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RESEARCH ARTICLE

2D Millimeter-Wave SAR Imaging with Automotive Radar

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HIGHLIGHTS

- *Development of low-cost, low-complexity, and easy-to-implement 2D mmWave SAR imaging system*
- *By employing single transceiver pair and taking sparse samples SAR imaging of UAVs is achieved.*
- *mmWave FMCW SAR imaging applications have the potential to be an innovative approach to UAV detection.*

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ABSTRACT

In recent years, millimeter wave (mmWave) frequency modulated continuous wave (FMCW) radars have gained popularity in radar imaging applications, coinciding with the advancement of mmWave technology. However, high cost and integration complexity still remain as issues in cases where the target aperture is large. This work introduces a low-cost, low-complexity, and easy-to-implement two-dimensional (2D) mmWave synthetic aperture radar (SAR) system. A commercial-off-the-shelf (COTS) mmWave FMCW radar sensor operating in the frequency range of 77-81 GHz is employed. A large mechanical scanning system which can move in both vertical and horizontal directions is constructed and integrated with the radar sensor. Developing a graphical user interface (GUI), an automatic movement of the scanner is achieved. Experimental measurements are taken in a laboratory environment and the effectiveness of the system is demonstrated. A cross-shaped metal object and a drone are chosen as targets and the SAR images of targets are obtained. For simplicity, by employing a single transceiver pair, sparse samples are taken in a large scanning aperture. It has been shown that the proposed scanning system has great potential in SAR imaging of large objects such as unmanned aerial vehicles (UAVs).

Keywords: *mmWave, Frequency modulated continuous wave radar, Synthetic aperture radar, Sar imaging, Drone, Unmanned aerial vehicle*

I. INTRODUCTION

In recent years, radar imaging has been in demand since having the ability to successfully operate in different weather conditions, distances, and surroundings [1]. Studies concerning imaging using mmWave sensors ranging from 30 GHz to 300 GHz have increased distinctively in many civilian, commercial, and military applications [2-4]. Specifically, millimeter-wave (mmWave) imaging has emerged as one of the most significant technologies of near-field imaging applications [5]. Custom-built systems are proposed in the initial studies including concealed item detection [6], three-dimensional (3D) imaging [7], and multistatic structures [8]. Along with the advantages such as health-wise nonhazardous frequency band and diffusion capability to a variety of materials, mmWave frequencies can bring some disadvantages such as demand for a large number of antennas to obtain a high-resolution image, relatedly high cost and integration complexity.

Lately, commercial-off-the-shelf (COTS) mmWave frequency-modulated-continuous-wave (FMCW) radar systems have gained popularity in synthetic aperture radar (SAR) imaging applications due to their advantages such as low cost, easy access and simple implementation [9]. Consequently, COTS mmWave FMCW radar sensors have begun to be employed in a variety of fields including automotive [10], medical [11], and defense [12] industries and the studies regarding achieving high-resolution imaging have gained diversity. To obtain high resolution, multiple-input multiple-output (MIMO) SAR systems take the lead in the literature. A novel algorithm is introduced in [13] for near-field MIMO-SAR imaging with irregular scanning geometries. An algorithm for mmWave MIMO-SAR imaging for automotive applications presented in [14]. [15,16] employ the MIMO-SAR imaging of small objects in near-field. Additionally, mmWave radar sensors have begun to take part in sensor fusion applications. Employing optical and mmWave SAR image fusion, indoor object recognition is proposed in [17]. Employing 68-92 GHz FMCW radar, 2-D multi-object indoor environment mapping is implemented. Using the combination of SAR and optical images, the recognition of the objects in the indoor environment is carried out. Yet, above-mentioned applications may bring also cost and complexity issues along in cases where the target aperture is large.

Recent advancements in mmWave FMCW radar applications offer great potential in the detection of hostile agents such as unmanned aerial vehicles (UAV). UAV detection and ranging are achieved by employing FMCW radar operating at 77-81 GHz in [18] and at 35 GHz in [19]. For the detection of nano-drones, a K-band FMCW radar is designed and the micro-doppler signatures are obtained in [20]. mmWave FMCW SAR imaging applications also have the potential to be an innovative approach to UAV detection due to advantages such as low cost, low complexity, and ease of implementation, however, the literature has remained largely insufficient.

