

Detection of flying nano-drone signatures with a K-band FMCW radar

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Abstract—Nano-drones are insect-like drones with a threat capability of intrusion to provide intelligence and potentially violate secure establishments and public privacy rights. They are an existing technology which is becoming increasingly more available, portable, affordable and easy to operate. As such, they represent a plausible defence and security threat.

In this paper, an FMCW radar prototype operating in K-band is presented which was used to detect signatures of a flying nano drone characterised by Radar Cross Section (RCS) values below -25 dB. Results show the radar prototype was capable of successfully detecting the nano drone in flight and collecting its micro-Doppler signatures in various flying trajectories.

Index Terms—Radar Cross Section (RCS), nano-drones, pico-drones, drone signatures, drone classification, drone recognition, drone detection

I. INTRODUCTION

Nano-drones are unmanned aerial systems of a size comparable to that of insects that can potentially be used to perform stealthy surveillance or to gather intelligence, even within enclosed locations and buildings. According to the classification of drones offered in [1], nano-drones are those unmanned flying systems with dimensions ranging between 15 cm and 2.5 cm and weighing between 50 g and 3 g. There also exists other weight based classification systems of drones, such as those proposed in [2] and [3], and they all have very similar weight ranges for each class.

Most of the available research literature on detection and classification of drones focuses on mini-drones and micro-drones, i.e. drones weighing a few kilograms and with dimensions comparable to those of birds.

A helicopter and a quadcopter UAV with rotor lengths of 70 cm and 20 cm, respectively, were measured in [4] using a X-band Continuous Wave (CW) radar. The micro-Doppler signatures were extracted using the Short Time Fourier Transform (STFT) and used to measure the maximum Doppler velocity shift and to determine the rotor size of the drones. In [5], [6] and [7] it was shown that the use of long window STFT produces frequency lines in the spectrogram that repeat up to the maximum Doppler frequency of the rotor tip. The separation between lines, called Helicopter Rotor Modulation (HERM) lines, is a factor of the number of propeller blades and of the rotation rate of the propeller. An example of the signature of a DJI Phantom 3 quadcopter micro-UAV in flight can be seen in [5]. A new method that exploits HERM lines to extract the rotation rate of the propellers of different drones,

based on a log harmonic summation algorithm commonly used in audio processing, was proposed in [6].

Research into the RCS of drones demonstrated that the material of the blades as well as the drone overall size and shape can significantly affect the micro-Doppler target returns. The use of carbon, metal and plastic rotor blades was investigated on a DJI drone platform and results were compared in [8]. Measurements of a DJI Phantom Vision 2 flying a specific flight path were compared to similar sized birds (such as the hooded vulture, the eurasian eagle owl and the barn owl) flying the same flight path in [9]. A similar experiment was conducted using K-band and W-band radars in [10]. The use of radar polarimetry was investigated in [11] as a potential method to distinguish UAVs from birds. Measurements of the RCS of five unmanned aerial vehicles (UAVs), comprising both consumer grade and professional small drones, were collected in a semicontrolled environment as a function of the azimuth aspect angle, polarization and frequency, within the frequency range 8.2–18 GHz, in [12]. The data was used to predict detection performance of a detector accounting for RCS fluctuations in [12] and for a frequency agility-based incoherent (square-law) detector in [13]. Additional results on RCS measurements of mini and micro drones can be found in [14], [15] and [16].

As most of the existing radar literature investigating drone detection and classification relates to the case of larger drones, conventional anti-drone radar systems have been designed and optimised to detect and classify bigger targets at long distance rather than nano-targets.

Measurements of a nano-UAV were conducted in [17] where a 35 GHz CW radar designed for 3D imaging was used to conduct a micro-Doppler analysis of a variety of UAVs, including mini, micro and nano-UAVs. Previous results of our research aiming at designing and prototyping a flexible K-band FMCW radar to detect and collect micro-Doppler signatures of nano drones was presented in [18] and [19]. Results showed that the micro-Doppler signatures of a moving Arcade Pico-Drone (attached to a fishing line) could be successfully gathered in a laboratory environment, at a short range, with little transmitted average power. Results of the measurements and calibration of the RCS of the Arcade Pico-Drone were presented in [20]. Some other relevant comparable literature investigates radar detection and classification of insects with wingspans in the range of the centimetres, that is similar to the size of the

propeller blades found in nano-UAVs. In [21], for example, a W-band radar and a S-band radar were used to measure the micro-Doppler signature of different species of moths with wingspans in the range of 30-100 mm. Using the W-band radar, the authors were able to detect and measure the micro-Doppler signature of all the moths under test allowing an estimation of the wing beat frequencies with good precision. The detection of nano drones is an emerging problem that needs to be addressed. In this paper, an FMCW radar prototype operating a K-band is presented and used to collect micro-Doppler signature of a flying nano drone. Results show the nano drone could be successfully detected indicating FMCW radar operating at these range of frequencies is a potential candidate solution for this type of applications.

