Drone Detection and Tracking Based on Phase-Interferometric Doppler Radar

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***Abstract*—In this paper, drone detection and tracking based on phase-interferometry are investigated. Data collected by a simple dual-channel Doppler radar is used for implementing the joint range-Doppler-azimuth processing. Experimental results show that micro drones can be detected and tracked by applying the joint range-Doppler-azimuth processing. Features extracted from the range-Doppler-azimuth domain can be used to identify drones.**

Keywords—Drone detection, interferometric radar, angle of arrival, micro-Doppler signature, range-Doppler-angle processing

I. INTRODUCTION

Radar has advantages over other sensors for detection and tracking drones at long distance, day/night, under all weather conditions, and diverse acquirable information (range, velocity, angle of arrival, micro-Doppler signature). Thus, varieties of radar approaches have been proposed to detect, track and classify drones.

Compared to other air targets, drones are usually small-sized and flying relatively slow and at low altitude. Thus, there are many challenges for radar detection, tracking, and classification of drones.

The RCS of a drone varies with its size and material, the operating frequency and viewing angle from the radar. The RCS of a drone body is small, and the RCS of its rotor blades is even smaller. Measurements of typical drones have been conducted and reported in [1, 2]. The RCS of its main body is about 0.01sm (or -20dBsm) and plastic blades is less than 0.001sm (or -30dBsm).

Other small targets that often fly at low altitude are birds. Surveillance radars see them from time to time. The RCS of a seagull is usually larger than that of a drone. Thus, how to distinguish a drone from birds is challenging [3,4]. Only from its flight velocity and height, it is not possible to tell a drone from a bird. Therefore, more detailed micro-motions of drones and birds become possible features for drone classification.

In general, for detection of a drone, the requirements for a radar system include: (1) high system stability and receiver sensibility for detecting RCS smaller than 0.01sm; (2) high clutter suppression (>50dB) and Doppler resolution (< 0.5m/s) for detecting slow flying targets from clutter; (3) maximum unambiguous range for covering the detectable range of 1–4km; (4) maximum unambiguity velocity for covering the highest radial velocity of < 8-10 m/s; (5) detecting flight height coverage up to 300 m and tracking height up to 100 m; and (6) azimuth angle coverage up to 90º and elevation angle coverage up to 30º.

For classification, the requirements may be modified by: (1) the receiver sensibility for detecting RCS smaller than 0.001sm; (2) maximum unambiguity range for classifying targets will be smaller than the detecting range; and (3) maximum height for classifying targets is no more than the tracking height.

Based on these requirements, we use a Doppler radar with dual-channel phase-interferometry to track drones as illustrated in Figure 1.

Fig. 1 – Dual-channel Doppler radar tracking drones.

The radar parameters for our experimental study are listed in the Table 1.

Table 1 – Radar Parameters

Frequency Band	C-Band at 5.8 GHz
Bandwidth	300 MHz
Transmit Power	19 dBm
Receiving Channels	2 receiving antennas with spacing of 0.8 λ
Azimuth Coverage	70º
Elevation Coverage	30º
Waveform	LFMCW Sawtooth + CW
Sweep Time	1 ms
Samples per sweep	128

By using two receiving channels, the radar configuration with phase-interferometry principle makes the radar system possible for estimating the angle of arrival (AOA). Along with

CFAR-based range-Doppler processing, the radar system is possible to track trajectories on 3-D range-velocity-angle map. The additional AOA information helps us improve target classification. The basic processing procedure includes (1) parallel reception in two receiving channels; (2) sequentially collecting number of sweeps to make a frame; (3) making range-Doppler compression by IFFT and FFT; (4) CFAR threshold for suppressing clutter and noise; and (5) combining range-Doppler data from the two channels to make 3-D range-Doppler-angle map through beamforming.