In this study, a low-cost two-dimensional (2D) mmWave SAR imaging system is proposed. Contrary to many existing studies, SAR measurements are taken by using a low-cost COTS radar and scanning system in a laboratory environment instead of high-cost, high-complexity, and difficult-to-access radars and scanners, and an anechoic chamber. To reduce the cost and complexity, monostatic SAR measurements are taken instead of employing MIMO topology. A SAR imaging system is created by employing a COTS mmWave FMCW radar sensor and mounting it on a scanning platform. A 1 meter by 1 meter scanner is constructed. Constructing a scanner with an extended aperture enables SAR imaging of large objects. While the scanning platform moves in both vertical and horizontal directions, the radar sensor collects measurements. By this means, a virtual antenna array is obtained in a desired scanning aperture. By considering the Nyquist sampling criterion along with the cross-range resolution of the image, SAR measurements are taken. After the image reconstruction process, the 2D SAR image of the target is obtained. The applicability of the scanner is confirmed by experimental measurements. A large cross-shaped metal object and a drone are used as targets. By employing the SAR scanning system of reduced cost and complexity and taking sparse samples, the imaging of the targets is achieved.

The remaining of the paper is organized as follows; Section II proposes the related literature in the field. In Section

III, the radar signal model, SAR system design specifications, and the employed image reconstruction method are mentioned. The construction of the scanning system and the experimental system configuration are presented in Section IV. The results are given in Section V. Section VI draws conclusions.

II. RELATED WORK

A low-cost, high-resolution mmWave FMCW SAR imaging system is proposed in [21]. The 77 GHz radar sensor is combined with a two-axis scanner. The maximum scanning range of the system in both directions is 40 cm which limits the size of the target to be scanned. Since the scanning aperture is small, SAR imaging of small targets is studied at close range.

In [9], a near-field MIMO-SAR mmWave imaging of small objects is achieved by taking sparse samples. A 77 GHz FMCW radar is mounted on the 40 cm scanner. High resolution images of small objects are obtained. However, employing MIMO array topology brings complexity issues.

A near-field mmWave FMCW-SAR based static hand gesture recognition application is presented in [22]. SAR images of different hand gestures are obtained with 77 GHz MIMO radar sensor and a two-axis scanner. The maximum distance between the radar and the scanner is set to 40 cm.

When the related works are examined, it can be concluded that mmWave FMCW SAR imaging applications are studied especially for near-field scenarios and small objects. To obtain high resolution, MIMO array topology is employed at the cost of computational complexity.

III. METHOD

A. FMCW Signal Model

An FMCW radar generates a frequency modulated signal which is also known as a chirp signal. The transmitted chirp signal can be expressed as in eq.(1)

$$m(t) = \cos(2\pi f_i t + S\pi t^2) \tag{1}$$

where f_i is the instantaneous carrier frequency and S is the frequency slope which can be derived from the bandwidth B and the chirp duration T

$$S = \frac{B}{T} \tag{2}$$

The transmit signal hits the target and is received back with a round trip delay τ

$$m(t-\tau) = \cos(2\pi(f_i\tau + S\tau \mathrm{t}) - S\pi\tau^2) \tag{3}$$

$S\tau$ indicates the beat frequency f_b and it provides the range of the target. $S\pi\tau^2$ is known as the residual video phase (RVP) and can be neglected. Thus, the received signal in eq.(3) can be rewritten as

$$r(t) = \cos\big(2\pi(f_i\tau + f_b \mathrm{t})\big) \tag{4}$$

B. SAR System Design

A cost-effective 2D SAR imaging system is designed by integrating a radar sensor with a mobilizing scanner as shown in Fig.1. This method yields a sampling of the target aperture vertically and horizontally. The sampling distance is indicated in the horizontal direction as a_x, and the vertical direction as a_y. By employing one transmit and one receive antenna, an array of virtual antennas is created. The radar scans the total area of $A_x x A_y$ with a sampling steps of a_x and a_y. After the image reconstruction process, a 2D image of the target at the distance z is created.