II. FMCW RADAR PROTOTYPE

The K-band FMCW radar transmits linear frequency modulated ramps of a user-selectable duration spanning the frequency bandwidth from 24.58 GHz to 25.06 GHz [18] [19]. A linear ramp voltage signal is generated by a Keysight Waveform Generator 33600A and fed into a HMC739LP4 Voltage Controlled Oscillator (VCO) to provide the frequency modulated signal at K-band. The VCO is an evaluation board manufactured by Hittite with an integrated chip mounted on the board. The output of the VCO is then passed to a mini-circuits ZC2PD-18263-S+ power divider which splits it into two signals; one is directed to the transmit antenna and the other one is fed to the LO port of a Marki Microwave MM1-1140HS double-balanced mixer and is used as the beating copy of the transmitted signal. Target echoes are collected by the receive antenna and are passed to a HD30172 Low Noise Amplifier (LNA) for signal amplification. The amplified received signal is then flowed to the RF port of the mixer and mixed down with the copy of the transmitted signal available at the LO port of the mixer. The IF product is filtered with a mini-circuits VLF-45+ low pass filter before being digitised with a Handyscope HS5 USB oscilloscope. A block diagram of the radar is illustrated in Fig. 1 and the RF components of the radar are shown in Fig 2. The transmit and receive antennas are identical with a gain of 18 dBi, length 135 mm and aperture 40 x 50 mm. The main advantage of this prototype is that it provides full control of the radar components and the flexibility to choose the radar parameters, and hence the radar performance, on a case to case as desired. The operational frequency range of the VCO, for example, is between 23.8 GHz to 26.8 GHz allowing a wide selection of the frequency span and bandwidth within the system linear response interval.

III. DRONE CHARACTERISTICS AND RCS

An Arcade Pico drone was used as the target under test [18] [20]. A photo of the Arcade Pico drone with an indication of the drone size is shown in Fig. 3.¹ Tests were carried

¹Note that, despite the name used by the supplier, the Arcade Pico drone falls under the nano drone category according to the classification in [1].

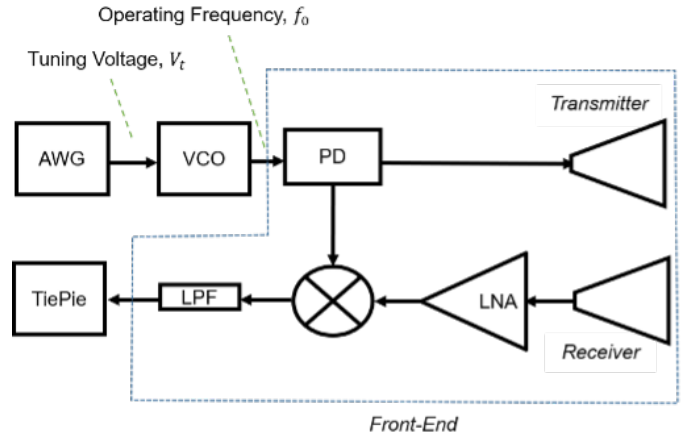


Fig. 1. Block Diagram of K-Band Radar Prototype.

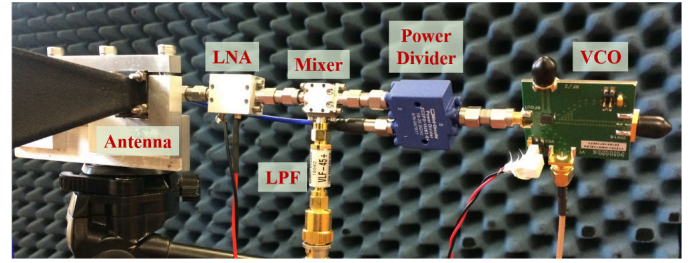


Fig. 2. Photo of the Radar Prototype.

