

A Sub-THz Micro-Doppler Radar for Counter-Surveillance Applications

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Abstract— We present a technique for detecting drones by exploiting their unique micro-Doppler signatures. While most commercially available drones are usually employed for recreational activities, their advantageous features, such as excellent camera resolution, load bearing capabilities, etc., could be misused to carry out illegal surveillances, drug trafficking etc. Because of their low-radar cross section (RCS) profile and low speed, it is difficult to detect drones using conventional radar systems. Moreover, additional information is needed to further distinguish them from surrounding clutter, such as birds. To address these issues, we have designed a sub-THz continuous wave (CW) micro-Doppler radar that can capture the micromotions unique to drones. The radar operates at 270 GHz and can successfully discriminate the rotational and translational motions of the targets. A real-world experimental setup is built to demonstrate the operation of the proof-of-concept radar designed in this work. A simple classification technique based on Short-Time Fourier Transform (STFT) is used to extract the micro-Doppler features of the drones.

Keywords— *micro-Doppler, drone, time-frequency analysis*

I. INTRODUCTION

There has been a burgeoning popularity of commercial drones in recent years due to their attractive features, such as ease of operation, excellent camera, load-bearing capacity, and little-to-no assembly requirements. These features, however, could also be easily exploited by perpetrators to carry out anti-social activities such as illegal surveillance, drug trafficking or to remotely dispense chemical/biological weapons. To counter such possible security threats, it is necessary to develop techniques that can promptly detect the presence of drones.

Traditionally radars or cameras have been used to detect the presence of illegally operated aerial vehicles. While the camera-based systems lose their accuracy and range in adverse operating conditions (snow, rain, lack of light, etc.), the unique features of drones present some unusual challenges to the radar systems as well (which otherwise operate well in such scenarios). Conventional Doppler radar systems typically use radar cross section (RCS) signatures to detect and classify targets. However, drones are characterized by low-RCS that is identical to the RCS of birds which makes it arduous for conventional radars to distinguish between the two. As such, it is necessary to obtain additional target-specific information to successfully detect drone activity.

The micromotions (e.g., gait, vibration, rotation, etc.) of a target induce time-varying frequency modulations on the reflected signal, called the micro-Doppler modulations [1]. These micro-Doppler modulations are target specific and may

contain information needed to detect and characterize the target. Additionally, most commercial drones possess three to six rotors powered by DC motors. As such, when a drone is in operation, in addition to its translational motion, it will also exhibit rotational (from rotor blades), vibrational (from motors and blades), and coning/tumbling micromotions. Moreover, the frequency response of these micromotions is much higher compared to the wing-beat frequencies of the birds. As such, by effectively capturing the micro-Doppler modulations of the drones, it is possible to improve target detection and classification accuracy significantly.

II. PROPOSED IDEA, DESIGN, AND OPERATION

In addition to low-RCS profiles, commercial drones usually operate at low speeds and possess non-metallic body construction, which presents additional challenges for target detection. As such, depending on traditional techniques can prove detrimental to the goal of drone detection, warranting the need to collect additional target-related data. The ability to acquire this additional information from the time-dependent micromotions of the target sets apart the micro-Doppler radar from conventional radars. The time-varying frequency response due to the micromotions appears as sidebands along the primary frequency shift caused by the translational motion of the targets. Subsequently, using time-frequency transforms, these features can be extracted and employed to identify the presence of drones. In the following sections, we present the design and operation of the proposed micro-Doppler radar.

A. Micro-Doppler Radar Design

In this work, we use a continuous wave (CW) micro-Doppler radar designed at a sub-THz frequency of 270 GHz and a DROCON X708W quadcopter to carry out the measurements [2]. The measurement setup is shown in Fig. 1. We use the frequency up-conversion technique to realize the THz signal. A 15 GHz signal from the vector network analyzer (VNA) is fed into a VNA extender, where the signal passes through a series of frequency multipliers ($\times 18$) to generate the 270 GHz signal. This 270 GHz signal is used to excite the transmitting horn antenna. The drone is made to hover in front of the radar at distances of 1.5, 2m, and 4m, and the reflected signals from the drone are captured by a receiving horn antenna. Both horn antennas are WR-3.4 (220 – 325 GHz) diagonal horns with a peak gain of 26 dB. The signals are then downconverted to an intermediate frequency of 279 MHz and processed on a spectrum analyzer.

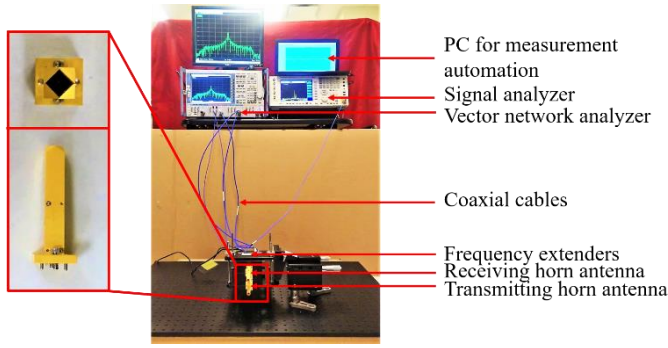


Fig. 1. Sub-THz micro-Doppler radar used to characterize a quadcopter. Inset: Front and side views of the horn antenna used for measurements.