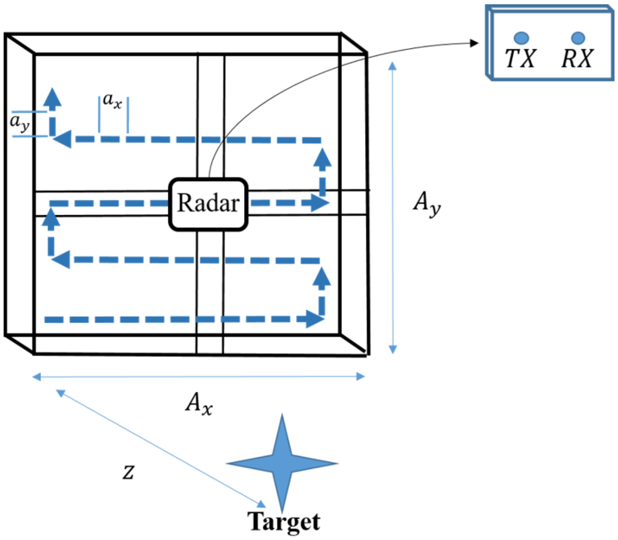


Figure. 1. SAR system motion demonstration.

By taking measurements at each xy measurement point, a data cube $r(x, y, t)$ is obtained based on the received signal in the eq.(4). The SAR image of the target is reconstructed by obtaining the reflectivity function $s(x, y)$ from the received data cube $r(x, y, t)$.

C. SAR System Specifications

The well-known range resolution z_{res} can be calculated from the bandwidth B and the speed light constant c as follows

$$z_{res} = \frac{c}{2B} \tag{5}$$

For 2D SAR imaging, the cross-range resolutions in horizontal and vertical directions represents the image resolution [23]

$$z_{x,y} = \frac{z\lambda}{2A_xA_y} \tag{6}$$

where λ is the wavelength, A_x and A_y are the total scanning apertures in horizontal and vertical directions respectively as shown in Fig.1.

Additionally, to prevent aliasing and consequently ghost images, the Nyquist spatial sampling criterion should be met while taking measurements. The sampling intervals a_x and a_x shown in Fig.1 should be specified accordingly

[7]. For the worst case, spatial sampling distances should satisfy $a_{x,y} < \lambda/4$.

Considering the above-mentioned criteria, spatial sampling intervals, SAR aperture size, and target distance from the radar are determined.

D. SAR Image Reconstruction

In SAR imaging applications, to reconstruct the target image, the reflectivity function should be recovered from the collected radar data. For this purpose, image reconstruction algorithms are employed. This paper uses a matched filter-based image reconstruction [24] to create a SAR image of the target from the collected data set by the constructed SAR system. Since the method is based on the distance of the target, SAR imagery of multiple targets at different distances on the same alignment can be achieved. The system's impulse response can be determined as follows

$$h(x,y) = \exp(-jk\sqrt{x^2+y^2+z^2}) \tag{6}$$

where k is the wavenumber, z is the distance between the radar and the target, x and y denotes the measurement points at horizontal and vertical directions respectively. The reflected signal can be determined by the following convolution operation

$$r(x,y) = s(x,y) * h(x,y) \tag{7}$$

Thus, taking the 2D Fourier transform (F_{2D}) of both the received signal and the filter, multiplying them in the spatial frequency domain, and subsequently taking the inverse Fourier transform (F_{2D}^{-1}) to return back to the spatial domain gives the reflectivity function

$$s(x,y) = F_{2D}^{-1}[F_{2D}(r(x,y))F_{2D}(h(x,y))^*] \tag{8}$$

The data cube creation and image reconstruction processes are conducted in the Matlab environment.

IV. EXPERIMENTAL SYSTEM CONFIGURATION

A low-cost SAR system is constructed by integrating an mmWave radar sensor and a two-axis scanner.

A. Radar Sensor

A COTS mmWave FMCW radar sensor AWR1642 developed by Texas Instruments (TI) is employed for experimental measurements. For data acquisition, TI's DCA1000 evaluation module is integrated with AWR1642. The radar system is shown in Fig.2. AWR1642 offers a maximum bandwidth of 4 GHz between the operating frequencies 77-81 GHz. It allows MIMO measurements with two transmit and four receive antennas. DCA1000 captures the data and transfers it to the host computer. At the host computer, mmWave Studio Suite environment is used to display and process the captured data. Using this environment, board control, setting the parameters of a chirp signal, post-processing of ADC data, and visualization of processed data operations can be conducted. From the mmWave Studio, the received signal can be extracted in the form of complex in-phase/quadrature (I/Q) at intermediate frequency (IF).