out using a Radar Cross Section (RCS) measurement setup, consisting of a Vector Network Analyser (VNA) operating in free space to measure the RCS of the drone [12] [20]. Results are given for two independent measurements at each elevation angle as a function of azimuth, which are indicated with the labels “Test1” and “Test2”. Fig. 4 shows the calibrated response of the drone (calibrated using a reference metallic sphere) as a function of azimuth, for an elevation angle of 0 degrees. Results show that the RCS of the drone presents



Fig. 3. Photo of the Arcade Pico-drone.

peaks at around -25 dB as well as significant RCS variations with aspect angle spanning RCS values down to about -55 dB. Background cancellation results at 0 degrees in elevation showed clutter returns reached level around -70 dB for azimuth angles below 200 degrees and higher values, with peaks reaching -51 dB, for azimuth angles higher than 200 degrees. For these reasons, the measurements of the drone RCS that fall below -40 dB (i.e. less than 10 dB than the background cancellation performance) at angles greater than 200 degrees might be less accurate than the measurements taken from lower aspect angles. Similar results are shown relative to an elevation angle of 5 degrees in Fig. 5, and for 10 degrees in Fig. 6. At both 5 and 10 degrees in elevation, background cancellation performance were in the order of -70 dB at all azimuth angles indicating a much better accuracy of the results for RCS levels around -50 dB.

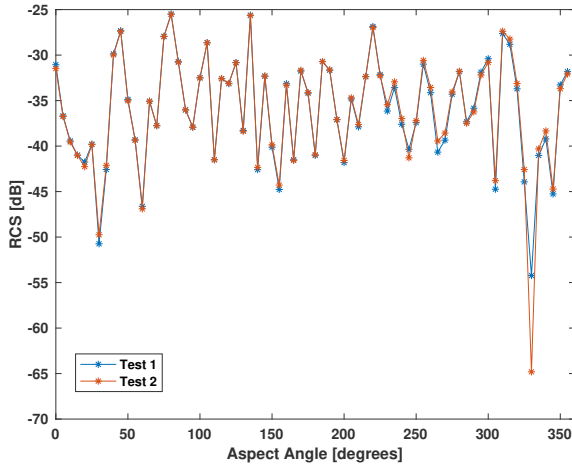


Fig. 4. Calibrated target RCS as a function of aspect angle for an elevation angle of 0 degrees. Results are given for the subtraction of two independent background measurements [20].

IV. SIGNATURES OF THE FLYING DRONE

The radar prototype was tested against the flying Arcade Pico drone, in an attempt to detect the drone in free flight and collect its micro-Doppler signatures, including contributions produced by its propellers.

The drone was flown in front of the radar setup, and continuous data packets representing time steps over a fixed period of time were recorded. These data packets were analysed in post-processing to yield a number of images of the drone micro-Doppler signature. The drone was flown so that the following manoeuvres were attempted:

- Hovering
- Flying towards the radar
- Flying away from the radar
- Completing a flip in front of the radar

Controlling the drone in flight was not straightforward and multiple attempts of the same targeted trajectory were carried out, each one resulting in different signatures. Fig. 7 and Fig. 8,

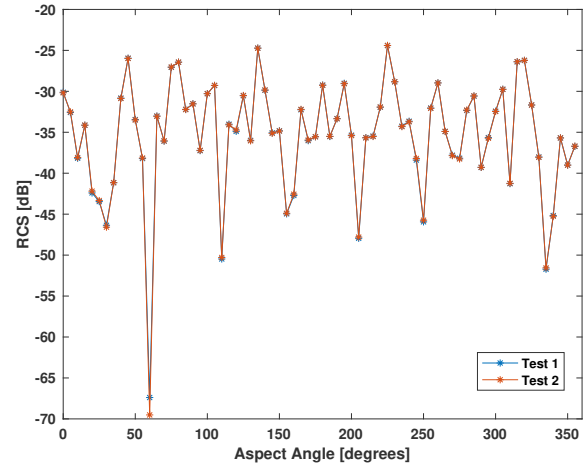


Fig. 5. Calibrated target RCS as a function of aspect angle for an elevation angle of 5 degrees. Results are given for the subtraction of two independent background measurements [20].