Having the 3-D range-velocity-angle map, we can track the range, velocity, and azimuth angle of detected targets from frame to frame. By applying feature extraction algorithms, such as mean spectrogram, maximal micro-Doppler shift, and micro-Doppler signatures [5], a set of features can be collected and, then, send to a classifier, such as support vector machine (SVM), neural networks, or deep learning, to perform target classification [4].

In this paper, we will mainly describe how to use our experimental Doppler radar and based on the phase-interferometry principle to detect and track range, velocity, and angle of arrival of mini-drones

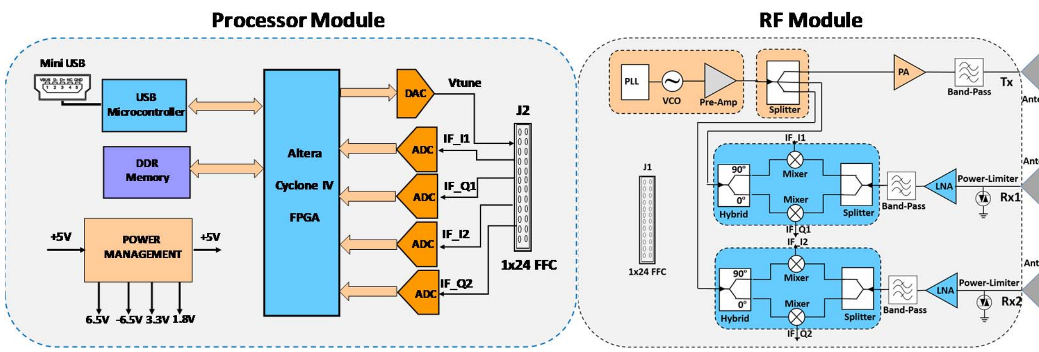

Fig. 2 – Radar system block diagram.

II. Radar System description

The C-band radar system, centered at 5.8 GHz with dual receivers is used for the drone detection and tracking. The system consists of an RF front-end and a processing board. The heart of the processing board is the Cyclone-IV FPGA. A system block diagram is shown in Figure 2.

The system consists of an RF front-end and a Processor Board. The heart of the processor board is the Cyclone-IV FPGA. A phase-locked loop (PLL) unit in the RF front-end is controlled by the FPGA to compensate the nonlinear nature of the VCO and provide better linearity in linear FMCW with accurate sweep bandwidth. Received signals are down-converted to base-band I and Q signals and sampled by four ADCs in the processing board. FPGA streams received I and Q samples to a PC via USB 2.0 port for further signal processing.

A patch antenna is used in the radar system via SMA RF cables. The radar transmitting power is 19 dBm and the gain for both receiving antenna is 15 dBi. For covering ±35º azimuth angle, The spacing between two receiving antennas is 0.8 wavelength.

A graphical user interface (GUI) was developed for easy-control of the waveform (FMCW/CW) and radar parameters, such as sweep bandwidth, sweep time, and sampling rate. It continuously receives data streamed from the USB port and for quick signal examination, it also provides time domain plot, range profile, range-Doppler map, etc. Data can be recorded for further processing.

