DETECTION OF SMALL-SCALE UNMANNED AERIAL VEHICLES USING ACOUSTIC RECONNAISSANCE TOOLS

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Abstract

This paper reviews the methods and tools for detecting small-scale unmanned aerial vehicles (UAVs) by acoustic reconnaissance tools. Information is provided on the methods for detecting small UAVs using acoustic waves across various types of sound ranges.

Keywords: unmanned aerial vehicles, acoustic signals, acoustic detection algorithms, antenna, signal-to-noise ratio, acoustic signal generation, sound signals.

I. Introduction

In this paper, we will primarily examine the acoustic detection methods for small-scale unmanned aerial vehicles (UAVs). As science and technology drive global progress, they have also accelerated the rapid development of the UAV sector. Today, UAVs attract not only legitimate users but also malicious actors, which presents numerous issues [1, 2].

Frequently, drones are exploited by criminals for acts vandalism, espionage, and invasion privacy, as well as for transporting prohibited substances to restricted areas, organizing and executing terrorist attacks in crowded areas and critical infrastructure facilities. Moreover, the prominent role UAVs in modern warfare and conflicts, alongside other military technology, further underscores the a forementioned concerns.

When addressing any potential threat, it is crucial to first establish the presence of the threat itself and then take appropriate actions to protect against or prevent it. Therefore, all technical security systems can be conditionally divided into two categories: detection (monitoring) tools and countermeasures [3, 4, 5].

The primary function of detection and monitoring systems is to transmit an alert to the security monitor regarding unauthorized proximity to the boundaries of the protected area, while also enabling the assessment of the situation and the dynamics of the changing threat level [6,7].

The initial applications of acoustic detection methods date back to previous centuries. Specifically, during the years 1941-1945 and in the wartime period of that era, acoustic detection devices, such as the ZT-5 (sound detector), were employed to detect bombers and fighter aircraft (Figure1). Certainly, if we compare UAVs with the aircraft from that period, it is evident that modern

UAVs, although generally not emitting strong acoustic signals, are not entirely silent in operation [1, 2, 8].

Figure 1: *Acoustic detection complex based on ZT-5*

In modern UAVs, the primary sources of noise include the operation of engines, the rotation of propellers, and the dynamics of flight. Compared to piston engines, electric engines produce less noise, and the level of noise varies depending on the engine power. Based on this observation, it can be stated that, compared to other types of UAVs, small-scale UAVs generate weaker noise levels during flight, as they require less power.

From this perspective, in our paper, we will investigate and analyse the detection of small-scale UAVs (SSUAVs) at greater distances using the acoustic detection method. Acoustic detection systems are used to detect the sound signals generated by unmanned aerial vehicles or their engines. In the application of modern acoustic detection methods, several highly sensitive microphones are typically placed equidistant from each other. This method is generally known as the triangulation method. However, anthropogenic (human-made) and natural noise sources in the surrounding environment reduce the acoustic detection range for drones to a minimum [9].

II. Modern digital technologies are utilized to solve these problems

This system consists of passive acoustic localization, microphones, analogue-to-digital converter systems, and digital signal processing technologies [3, 5, 7, 10]. Except for the antenna, almost all components can be purchased from retail outlets. In this context, it is considered appropriate to use two-channel selection with antennas placed in a horizontal plane, providing a wide directional diagram in comparison to acoustic antennas. This will, in turn, allow the use of inverse aperture synthesis methods to enhance triangulation techniques for measuring azimuth resolution and range determination capabilities.

Active acoustic (ultrasonic) localization significantly impacts the acoustic detection method. Specifically, this method helps to detect silent objects that do not reflect radio waves under visual observation conditions. In this case, ultrasonic emitters with high power (pulses with tens of kilowatts) are used to determine specified acoustic detection ranges under high ultrasonic loss conditions. However, this has a highly detrimental effect on the human body, which makes the application of this technology inappropriate. This method can only be employed in the operation special-purpose facilities where the activity of surrounding objects is prohibited [11, 12].

