DRONE DETECTION IN URBAN ENVIRONMENT – THE NEW CHALLENGE FOR THE RADAR SYSTEMS DESIGNERS

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Abstract: *Small UAVs and micro-drones are becoming more and more available to the general public for leisure activities and exploited in commercial applications. However, there is growing concern for accidental or even criminal misuses of these platforms. Radar systems can provide good capabilities, especially at long ranges and poor visibility conditions. Design considerations for distributed millimeter wave radar networks, particular suitable for high density populated urban areas, are given in the report. Special attention is given to: The choice of suitable working frequency bands; The use of antenna beam-forming networks, based on proposed by the author Random Phased Radial Line Slot Antennas and correlation signal processing; The radar signal waveforms in order to obtain un-ambiguity autocorrelation function and small radar resolution volume, as well as to the use of the external coherency principles of Doppler detection.*

Keywords: UAV, DRONE, DOPPLER RADAR, RP-RLSA.

1. Introduction

Small Unmanned Aeronautical Vehicles (UAVs) and micro-drones are becoming more and more available to the general public for leisure activities and exploited in commercial applications (inspections, professional filming, support to agriculture, deliveries). However, there is growing concern for accidental or even criminal misuses of these platforms (privacy violation and illegal filming, flying over restricted areas, collision hazard with other aircraft, smuggling of illicit substances, use in terrorist attacks with explosives or chemical payloads) [1].

Radar systems can provide good capabilities, especially at long ranges and poor visibility conditions (thick fog, night-time), but conventional radars are not optimized to sense these platforms, as they are smaller and slower than traditional aircraft and fly at lower altitude. The proposed on the market and in literature anti - drone radar systems are not suitable for urban environments due to the very limited lines of sights and the big number of false radar targets, moving with the same speed as the expected drones.

Design considerations for anti-drone radar sensors are considered in this report. The sensors are parts of distributed millimeter wave radar network, particular suitable for high density populated urban areas.

1. UAV detection by Doppler radars

Radar is believed to be a valuable sensor in dealing with the detection and classification of a variety of targets in crowded littoral and urban environments [2]. However radar detection of micro UAVs present challenging factors, as these tend to be low and slow flying, with a small Radar Cross Section (RCS). Low altitude and reduced velocities may lead to difficulties in separating the target from a significant clutter response. Low RCS makes the detection within cluttered environments very demanding. In addition to detection the drones need to be distinguished from biological targets like birds and insects frequently present in the same surveillance volumes. Birds and UAVs may have comparable RCS values and flying patterns which present a very tough challenge for classifiers to separate them. Micro-Doppler based techniques is a promising approach to solve the problem. Whereas the total RCS is important for target detection, the energy backscattered from rotating parts like propeller and rotors are crucial for extraction of useful micro-Doppler signatures. Tri-copter, quad-copter and octo-copter like UAVs normally use rotor blades made of carbon, fiber or plastic materials. The smaller the drone the larger probability it has plastic blades. This choice of material may be important when it comes to the visibility of the blades in radar systems. While carbon fiber blades are believed to behave close to a perfect electrical conductor, plastic material may have dielectric properties closer to air, thus resulting in little reflection back to the transmitter.

In order to investigate these aspects, paper [2] presents RCS simulation results and their comparison to real measurements taken of rotor blades made from different materials. The blades under test were taken from the platform of interest, which was the easily available DJI Phantom Vision 2+ micro drone. The DJI drone platform was then measured using an experimental pulsed Doppler radar system, NetRAD. The NetRAD system is a coherent, 2.4 GHz, 45 MHz bandwidth, 0.2 W (in low power configuration) radar. The radar was configured to take pulse to pulse interleaved horizontally and vertically polarized measurements. The interleaved operation allowed for the direct comparison of HH and VV data. The DJI drone flew in a straight line at approximately 2 m height from the ground at ranges of 70 m to 150 m from the radar. The drone was configured to use carbon fiber rotor blades rather than the reduced RCS typical plastic blades.