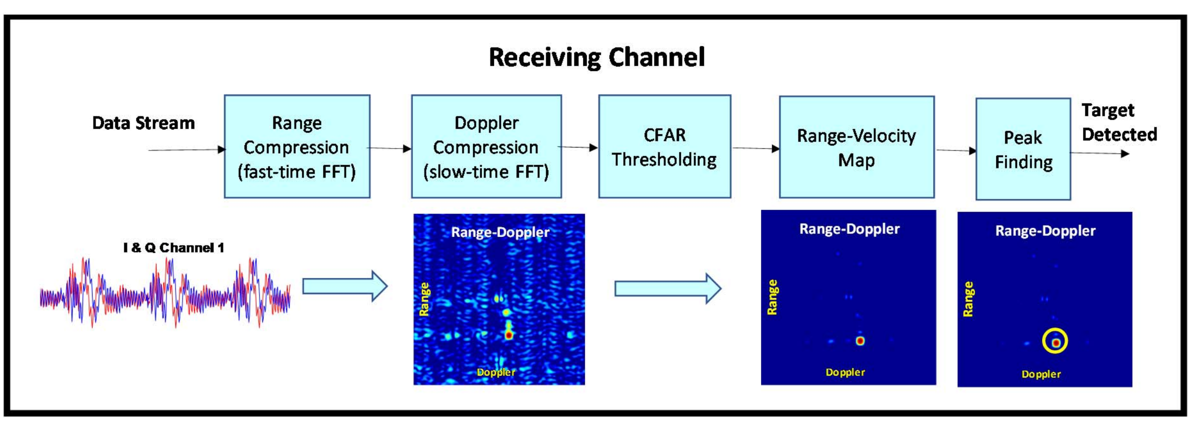

Fig. 3 – Range-Doppler processing.

III. Signal Processing

A. Range-Doppler Processing

Range-Doppler processing is performed on time sequence of the data stream for each receiving channel as shown in the Figure 3. After range compression and Doppler compression, a sequence of 2-D range-Doppler frames can be formed. Then, by applying a constant false alarm rate (CFAR) thresholding, a sequence of clutter and noise suppressed range-Doppler frames is obtained for detecting targets.

For 300MHz bandwidth, the range resolution is $\Delta r = c/2B = 0.5$m, where c is the propagation speed. If the sweep time T is 1ms or the pulse repetition frequency (PRF) is 1,000 Hz and the number of sweeps for each frame is L = 64, then the Doppler resolution is $\Delta f = PRF/L = 15.625$ Hz, or the velocity resolution is $\Delta v = \Delta f \cdot \lambda/2 = 0.4$ m/s. The unambiguous velocity is $V_{max} = \pm(PRF/2) \cdot \lambda/2 = \pm 12.6$ m/s. If we select 128 samples per sweep, the fast-time sampling rate becomes $F_S = 128$ kHz. Thus, the maximum range coverage R_{max} is 32m.

B. Range-Azimuth Processing

Analysis of the data across the receiving channels makes it possible to examine the spatial frequency content. The field of view is determined by $\theta_{max} = \pm\sin^{-1}(\lambda/2d)$, where d is the antenna spacing. We use 0.8 wavelength spacing between two receiving antennas to make the field of view of ±35º.

We detect a drone displayed in the range-Doppler map by finding local peaks in the range-Doppler domain. Then, FFT-based beamforming method is used to measure the angle-of-arrival information on the detected targets, which may be realized by performing the FFT along the 3rd spatial-sampling dimension. Modern spectral analysis method, such as the Multiple Signal Classification (MUSIC) algorithm can be used to obtain a high-resolution angle profile.

Figure 4 illustrates joint range-Doppler-azimuth processing. Based on a sequence of 3-D range-Doppler-azimuth map generated by the processing, we can generate range trajectory, Doppler trajectory, azimuth angle trajectory, and micro-Doppler signatures of the detected targets. Features extracted from these trajectories and maps can be input to the classifier.