During harmonic detection, narrow-band frequencies are analysed over short time intervals. The signal arrives in a harmonically summed form with indeterminate frequencies and phases. When the signal is weak, the harmonic detector will function more reliably and effectively than an energy detector [9, 11, 12]. The concentrated spectrum of acoustic emissions from tactical UAVs is broadband and harmonic. This includes emissions from engines, rotor rotations, mechanical processes, as well as continuous low- and high-frequency noise generated by the engines at spectral frequencies.

III. Detection of Unmanned Aerial Vehicles through Acoustic Reconnaissance Methods

The scientific and technological advancements of the last decade have led to a major revolution in military operations, with conflict parties increasingly utilizing electronic computing machines (ECMs), artificial intelligence, robotic systems, and high-precision weapons. In the near future, the boundary between unmanned aerial vehicles (UAVs), robotic systems, and high-precision weaponry will be completely eliminated through the integration of technical vision and artificial intelligence in weapons control [1, 2, 4].

The application areas of small-sized unmanned aerial vehicles (SSUAVs) are highly diverse. These types of UAVs are considered advanced flight technologies with high manoeuvrability, including the ability to "hover" and alter flight trajectories, as well as to execute flights at low altitudes in complex geographic positions. For these reasons, SSUAVs are capable of evading the counterparty's active and passive countermeasures, such as radio detection, infrared radiation, visual detection, and acoustic radiation. These superior capabilities limit the ability of radio technical systems and complexes (RTSCs) to detect SSUAV flight trajectories [1, 2, 6].

The concept of UAVs is constantly evolving and advancing. As evidence of this development, it is necessary to examine the chronology of their use in conflicts and battles in the Middle East and within the post-Soviet territories. In these war zones, we have witnessed the significant advantages of small-sized UAVs equipped with artificial intelligence.

Therefore, from this perspective, the detection and neutralization of small-sized UAVs have become one of the foremost challenges in contemporary warfare as armed conflicts continue to arise [1, 2, 4, 6, 9].

In our article, to solve the above problems, namely the problem of detecting a small-sized UAV, we propose complex methods and technical solutions for processing information obtained in the optical range using acoustic vector sensors (Microflown AVISA) that generate three-dimensional acoustic information and electromagnetic waves based on various principles [2,4,14]. However, these proposed methods do not guarantee timely detection of modern SSUAVs, as detection ranges are often reduced, or practical detection within designated distances becomes impossible. Reality demonstrates that in most contemporary conflicts, SSUAVs are used for diverse, multi-purpose operations, flying at low altitudes in complex geographical conditions, adapting seamlessly to natural camouflage. Additionally, SSUAVs are capable evading detection through radio, infrared, and acoustic emissions by employing active and passive countermeasures, as well as demonstrating high manoeuvrability, such as "hovering" and altering flight trajectories [9. 11].

Acoustic detection and targeting provide an auxiliary detection factor. When "traditional" detection methods, such as optical and radar technologies, cannot meet required detection levels, acoustic detection methods offer a supplementary approach to ensure more reliable detection of small UAVs. Furthermore, ground-based acoustic sensors and reconnaissance systems help reduce the risk of detection by the adversary. For this reason, the existing acoustic search system's modification facilitates more robust UAV detection [1, 4, 8, 9, 11].

Acoustic vector sensors are installed on unmanned aerial vehicles (UAVs) and determine the location (coordinates) of objects based on acoustic signals emitted by targets. The system detects the source of the acoustic signal and turns the acoustic cameras in the direction of this signal.

The advantages of the Microflown AVISA acoustic target detection system include [1, 11, 12]:

-Small arms and artillery location detection;
-Detection and rejection of other aircraft in the vicinity of the UAV;
-Full spherical field of view;
-Simultaneous location of multiple noise sources, both ground and airborne;
-Target detection in the presence of wind and engine noise, etc.;
-Ability to direct other sensors to the target;
-Work in all weather conditions - fog, rain, clouds, night;
-Extremely small size and weight;
-Low power consumption.