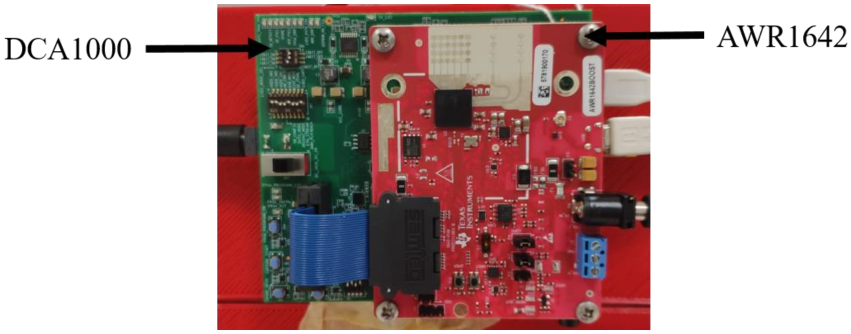


Figure. 2. Radar system.

B. SAR Scanner

A 2D mechanical scanning system that can move in horizontal and vertical directions is designed and the radar module is mounted on the system as shown in Fig.3. The scanning aperture of the system is 1 meter in both vertical and horizontal directions. The large aperture of the scanner provides the flexibility to obtain high-quality SAR images of small targets along with sparse sampled SAR imagery of large targets. The system takes stationary measurements between the sampling distances and the minimum sampling distance is achieved as 1 mm. The motion of the scanner is enabled with four stepper motors. The measurements are taken in a laboratory environment without an anechoic chamber.

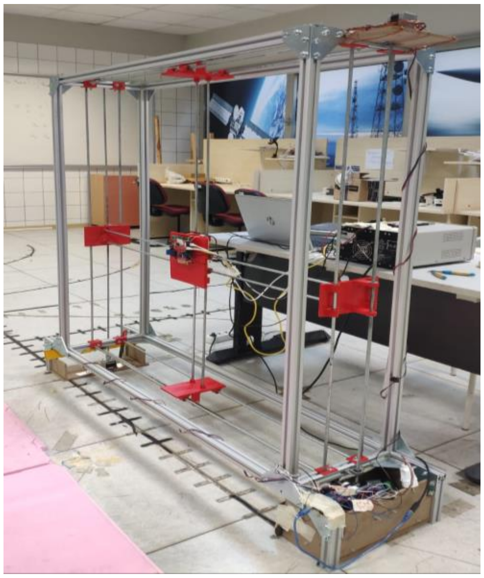


Figure. 3. SAR scanner.

C. *SAR System*

The SAR scanning system is constructed by combining the mechanical scanner and the mmWave radar sensor. Both the radar sensor and the microcontroller are linked to the host computer. As a microcontroller, Arduino UNO is employed. The radar sensor is controlled by the mmWave Studio. A graphical user interface (GUI) is designed to control both the mmWave Studio and the motion of the system as demonstrated in Fig.4. The system is designed so that the elapsed time between successive samples is 5 seconds.