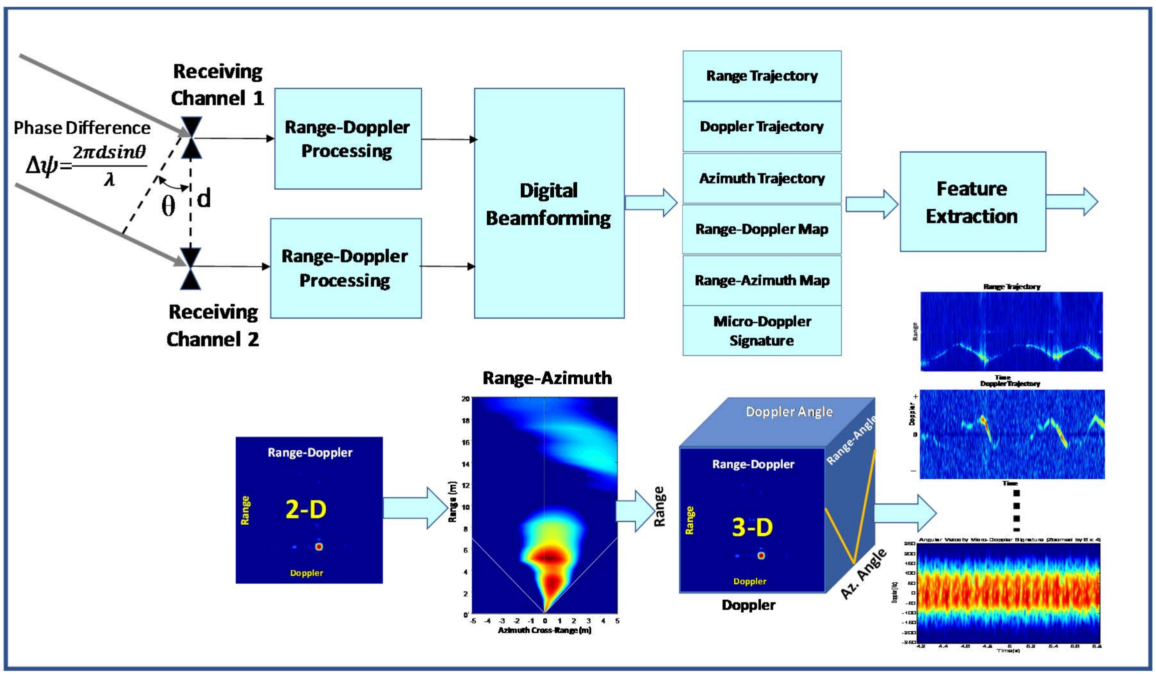

Figure 4 – Joint range-Doppler-azimuth processing.

IV. Experiments on Detection and Tracking of Drone Using Range-Velocity-Azimuth Analysis

A DJI Phantom 3 was used in this study. The Phantom 3 is categorized as a micro-UAV system, with radar cross section of 0.05sm (-13dBsm). The maximum speed when flying horizontally is 15 m/s that is larger than the 12m/s maximum unambigous velocity the radar can measure. For experimental purpose, we limit the speed of the drone within 3 m/s.

To demonstrate tracking capability of the system, circular flying trajectory was recovered in a range and cross-range map as shown in Figure 5 (75 time frames excerpted). The drone started at around 10 degrees to the left of the radar, 4 meters away (the green dot). At 11 meters, it made a turn and flew back next to its starting point (the red dot). The range trajectory is shown in Figure 6, and the velocity tracjectory is plotted in Figure 7.

V. Micro-Doppler Signatures

The rotor rotation rate of a DJI drone is around 33 rps when idle, and 150 rps when at full power. When hovering, the average rotation rate is about 110 rps. The length of the rotor blade is 12 cm. The main scattered center is around 3 cm away from the center of the blade. When the blade rotates at the rate of 110 rps, the 3-cm-away-from-the-center-of-the-rotor is at 20 m/s, hence the main expected Doppler frequency shift we can observe of a rotating blade is around 774 Hz, higher than our current FMCW configuration can afford. Hence, we switched the system to work in the CW mode, where the sampling rate is 128 kHz. This sampling rate provides plenty of frequency room to work with.

The length of data recording is 30-second while the drone was flying back and forth relative to the radar. Data was down-sampled to 4kHz. Part of the data was used to generate the micro-Doppler signature shown in Figure 8. The body of the drone is the main Doppler component. Majority of the energy reflected from the blades is ± 500Hz around the main Doppler shift, spreading beyond the 2kHz limit.

Due to arbitrary initial phase of the four rotors in the drone, information such as blade length, rotation speed cannot be identified from the micro-Doppler signature. However, the maximal micro-Doppler shift can serve as an important feature to classify the target to a drone from birds.