The reconnaissance systems discussed above should be combined into an integrated system to detect SSUAVs, which would then distribute targets among destroyers according to target destruction capabilities and zones.

Naturally, when UAVs are in flight, they generate specific acoustic sound waves according to their purpose, which can be captured by acoustic microphones that convert sound pressure into electrical signals. During this process, the sound sources typically include the UAV's engines, wings, or propellers. The frequency of the generated sound is determined by the frequency of the exhaust of hot gases and the number and rotation frequency of the wings (or propellers). The sound intensity depends on the speed of the airflow around the blade angles.

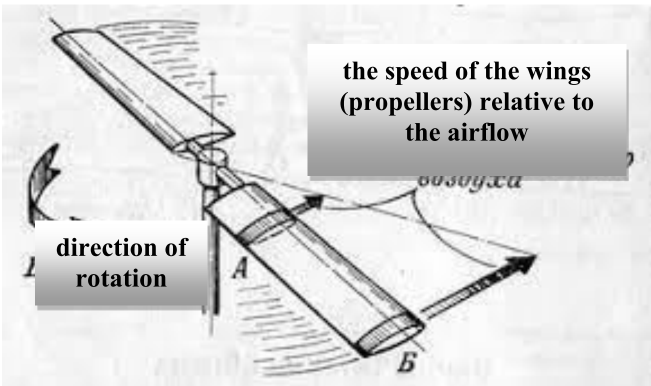

Figure 2: *Sound intensity as a function of airflow velocity around the angles of the propeller*

In real environments, sound waves diminish due to the inertia of the air medium and molecular attenuation. As sound waves propagate along the surface, they weaken depending on the additional absorption coefficient; the higher the absorption coefficient of the surface, the more significantly the propagating wave is attenuated. Moreover, the turbulence process occurring in the air plays a more significant role in the attenuation of sound waves and their scattering in various directions. Wind and rising air currents contribute greatly to this phenomenon. At lower frequencies, additional attenuations do not depend on the distance from the sound source. At greater distances (more than 4 km), high frequencies are practically not accepted.

In windy conditions, while detecting UAVs against the background of noise created, the acoustic signal generated by the microphone of the acoustic detection device is received in the form of a random signal with the assistance of acoustic microphones. At this time, the internal noise of the receiver combined with the acoustic noise forms a multidimensional density that is referred to as algorithm synthesis. Algorithm synthesis is based on the Neyman-Pearson criterion.

The Neyman-Pearson criterion is utilized in the uniform synthesis of the most powerful signal detection algorithms. This criterion can be applied in two states of nature, one of which is under control, the more significant of the two. The Neyman-Pearson criterion is considered one of the most common criteria related to radar detection devices. This criterion implies ensuring a constant value of the false alarm probability, F = const, by appropriately selecting the detection threshold.

It is precisely for this reason that the acoustic noise generated by UAVs must be separated from the internal noise of the receiver [9, 11, 12].

$$\rho_0 = [(2\pi)^N Det\ |R_{km`h}|]^{-1} exp\ \langle -\textstyle\sum_{l(k,n)}^{N} Q_{kl`h}\xi_k^t \cdot \xi_n \rangle, \quad (1)$$

Here, $N\text{-}T_N$ represents the number of recorded random signals received during the observation period; $\|R\|^{km`h}\|R\|^{-1}$ denotes the correlation matrix of the random signal received in the absence of acoustic noise that can be generated by the UAV; $R_{km}^{h}$=[? ?$_k^*$ ? ?$_{n]}$ ], k,n=; $Q_{kl}^{h}$, where $\|R\|_{km`h}$; is the cross-correlation matrix; ? ?$_n$- n- is the discrete report recorded by the n[th] acoustic microphone.

In the absence of external acoustic noise sources, only the acoustic noise (sound) of the wind is considered. The acoustic noise of the wind is characterized by correlated, rapid (0...50 Hz) and weak (50...150 Hz) pulsations, which reflect the wind's rapid pulsation speed (WRPS) and the wind's weak pulsation speed (WWPS). The moments rapid and weak pulsation of the wind are defined by the condition <$\tau_{k,WWPS}$ (see Figure 3).

