Enhanced ISAR Imaging for Surveillance of Multiple Drones in Urban Areas

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***Abstract*—In this paper, we attempt to generate high resolution profile of flying drone targets. To this purpose, multi-bands radar signals are adopted to carry out inverse synthetic aperture radar (ISAR) imaging of moving drones. After theoretical analysis is performed, experimental results are acquired through field tests. demonstrate that high resolution ISAR imaging provide effective measures to detect and classify the class of multiple target drones.**

Keywords—Drone detection; Inverse Synthetic Aperture Radar; Micro-Doppler; Radar; Target detection

I. INTRODUCTION

There are increasing demands to provide early warning against intruding drones and recognize potential threats. Recent anti-drone systems are mostly based on simple target radar reflections. In real scenario, however, it will be essential to obtain drone radar signatures so that hostile targets are recognized in advance. Micro-Doppler radar signature delivers partial information on multi-rotor platforms and provides only limited performance for drone recognition and classification.

In future urban environment, it is anticipated that multiple number of drones are flying at near distances. Subsequently, there is also a growing safety issues concerning the terrors, crimes and national security. In particular, the increasing number of unidentified drones will become a prominent threat on national security. Despite the recent efforts to cope with this problem, there still exist concerns in regards to technical development against drone threat. In this study, ISAR image analysis is employed for drone surveillance purpose and experimental test results are presented for drone detection and classification. The technique may be further developed to become a major strategic tactic for the development of a weapon system that enables to classify the incoming drones from hostile forces.

Drone detection problem is characterized by the stealthy operation flying at low altitude under low level signature. Conventional anti-drone problem is mostly limited by the simple target detection by overcoming the low radar cross section of small drones. Multi-quadrotor drones are intensively investigated through micro-Doppler phenomenon. Dones based on multi-rotor platforms that fly in remote distances are usually difficult to detect or identify as their components exhibit low heat dissipation, noises and reflectivity. Research works have been actively carried out on drone detection that adopt networks of various sensors such as heat, sound, radar and laser. Among others, radar is considered as the most promising candidate for active sensing and tracking of the flying drone [2]. Recent works for drone detection are mainly based on FMCW (Frequency Modulated Continuous Wave) radar as they are useful to detect the micro Doppler pattern generated from the operational multi-rotors platforms [3]. Although they provide unique Doppler signature distinguished from other surrounding objects, the detection ranges are limited. In addition, the detailed target profiles, essential for a complete target classification, are missing in micro-Doppler images.

An ultra-high resolution ISAR (Inverse Synthetic Aperture Radar) image has been obtained with UWB (Ultra-Wide-Band) radar [4]. However, like FMCW, a low-powered UWB short-pulse systems would suffer from short detection ranges.
Typical commercial drones have physically small sizes that are not visible in a few hundred meters and exhibit RCS below -20 dB [5]. ISAR technique may extend the target detection range by improving signal-to-noise ratio (SNR) in pulsed mode operation. Moreover, the coherent high-gain image processing of ISAR would be useful to increase the sensitivity of the weak echo signal at the receiver.

This paper present some of test results that have been recently performed against flying multi-rotor drones flying in long distances. ISAR is typically used to acquire high resolution radar images for target recognition purposes. We implement a FMCW radar-based drone detection system in urban environment. Through repeated experimental tests, the feasibility of the ISAR drone detection and classification is investigated in practical scenarios against intruding drones. For a good ISAR images acquisition, it is essential to compensate for irregular paths of the moving targets. Accurate motion compensation (MOCO) in both rotational and translational directions is required. The problem is further aggravated for multi-rotor drones as, without navigation data, their flying paths are non-predictable and suffer from irregular disturbances. It is desirable to extend the target observation duration to increase the target resolution but with the increased complexity of MOCO implementation. Another issue is derived from the phase disturbance by rotating blades that cause micro-Doppler (m-D) corruption within reflected signals. In this paper, m-D phase corruption is compensated with high efficiency by adopting time-varying clutter suppression along the azimuth slow time interval. This is in contrast with the conventional approach where m-D suppression is mostly performed in fast time domain during range compression procedure.

We have demonstrated that, multiple number of rotor based commercial drones are identified and classified with high resolution ISAR imaging. The target drones are taken in real operation scenario while simultaneously flying over urban areas

II. ISAR IMAGING FOR DRONE

A. Overview

ISAR technique is widely used in surveillance application like military purpose for auto target recognition. Fig. 1 illustrates the geometry of ISAR for multiple drones.