The data from the Horizontal (HH) and Vertical (VV) channels have been analyzed using micro-Doppler processing algorithms. A Short Time Fourier Transform (STFT) was applied to the range gates the target was present within. For this processing a window length of 0.3 seconds, with a 95 % overlap was applied to data which was generated at a PRF of 10 kHz, which gave equivalent PRF of 5 kHz after de-interleaving. The results from a 5 second capture of HH and VV data can be seen within fig. 1 (a) and (b) respectively [2].

The Micro-Doppler components from the two different polarizations is markedly different. The horizontally polarized result has two key features, this first is the slanted line of the main bulk motion of the drone moving away from the radar relatively close to the 0 Hz line at -50 to -70 Hz. The second is the multiple discrete signatures from the rotor blades up to 1 kHz in frequency. The VV polarized result only has signal from the main body of the drone, no components of the rotor blades are visible. From the simulation results these components are expected to be 30-40 dB lowed in VV polarization and hence were below the sensitivity of the radar. These key differences show the importance of polarization when hoping to observe the blade contributions to a small drone platform Doppler signature. The micro-Doppler contributions contain additional information on the target and show good potential for target classification purposes.

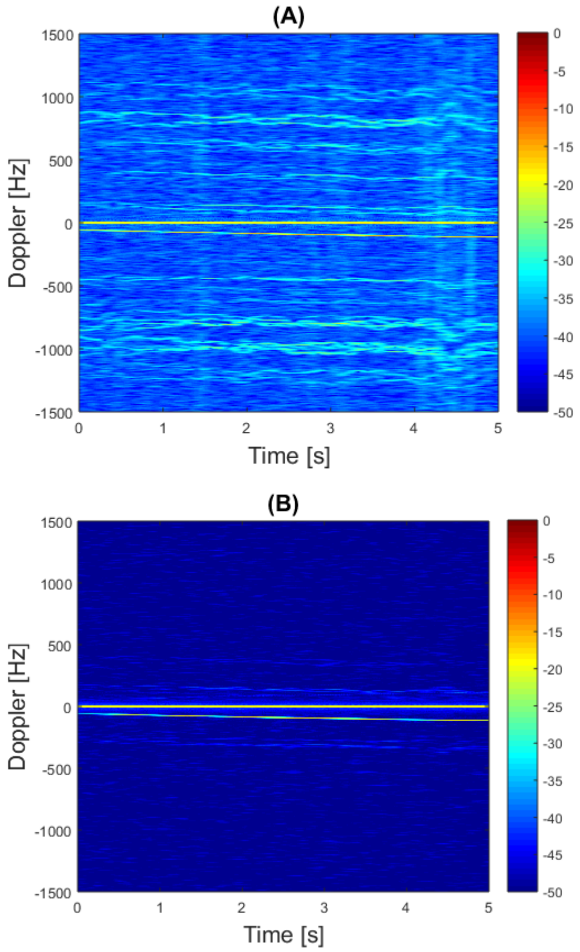

Fig. 1 *Micro-Doppler Spectrograms from DJI platform in (a) HH and (b) VV polarization*

2. Design considerations for distributed millimeter wave radar networks, suitable for high density populated urban areas

2.1. Introduction

In this paragraph design guidelines for the future research and developing activity, dealing with anti – drone radar sensors and systems, are considered. Special attention is given to:

- Choice of suitable working frequency bands;
- The use of external coherency principles of Doppler detection;
- The use of antenna beam-forming networks, based on proposed by the author Random Phased Radial Line Slot Antennas and correlation signal processing (SCP-RPSC technology);
- Radar signal waveforms in order to obtain un-ambiguity autocorrelation function and small radar resolution volume, increasing in such way the signal to interference ratio;
- Implementation of Drone Detection Multistatic Radar Networks (DD-MRN).