To correlate these noises, frequency filters and acoustic microphones with unique filter functions capable of protecting against the wind are used, which ultimately allows for the acquisition of useful signals free from noise [12].

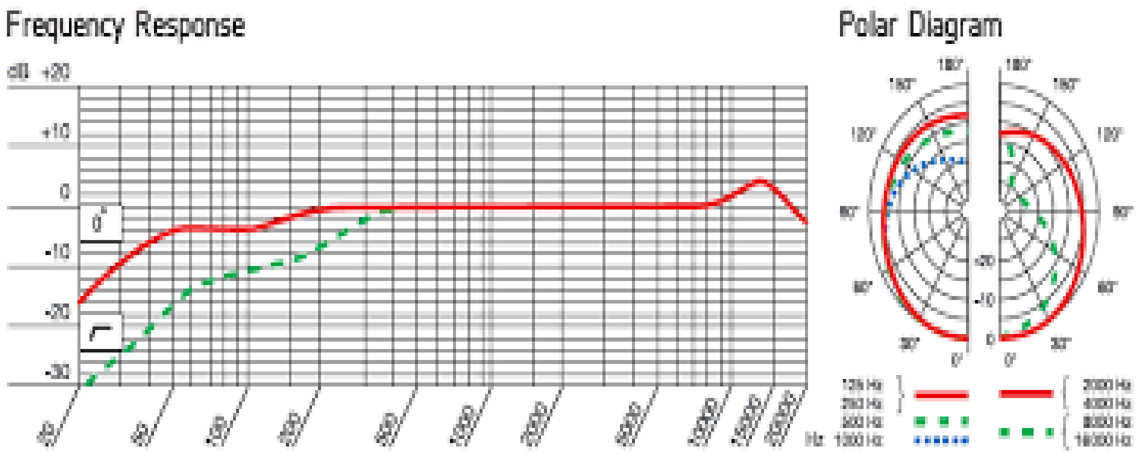

Figure 3: *Frequency characteristics of a wind-resistant acoustic microphone*

Thus, the stage of isolating the useful signal from the decorrelated background is performed by the filter, and the impulse characteristics are aligned with the expected useful signal. The processing of the output signal is carried out with the help of a device that separates the useful signal (DSUS), which is reflected by the following expression [11, 12].

$$Z_m = |\textstyle\sum_{n=1}^{N} \xi_n h_{m-n}| \quad (2)$$

here, h_n,n=represents the discrete report of the impulse characteristics of the DSUS filter.

The potential effectiveness of the device that separates the useful signal is reflected by the following expression:

$$\vartheta_{kn} = \frac{(N_{pfs}N_L)\cdot(V_{sswp} \pm 2V_{UAV})}{\Delta} \tag{3}$$

here, V_{sswp} denotes the speed of sound wave propagation in the atmosphere;

V_{PUA} represents the flight speed of the UAV;

N_{npr} is the number of propeller rotations in the UAV and $\Delta F_a = \Delta f_s$ refers to the width of the step of the AFC filter.

It is evident that the effectiveness of the DSUS varies depending on the speeds of flight and sound, the number propeller rotations, and the width of the step of the AFC filter.

Under the condition of sound wave transmission, the acoustic detection range can increase from 20 km to 50 km. In foggy conditions, however, this indicator, that is, the distance of detection, will decrease by 1.5 to 2 times.

IV. Conclusion

1. This article reviews methods and tools for detecting small-sized unmanned aerial vehicles using acoustic reconnaissance means and provides information on methods for detecting small-sized UAVs across various sound frequency ranges.

2. Additionally, the principle of detecting small-sized UAVs using acoustic reconnaissance means has been ensured by utilizing frequency filters and acoustic microphones with unique filter functions capable protecting against wind, which allows for the acquisition useful signals free from noise.

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