared to traditional methods like metal detectors and X-ray scanners [2-3].

However, achieving high-resolution millimetre-wave imaging remains technically challenging. Achieving high-quality millimeter-wave imaging requires many echo signals, leading to increased hardware complexity and associated costs. And the acquisition of many echo signals may suffer from problems such as data loss [4]. The basic capability of millimeter-wave imaging depends mainly on its spatial resolution, which is inherently limited by the size of the antenna array, which is determined by the number of antennas arranged at half-wavelength intervals. Most current high-resolution

millimeter-wave imaging systems are based on the synthetic aperture radar (SAR) principle [5], which exploits the relative motion between the radar sensor and the target to synthesize a larger virtual aperture from physically smaller antenna arrays, resulting in a significant increase in spanning resolution. In [2], the development of a SAR millimeter wave imaging test bed has been realized in which a commercial frequency modulated continuous wave (FMCW) automotive radar is used instead [6]. Many imaging algorithms have been proposed to obtain accurate target image based on collected echo data from target. For example, the Back Projection Algorithm (BPA) [7-8] obtains reconstruction results by traversing all points in the imaging space, but the method is computationally inefficient. Therefore, Range Migration Algorithm (RMA) [9] was proposed to reconstruct target images by using Fast Fourier Transform (FFT) and matrix multiplication in the frequency domain. However, it is still limited by the Nyquist sampling standard, and a high sampling rate must be used for high precision imaging results.

To overcome the limitation of Nyquist sampling rate, sparse imaging including compressed sensing (CS) methods [10] have been proposed as a cost-effective alternative to reconstruct high-resolution images from sparse data [11]. Meanwhile, deep learning (DL) techniques have been integrated into radar imaging systems [3], which have shown considerable efficiency in reconstructing images from sparse data and accurately classifying targets.

In this paper, a controlled automated collection millimeter-wave radar system is provided, which can synchronously control the radar and the scanning platform for accurate automated data acquisition and image reconstruction.

II. METHODOLOGY

A. FMCW Signal data collection

The imaging system is mainly based on frequency modulated continuous wave (FMCW) chirp signals. The frequency of its FMCW signal is a linear function of time. When a signal is reflected from a target at a distance R , it is mixed with the transmitted signal to produce an intermediate frequency (IF) signal. The IF signal can be expressed as

$$s(t) = \sin(2\pi f_0 t + \phi_0), \phi_0 = \frac{4\pi R}{\lambda} \quad (1)$$

And the intermediate frequency f_0 is proportional to the target distance R and can be expressed as:

$$f_0 = \frac{2KR}{c}, K = B/T, 0 \leq t \leq T \quad (2)$$

where c is the speed of light, K is the chirp slope, B is the bandwidth, T is the chirp duration.

The imaging system comprises an FMCW radar mounted on a motorized X-Y scanning platform and dedicated control software. The control software manages both the mechanical motion of the scanning platform and the radar operations. This enables automated scanning and synchronous radar data acquisition. The radar sensor is mounted on the X-Y stage, which translates to predefined spatial coordinates to synthesize a virtual aperture. Acquisition proceeds as follows: upon system initialization, the control program commands the platform to move to a start position, then communicates with mmWave Studio to trigger chirp transmission and reception. The radar emits a programmed number of chirps and receives the corresponding reflected data from target which will generate an IF signal after a mixer with transmitting signal. Each IF signal is separated into I/Q channels and then stored. Upon completing one line of scanning and recording, the process will be repeated until the full area of interest is scanned.

B. Image Reconstruction

Imaging is performed spatial-frequency domain phase compensation. After range-FFT, each frequency bin corresponds to a specific depth. For a center frequency f_0 , the wave number is:

$$k_c = \left(\frac{2\pi f_0}{c} \right) \quad (3)$$

The spatial frequency components in the x- and y-directions, and define the axial spatial frequency component:

$$k_z = \sqrt{(2k_c)^2 - k_x^2 - k_y^2} \quad (4)$$

Each 2D slice is compensated for:

$$P(x, y) = \mathcal{F}_{x,y}^{-1} \{ \mathcal{F}_{x,y} [S_r(x, y)] \cdot k_z \cdot e^{-jk_z R} \} \quad (5)$$

where $S_r(x, y)$ is the range FFT of the received signal at depth R . $\mathcal{F}_{x,y}$ and $\mathcal{F}_{x,y}^{-1}$ denote the 2D forward and inverse spatial FFTs.

III. EXPERIMENTAL SETUP AND RESULT

The system equipment consists of a three-axis controlled stepping system, a TI AWR 2443 MMW radar sensor, a DCA 1000 data acquisition card, a personal computer, and a target to be measured, as shown in Figure 1.

Metal objects containing different numbers will be detected and imaged.

The imaging experiment was conducted over a planar area of $200 \text{ mm} \times 200 \text{ mm}$, discretized into 101×101 sampling points with a spatial step size of 2 mm (approximately 0.51λ at the



Figure 1 The Prototype of Automated Millimeter Wave Imaging System (center frequency of 76.5 GHz), ensuring half-wavelength spatial sampling. At each scanning position, 256 ADC samples were acquired with a sampling rate of 10 MHz.