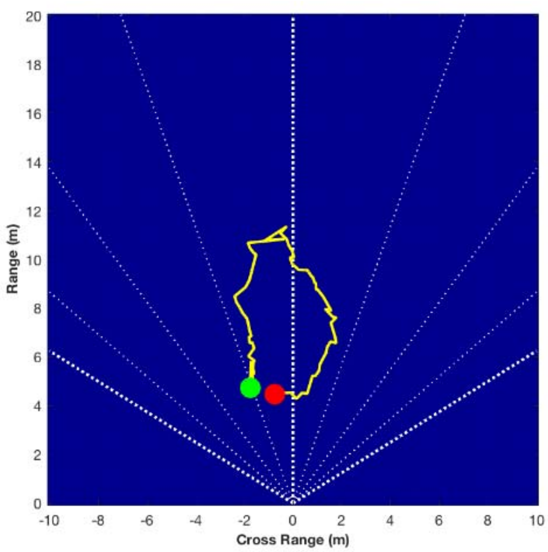

Fig. 5 - Joint range and cross-range trajectory.

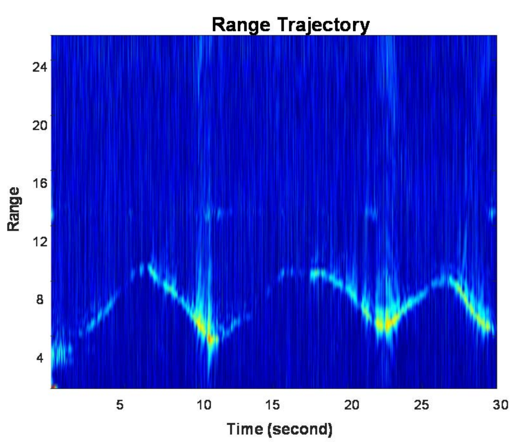

Fig. 6 - Range trajectory.

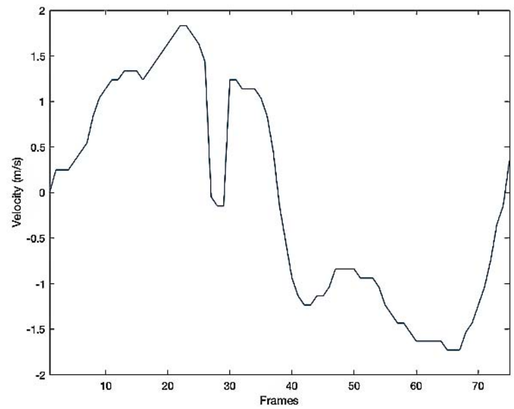

Fig. 7 - Velocity (Doppler) trajectory.

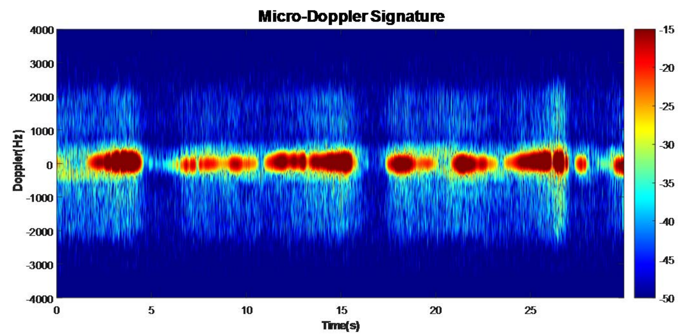

Fig. 8 - Micro-Doppler signature of the flying DJI phantom 3.

VI. CONCLUSION

A phase-interferometric Doppler radar system in C band was used to collect data from a flying drone. In each defined time frame, a range-Doppler-azimuth cube was generated. Trajectories in range, velocity, range-azimuth domain were recovered. Micro-Doppler signature was obtained. All of these features can be useful in drone classification.

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