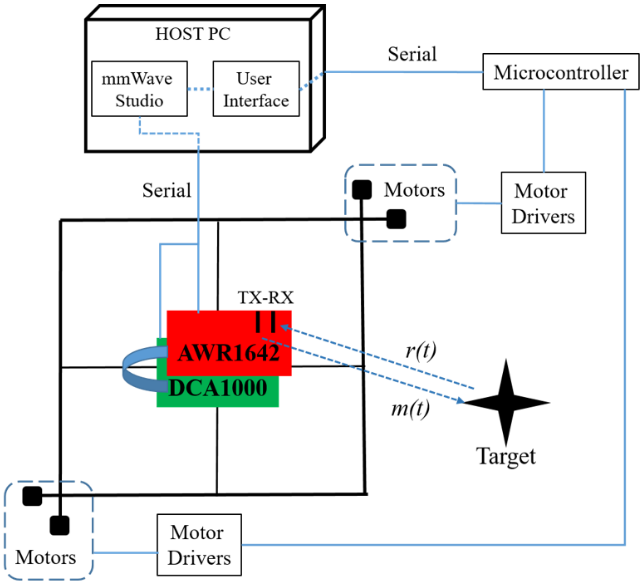
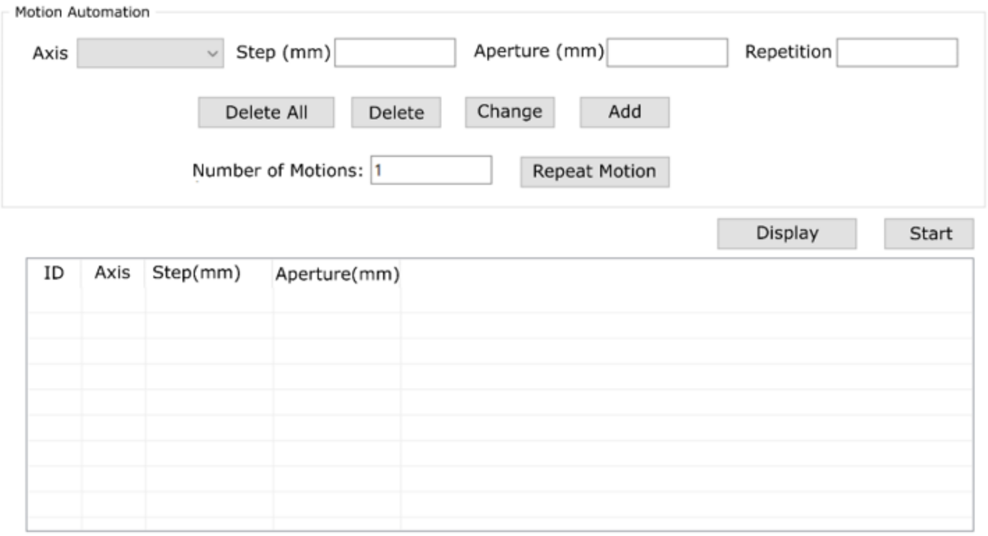


Figure. 4. Structural diagram of the SAR system.

Using the interface, users can specify sampling distances, total scan apertures, and motion repetition in both the vertical and horizontal axis. The designed user interface is shown in Fig.5.



Number of Motions: 1

Figure. 5. User interface.

V. RESULTS

By taking monostatic measurements of different types of objects in a laboratory environment, the constructed SAR imaging system is verified.

A 45x45 cm cross shape metal object is used as target as shown in Fig.6. One transmit and one receive antennas were used. The distance between the scanner and the target was set to 70 cm. The total scanning aperture was 30 cm and the sampling distance was 4 mm which gives the image resolution of 4,3 mm in both vertical and horizontal directions. A 256x75x75 radar data cube is obtained with a total of 5625 measurement points. By taking sparse sampling, a SAR image of a large object is reconstructed successfully.

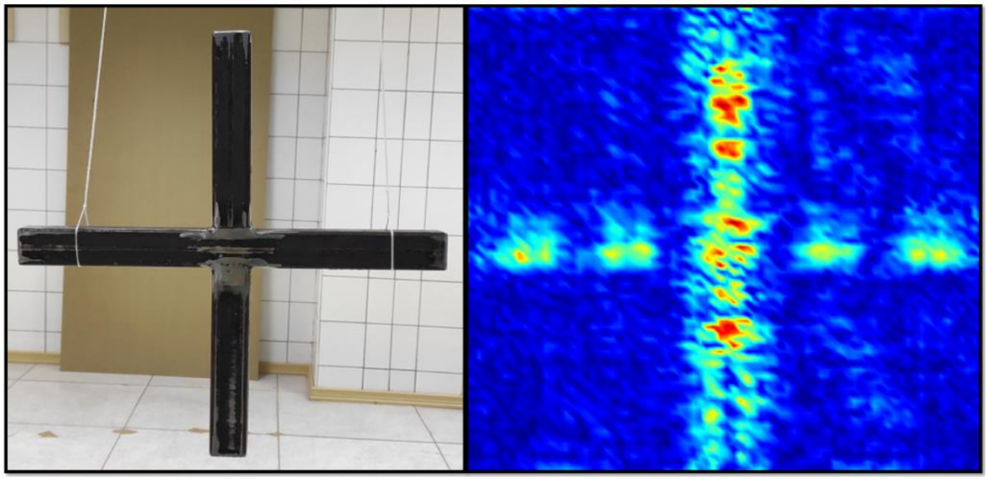


Figure. 6. SAR imaging result of cross object at 70 cm distance.