2.2. Choice of suitable working frequency bands

Due to very small dimensions and high maneuverability, the drones are extremely difficult to detect [3]. According to the radiophysics, objects smaller than the radar wavelength does not reflect the signal at all. Therefore, conventional radar systems operating in the centimeter and decimeter waves are powerless against drones as were engineered for the identification of large airborne targets like planes and helicopters. Drone is composed of many small parts and traditional radar does not see it. To detect the drone, it is required to use radar operating in the millimeter wave range, as wavelength is smaller than the drone parts. The proposed by ELVA-1 anti-drone radar DDR-76 [3] operates at 76 GHz (wavelength of 4 mm), catching the returning signal from a variety of small drone parts.

According to the Bulgarian National Radiofrequency Plan, harmonized with the European, the frequency band 76 – 77,5 GHz is allocated on primary status for short range radar equipment. This frequency band is very attractive for use in anti – drone systems, but it needs implementation of new reliable and cheap semiconductor technologies, suitable for mass production.

Another benefit of the used 77 GHz band is the expected substantial increase of the reflected vertical component due to the fact, that the transverse rotor blades dimensions are several wavelength larger than the experiment at 2,4 GHz, shown in fig.1–b.

2.3. External coherency principles of Doppler detection

Coherent radar uses coherent signals and signal processing [4]. Coherence provides the ability to maximize signal-to-noise ratio, to measure target radial velocity, and to provide Moving Target Indication (MTI) and other Doppler-based clutter rejection techniques. Coherent pulsed radars are the most widely used types, although coherent Continuous Wave (CW) radars appear in specialized applications such as missile guidance and police speed-control radar. Coherent pulsed radars are classified as truly coherent or pseudo-coherent, also known as coherent-on-receive. Both types are known as internally coherent, to distinguish them from externally coherent types, which use the clutter itself as a phase reference.

Advantages of internal coherence lie in the high sensitivity and the possibility of measuring the Doppler frequency shift with good accuracy. Disadvantages are the relative complexity and need to ensure high stability of all the oscillators used in the system. Most of the proposed anti-drone radar architectures use internal pulse coherent radar approach.

In a radar with external coherence, the system local COHerent Oscillator (COHO) is phased not by the transmitted signal but by a clutter signal, or the clutter itself is used as the reference voltage. Advantages of the external coherence lie in the possibility of suppressing extended interference. A disadvantage is that the detection of moving targets in them is possible only if there is extended clutter present. If the clutter does not enter the antenna pattern of the radar, then phasing of the COHO is controlled only by target signals, which leads to suppression of those signals.

The implementation of the extended clutter based coherent principles in anti-drone radars could be very promising, due to:

- The reflected from the drone body signals can be considered as extended clutter (fig.1 – the spectrum line centered at 70 Hz). They could be compared with 1 KHz Doppler signal, obtained from rotor blades, in a correlator. Its output signal will be with difference frequency and will not carry information about the drone speed. It will contain the specific multiple discrete signatures from the rotor blades up to 1 kHz in frequency. When the used radar frequency lies in 77 GHz band, the corresponding difference frequency will be about 30 KHz;
- The experimental RCS results [2] show very low back scattering from plastic rotor blades. This will be problem for the design efforts to create universal anti-drone radar sensors. In such cases another physical propagation

phenomena could be very useful. The plastic blades will shadow partially (if they introduce substantial losses) and will introduce additional phase shifts for the signals, reflected from some parts of the drone body. The final effect could be even better then in the case of metal rotor blades. Simulations of these phenomena should be done in experimental way.

2.4. Antenna beam-forming networks, based on SCP-RPSC technology

The Spatial Correlation Processing – Random Phase Spread Coding (SCP-RPSC) is an entirely new approach in the field of microwave beam forming antenna theory, developed by the author one decade before. The goal was solving the problems of the tracking microwave antenna systems for mobile satellite communications. It was studied first in receive mode (SCP technology) [5, 6], where its main objectives include:

- Receiving one or more radio signals coming from one or several spatially distributed sources (satellites), insuring high gain of the antenna systems and using fixed or mobile receiving terminals, equipped with SCP signal processing systems;
- Insuring spatial selectivity high enough to cancel the same frequency channel interference, coming from different space directions, using simple one-channel receiver and patented signal processing principle.