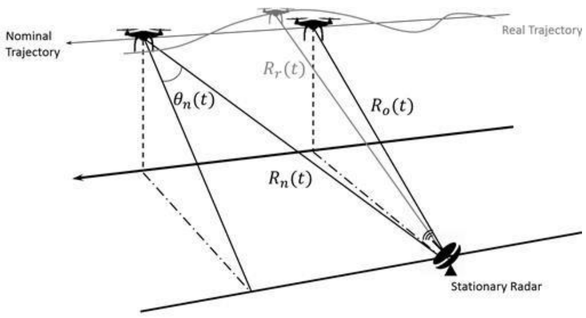

Fig. 1. Geometry of ISAR imaging against flying drones

Unlike SAR case, the nominal trajectory of the ISAR target path should be estimated with no prior knowledge of its flight information. The problem becomes further complicated for multi-rotor drone targets, where motional disturbances are affected by weather conditions or hardware instability. It is highly likely that tracking errors may become severe and lead to poor parameter estimation. Hence, extra care should be taken to generate focused target image with acceptable accuracy

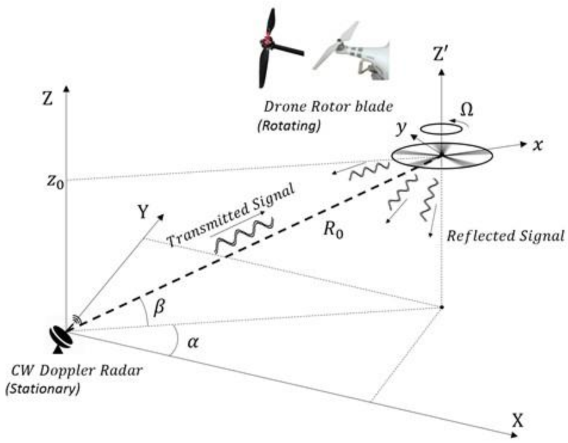

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Fig. 2. Time varying micro-Doppler clutter generation by rotating blades

Fig. 2 shows a typical configuration of multi-rotor platform. In conventional ISAR geometry, motion errors can be separated in translational and rotational directions. With the range error given as $\Delta R(t)$, the distance between the target and radar transmitter can be written as

$$R_r(t) = R_n(t) + \Delta R(t) \\ = \Delta R(t) + \sqrt{R_o^2 + V_R^2 t^2} \quad (1)$$

, where R_n is the nominal flight trajectory and R_0 is the nearest distance between the radar and target. The position of an arbitrary rotor is expressed as

$$R_P(t) \approx R_n(t) + x_p \cos(\theta(t) - \alpha) \\ - y_p \sin(\theta(t) - \alpha) + \Delta R(t) \quad (2)$$

There would appear N R_p equations for N rotor platform.

In most cases, the drone velocity V_R can be assumed as a constant but may need corrections when the duration of the observation is extended. Usually, the rotational motion error is relatively small compared with the translational case but it may be no longer valid for drone case as it directly affects $\Delta R(t)$. Then the slant range equation is expanded in power series as

$$R(t) = R_o + \frac{dR_r}{dt}(t_o)\,(t - t_o) \\ + \frac{d^2R_r}{dt^2}(t_o)(t - t_o)^2 + \cdots \quad (3)$$

, where the second and the third terms designate the first and second derivate of (1). They are equivalent to the linear and quadratic range migrations respectively. By replacing these approximate expression, (1) can be expressed as

$$R(t) = R(t_o) + \left\{\frac{d\Delta R(t_o)}{dt} - V_R sin\theta(t_0)\right\}(t - t_o) + \left\{\frac{d^2\Delta R(t_o)}{dt^2} + \frac{V_R^2\cos^2\theta(t_o)}{2R(t_o)}\right\}(t - t_o)^2 + \cdots \quad (4)$$

B. Processing algorithm

In this paper, an enhanced focusing module is implemented by employing conventional spotlight approach to generate improved ISAR images. The sub-aperture processing scheme is applied to take full advantage of wide aperture data.

We employ range Doppler algorithm (RDA) for range processing, however, this can be replaced by conventional SAR processing algorithm such as frequency scaling algorithm (FSA). For azimuth processing, spectral analysis algorithm is used for full aperture data processing.

In general ISAR image is not easily matched to the optical target scene and may demand additional process for image enhancement prior to target classification. In this paper, we have attempted to clean up phase corruption by compensating the motion disturbance through full aperture ISAR processing [6]. The initial ISAR images are further enhanced by clutter rejection to clarify the detailed structure that have been obscured by m-D phase corruption. The process is independently applied to each drone in scene. Initially a number of ISAR images are experimentally collected and saved at database to be used as reference images. Then newly obtained ISAR image is repeatedly compared to search for the best fitting database image. Fig. 3 illustrates the general procedure.

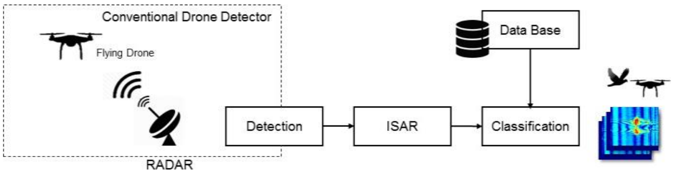


Fig. 3. FMCW ISAR processing for drone classification

III. Experimnetal results

A. Field test

We employed a lightweight X-band radar system that transmits FMCW chirp signals with bandwidth of 500MHz. The transmit power is 40dBm with PRF (Pulse Repetition Frequency) and pulse width given as 1 kHz and 20 ms respectively.

Three different type of commercially available drones are designated as flying targets. Two of them are from DJI and the third one is from Huins. The antenna beamwidth is 30^0 and the illumination time is limited below 10 sec.