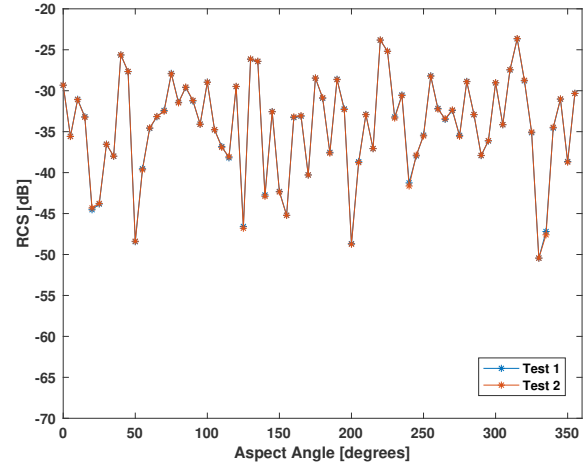


Fig. 6. Calibrated target RCS as a function of aspect angle for an elevation angle of 10 degrees. Results are given for the subtraction of two independent background measurements [20].

for example, show two micro-Doppler signatures for the drone hovering in front of the radar at a range of approximately 2.5 m. In Fig. 7 that drone was detected at an angle where the body scattering was dominant and for which the contribution of the propellers was not visible. The results in Fig. 8 instead show the contributions of the propellers clearly at approximately 2.5 m. The spectrogram in Fig. 9 is relative to the drone decelerating away from the radar before inverting its direction of travel towards the radar at about 2 m. The signature clearly show an initial contribution at negative Doppler before the Doppler signature exhibits positive Doppler frequencies. The quadcopter is clearly visible moving away from the radar or towards the radar in all plots. Fig. 10, Fig. 11 and Fig. 12 show the micro-Doppler signature of the quadcopter drone attempting to complete a flip, at ranges between 2.5 m and 3

m from the radar. Results show the drone was caught flipping only in Fig. 12 where a sudden switch in Doppler is clearly visible.

Additional measurements were taken with the drone in the presence of a stationary target at a longer range to confirm the ability of the radar to provide range and Doppler resolution.

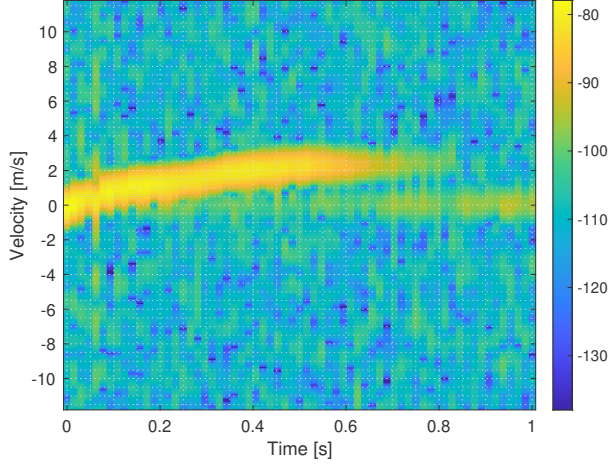


Fig. 7. Micro-Doppler signature of the quadcopter drone in hover.

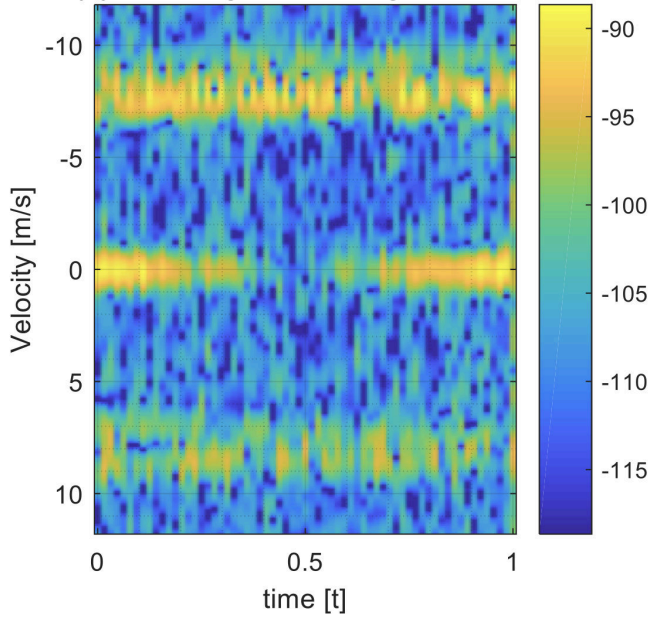


Fig. 8. Micro-Doppler signature of the quadcopter drone in hover with propeller signature.