Then, the same object is settled 30 cm before the radar. 10 cm of aperture is scanned with 3 mm sampling distances in both vertical and horizontal axes. The imaging result is given in Fig.7.

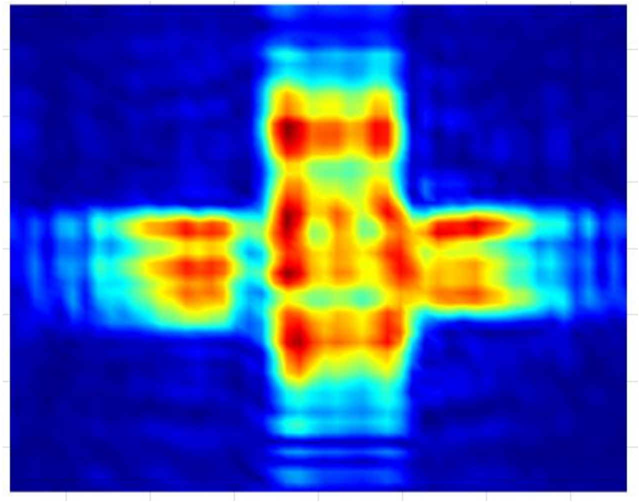


Figure. 7. SAR imaging result of cross object at 30 cm distance.

Lastly, the imaging of a 45x45 cm drone is achieved. The drone is put at 70 cm distance from the radar. 30 cm aperture is scanned with 4 mm sampling distances. The imaging result is shown in Fig.8.

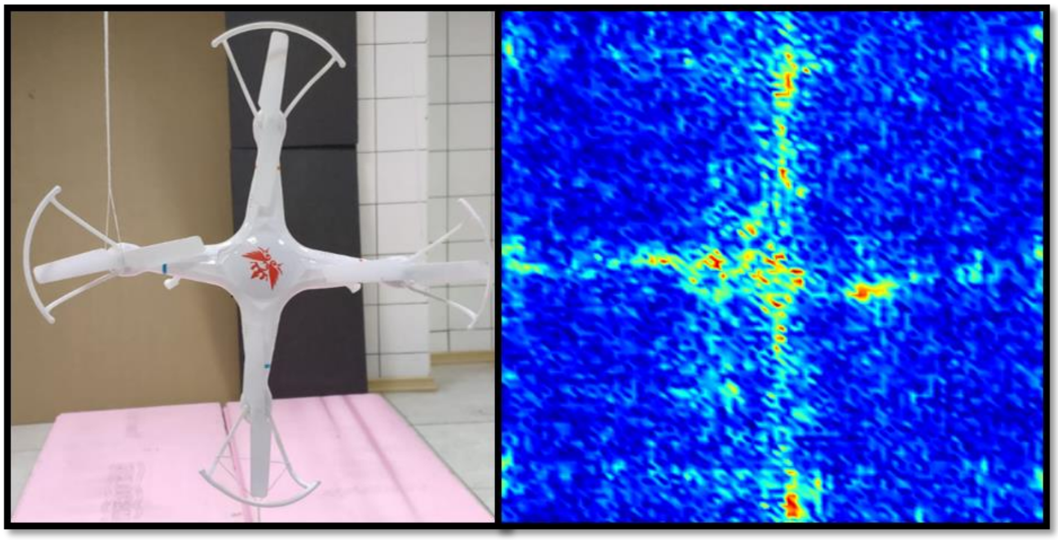


Figure. 8. SAR imaging result of drone at 30 cm distance.

VI. CONCLUSION

In this work, as a part of an ongoing study, employing mmWave SAR imaging techniques and using low-cost COTS radar and scanning system, SAR imaging of different types of targets is achieved in a laboratory environment. First, a low-cost radar scanner is built to obtain a SAR imaging system. Then, a radar data cube is created by taking monostatic measurements with mmWave FMCW COTS radar mounted on the scanning system. By taking sparse samples, the SAR imagery of large cross-shaped metal object and a drone is obtained. Promising results have been obtained for future UAV detection studies. In future work, employing deep learning applications, the recognition of SAR images of different types of targets can be employed. The recognition success can be studied in different image resolutions.

CONFLICTS OF INTEREST

They reported that there was no conflict of interest between the authors and their respective institutions.

RESEARCH AND PUBLICATION ETHICS

In the studies carried out within the scope of this article, the rules of research and publication ethics were followed.

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