Fig. 4 shows the experiment site where multiple drone are flown in distance from the ground FMCW radar. The moving paths of the target drones are arbitrarily given with no interference with each other.

Fig. 4. ISAR imaging experiment site

Drones are flying approximately in 50 m away but their flight paths have different signatures. The RCMC and azimuth compression were proceeded by estimating the Doppler parameters as described in (4).

Fig. 5 shows Doppler centroid (right) and velocity estimation (left). Based on this, range cell migration correction is performed to align the range compressed data along the azimuth domain in slow time.

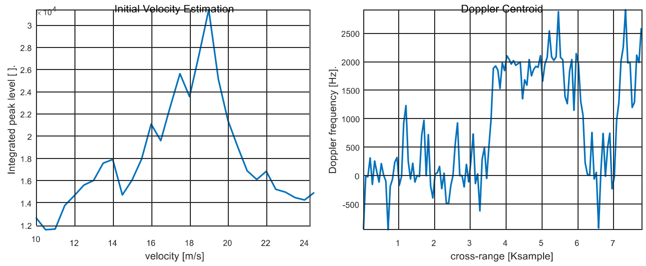


Fig. 5. Drone velocity and Doppler centroid estimation

Prior to azimuth ISAR focusing is performed, m-D effects should be removed to refine the generated images. This type of phase error correction is highly difficult as there is no prior knowledge of the rotor movements or speeds. Hence the phase disturbance should be estimated from the collected data. We have divided the slow-time zone into multiple sub-aperture intervals. Then peak search is performed to separate target zone from clutter intervals. The target aperture interval is dominated by the target reflections and hence the m-D effect is underlying without being detected. The hidden m-D parameters are extracted from the non-target intervals and estimated to be subtracted from the target zone. Fig. 6 shows that m-D effects (above) prominent in original radar reflections, are hardly visible after phase compensation is performed (below)

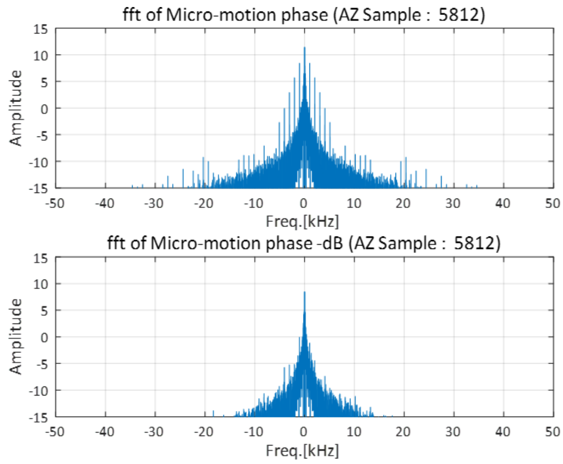


Fig. 6. Compensation of micro-Doppler phase corruption in ISAR

B. Test results

Afterward, ISAR images are obtained by performing conventional azimuth compression against m-D phase compensated signals.

Fig. 7 illustrates thus generated ISAR images. The resolution in azimuth is 0.1 m and the structure of the small drone are visible. The resolution is highly enhanced such that three different type of drones are easily distinguished by their sizes and rotor structures.

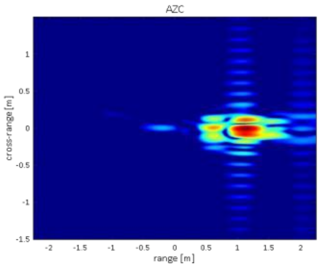
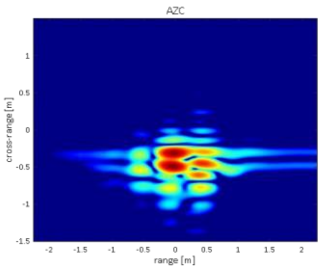
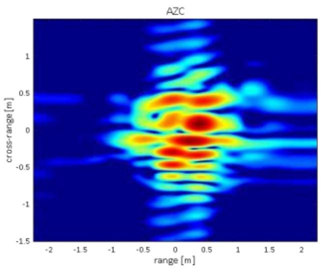
Target drone	ISAR images
	
	
	

Fig. 7. ISAR images for classification of drones

IV. CONCLUSION

In this paper, the feasibility of ISAR imaging for classification of simultaneously flying drones is investigated and successfully verified through field tests. Enhanced ISAR imaging reveals the detailed structure of multi-rotors with precision such that different type of drones are distinguished with each other.

After subtle compensation of motion and phase corrupted by m-D effects, high resolution ISAR images are obtained with a good knowledge of the structure and the number of rotors.

In this paper, m-D phase corruption is compensated with high efficiency by adopting time-varying clutter suppression along the azimuth slow time interval. This is in contrast with the conventional approach where m-D suppression is mostly performed in fast time domain during range compression procedure.

We have demonstrated that, multiple number of rotor based commercial drones are identified and classified with high resolution ISAR imaging. With further refined ISAR processing, the obtained ISAR images will be used as reference database to apply for real-time matching in anti-drone operation.

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