V. CONCLUSIONS

In this paper a K-band FMCW radar is presented which was developed to collect signatures of flying nano drones, that is drones of a size comparable to that of insects. The radar was used to run experimental trials aiming at collecting the Doppler signature of a flying drone in an indoor environment

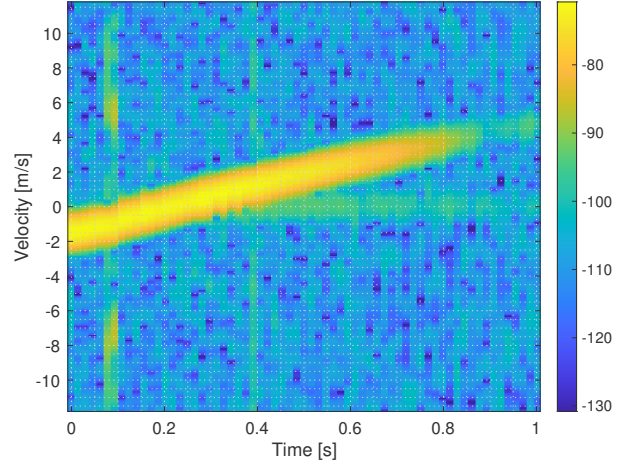


Fig. 9. Micro-Doppler signature of the quadcopter drone decelerating to stationary and then accelerating towards the radar.

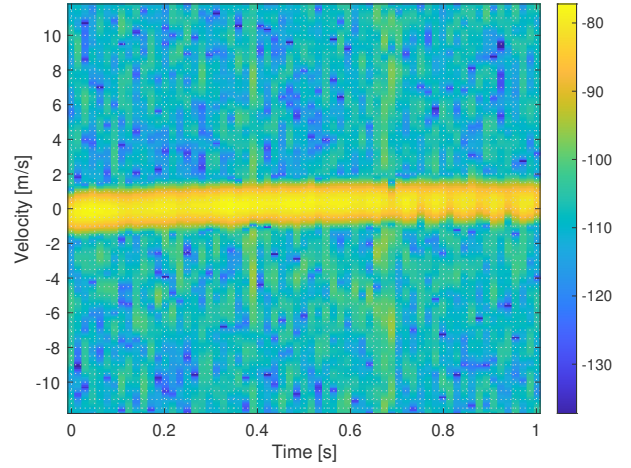


Fig. 10. Micro-Doppler signature of the quadcopter drone completing a flip.

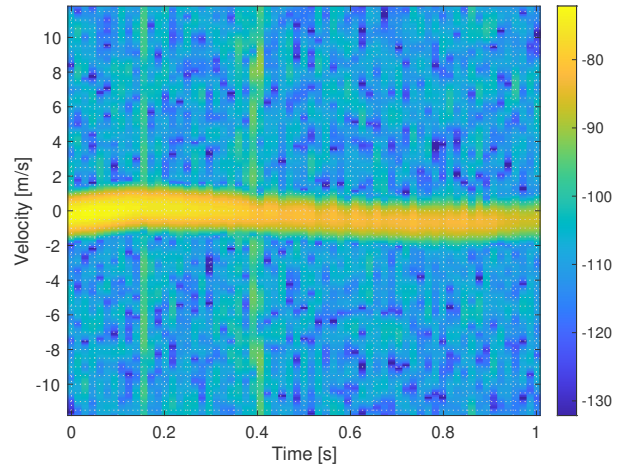


Fig. 11. Micro-Doppler signature of the quadcopter drone completing a flip.

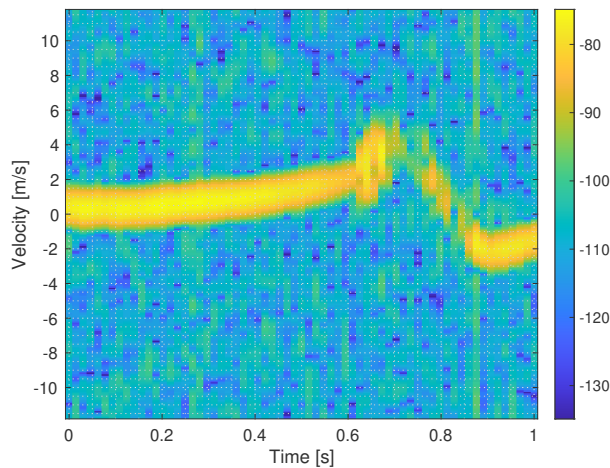


Fig. 12. Micro-Doppler signature of the quadcopter drone completing a flip.

setup. Results have shown the radar was capable of detecting the drone under various flight trajectories.

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DATA AVAILABILITY STATEMENT

Data supporting this study cannot be made available due to commercial restrictions.

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