Short-time Fourier transform (STFT) with 50% overlapping windows is used to obtain the spectrograms of the micro-Doppler data, as shown in Fig. 2 and 3. While STFT offers low complexity, good resolution can only be achieved either in frequency or time. However, it provides sufficient physical insight for this proof-of-concept design. If $s(t)$ is the time domain signal with time-dependent frequency variations and $h(t)$ is the sliding window function, then the spectrogram, which represents the power of the STFT signal $P_{STFT}(t, \omega)$, is obtained as

$$P_{STFT}(t, \omega) = |S_t(\omega)|^2 = \left| \frac{1}{\sqrt{2\pi}} \int s(\tau)h(\tau - t)e^{-j\omega\tau}d\tau \right|^2 \quad (1)$$

where $S_t(\omega)$ is the Fourier transform of the STFT signal $s_t(\tau) = s(\tau)h(\tau - t)$, t is the measurement time, and τ is the running time of the sliding window function.

B. Measurement Results

The DROCON X708W drone used for the measurements has four rotors with two blades each. Both vibrational and rotational micromotions are characterized in this work. While characterizing the response due to vibrational micromotion, the blades are removed to extract the response due to vibrations of the motor alone. The drone is placed in front of the radar at 2m, and the reflected signals from the drone are captured for a duration of 6s. At first, the drone motors are turned OFF, and the reference data of the stationary drone is recorded, as shown in Fig. 2(a). Then the motors are turned ON, and the measurement is repeated for 6s to obtain the spectrogram shown in Fig. 2(b). The plots clearly show the additional spectral components (along vertical axis) resulting from the periodic mechanical vibrations due to the motor.

Similar measurements are carried out to characterize rotational micromotion. Three different translational micromotions are considered: back-and-forth, sideways, and precession. At first, the drone motors are turned OFF and the drone is manually moved back and forth in front of the radar. This produces a sinusoidal oscillation in the spectrogram, as shown in Fig. 3(a). When the drone is turned ON and made to hover in front of the radar, the additional spectral components due to the rotation of the blades appear as sidebands along the sinusoidal profile of the drone in the OFF state, as shown in Fig. 3(b). Although STFT lacks the necessary resolution to extract the variations due to blade rotation, the spectral distribution in Fig. 3(b) provides a good representation of the

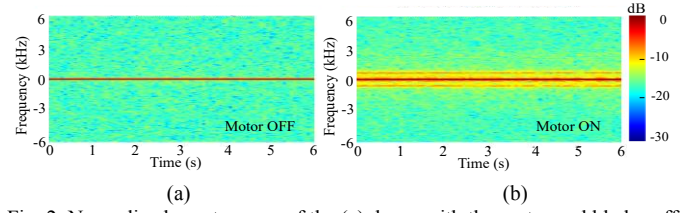


Fig. 2. Normalized spectrogram of the (a) drone with the motor and blades off and (b) vibrations captured by the radar when the drone is in operation.

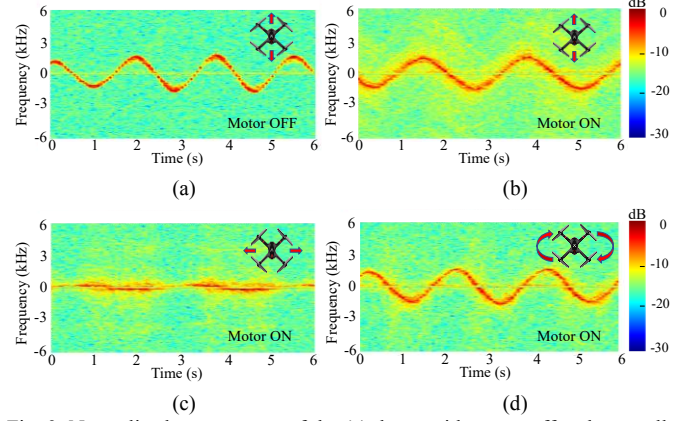


Fig. 3. Normalized spectrogram of the (a) drone with motor off and manually moved back-and-forth in front of the radar, (b)-(d) drone hovering in front of the radar with back-and-forth (b), sideways (c), and precession (d) motions.

impact of the blades. When the drone moves sideways, motion is minimal as the direction of target motion is perpendicular to the radar, but the rotation of the blade results in a frequency shift centered around 0, as shown in Fig. 3(c). A similar sinusoidal profile with the micro-Doppler spread is also seen for the precession motion, as shown in Fig. 3(d). The entire measurement process is repeated for 1.5m and 4m target distances, and the spectrograms are recorded. In all the three cases, an average micro-Doppler frequency shift of 1.2 kHz is achieved at 279 MHz.

III. CONCLUSION

We presented a technique for detecting low-RCS targets with periodic motions employing a sub-THz CW micro-Doppler radar. Specifically, we exploit the micro-Doppler variations resulting from the periodic micromotions, such as the vibration of motors and rotation of blades, to improve the target detection accuracy. Since a linear transform, STFT, is used for post-processing the measured data, it is difficult to extract the individual micro-Doppler features. Future works will focus on improving feature extraction using techniques such as Wigner-Ville distribution and Wavelet transforms. Target classification accuracy can be further enhanced by employing machine learning algorithms. Although this proof-of-concept setup used a fixed-beam, practical implementations would require a fast, narrow beam scanning capability.

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