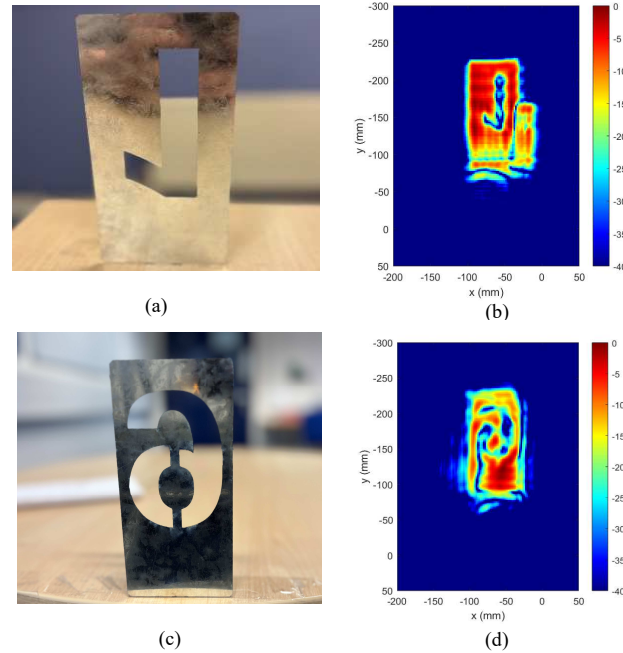


Figure 2 The Reconstruction Results for Two Metal Targets with Different Numbers: (a) First Metal Object with Digital Number 1. (b) The Corresponding Reconstruction Result with Number 1. (c) Second Metal Object with Digital Number 6. (d) The Corresponding Reconstruction Result with Number 6.

Figure 2 shows different reconstruction results. In this experiment, a metal object engraved with numbers was selected as the imaging target. The dimension of target is $8 \text{ cm} \times 6.2 \text{ cm}$. The distance between the object and the imaging system is approximately 0.78 m. The first target is a vertically placed metal plate containing number 1. The synthetic aperture radar (SAR) image successfully reconstructed the overall rectangular contour and the characteristic straight line structure of the number. Its vertical and horizontal extensions below are clearly distinguishable. The second target is a metal plate containing the number 6, with a notch shaped like the number '6.' The reconstructed image shows the curved boundary of the number

and the central gap. However, it is worth noting that the reconstruction results are not entirely ideal. Slight distortion and artefacts can be observed in both images, which are mainly attributed to measurement errors caused by target displacement during the measurement process and approximate calculations in the imaging algorithm. These factors affect the overall reconstruction quality.

Overall, these reconstruction results indicate that the system is capable of reconstructing complex targets.

IV. CONCLUSION

This paper presents a fully automated millimeter wave (mmWave) imaging system that integrates a commercial FMCW automotive radar module, a programmable motorized X-Y scanning platform and dedicated control software. Experimental results show that the proposed system can successfully detect and image metal targets of different sizes with a resolution of 4 mm at 0.78 m achieved, verifying the effectiveness of the proposed method in accurately imaging targets.

REFERENCES

- [1] F. de Chaumont et al., "Real-time analysis of the behaviour of groups of mice via a depth-sensing camera and machine learning," *Nature Biomedical Engineering*, vol. 3, no. 11, pp. 930–942, May 2019.
- [2] M. E. Yanik, D. Wang, and M. Torlak, "Development and Demonstration of MIMO-SAR mmWave Imaging Testbeds," *IEEE Access*, vol. 8, pp. 126019–126038, 2020.
- [3] L. Bian et al., "Towards large-scale single-shot millimeter-wave imaging for low-cost security inspection," *Nature Communications*, vol. 15, no. 1, Jul. 2024.
- [4] Rawin Assabumrungrat et al., "DipSAR: Deep Image Prior for Sparse Sampled Near-Field SAR Millimeter-Wave Imaging," Oct. 2023.
- [5] S. Wei et al., "3DRIED: A High-Resolution 3-D Millimeter-Wave Radar Dataset Dedicated to Imaging and Evaluation," *Remote Sensing*, vol. 13, no. 17, p. 3366, Aug. 2021.
- [6] S. Rao and T. Instruments, "Introduction to mmwave Sensing: FMCW Radars." Available: https://www.ti.com/content/dam/videos/external-videos/ko-kr/2/3816841626001/5415203482001.mp4/subassets/mmwaveSensing-FMCW-offlineviewing_0.pdf
- [7] Nafiseh Mohammadian, Orges Furxhi, R. D. Short, and R. G. Driggers, "SAR millimeter wave imaging systems," May 2019.
- [8] J. Moll, P. Schops, and V. Krozer, "Towards Three-Dimensional Millimeter-Wave Radar With the Bistatic Fast-Factorized Back-Projection Algorithm—Potential and Limitations," *IEEE Transactions on Terahertz Science and Technology*, vol. 2, no. 4, pp. 432–440, Jul. 2012.
- [9] Y. Zhang, B. Deng, Q. Yang, J. Gao, Y. Qin, and H. Wang, "Near-Field Three-Dimensional Planar Millimeter-Wave Holographic Imaging by Using Frequency Scaling Algorithm," *Sensors*, vol. 17, no. 11, p. 2438, Oct. 2017.
- [10] R. Baraniuk, "Compressive Sensing [Lecture Notes]," *IEEE Signal Processing Magazine*, vol. 24, no. 4, pp. 118–121, Jul. 2007.
- [11] Amir Masoud Molaei, R. Kumar, S. Hu, V. Skouroliahou, V. Fusco, and Okan Yurduseven, "A Compressive Sensing-Based Approach for Millimeter-Wave Imaging Compatible with Fourier-Based Image Reconstruction Techniques," *Research Portal (Queen's University Belfast)*, Sep. 2022.