The SCP approach uses simple and cheap passive Radial Line Slot Antenna (RLSA), suitable for mass production in Ku and Ka frequency bands, as well as one channel microwave receiver with simple signal processing.

The transmit mode (RPSC technology) [7, 8] is based on transmission of broadband microwave signals in the open space by means of multi element random phased antenna arrays. The sum of the different element signals in a given point in the space has Gaussian probability distribution and noise like properties. The sums in the different directions of the space are not correlated each other. In such way the proposed principle solves simultaneous the problems of signal spreading and beam forming of the future sophisticated microwave terrestrial and satellite communication and radar systems with fixed and mobile applications.

The “magic” properties of the SCP-RPSC technology, applied in the future sophisticated millimeter wave anti-drone radars, could be very attractive. One simple and cheap RLSA will be used both for transmission and reception, ensuring simultaneous high antenna gain and omni-directivity, typical for low gain antennas. The typical for SCP-RPSC procedure of correlation among several thousand random phase spread information and pilot signals will be replaced with correlation among the phase spread in the same manner signals, reflected by the drone body and its rotor blades.

2.5. Radar signal waveforms for obtaining un-ambiguity autocorrelation function and small radar resolution volume

In radar, resolution is the ability to separate the signals from adjacent sources [4]. The ability to distinguish one target from another is defined by a four-coordinate radar response, so angular, range, and Doppler resolutions typically are distinguished. The common measure to consider two targets to be resolved in a particular dimension is when they are separated by a distance equal or more than half-power width of the radar response in this dimension: angle, range (time), or velocity (Doppler frequency).

The resolution element [4] is a spatial and velocity region, contributing echo energy that can be separated from that of adjacent regions by action of the antenna or receiving system. In conventional radar, its dimensions are given by the beam-widths of the antenna, the transmitter pulse-width, and the receiver band-width. It is also called the **resolution cell**. When the resolution element is only spatial region (angular and range), it is called resolution volume.

Very important requirement to the proposed anti-drone radars, which is common for all kinds of microwave intruder alarm Doppler sensors, is the use of very small resolution volumes, which can be done using step by step approach. In such way the signal to interference from another targets ratio increases in maximal way. The first step is to reduce the virtual antenna beam-width, which is final results of the used basic SCP-RPSC principles. The second step is the use of modulated waveforms, ensuring narrow and un-ambiguity autocorrelation function in time (range) domain. A possible solution here is the use of Frequency Modulated – Continuous Wave (FM-CW) signals with sinusoidal FM [9]. In such way several advantages appear, as follows:

- The used FM will de-correlate the off-diagonal terms of the SCP-RPSC correlation matrix and their sum will be zero for all space directions. It is very important in order the rules of Central Limits Theorem (CLT) to be valid;
- The beam-width of the autocorrelation function in time (range) domain depends on the dispersion of the Gaussian random process and is inverse proportional to the number of the used random phase spread signals, obtained from the different antenna elements (slots if RLSA is used).
- If pure Doppler processing is used, the amplitudes of the correlator output signals are time (range) depending as Bessel function of zero order [9]. This fact reduces the resolution volume too.

2.6. Drone detection multistatic radar networks

Drone Detection Multistatic Radar Networks (DD-MRN), using the basic principles of the SCP-RPSC technology, could be very promising if the knowledge of the exact drone coordinates are of great importance [10].

3. Conclusion

In this paper design considerations for anti-drone radar sensors are considered in details. The sensors are parts of distributed millimeter wave radar network, particular suitable for high density populated urban areas. The report can benefit manufacturers of sensors and systems for drone detection and classification, regulators and air traffic controllers as well as commercial operators and manufacturers of drones by providing a safer and better managed operational context for drones. The same is valid for law enforcement authorities, responsible for protection of national assets and infrastructure, which may be threatened by criminal usage of drones.

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