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# No Drone's Sky: Full Spectrum Drone Surveillance and Neutralisation Concept for Enhanced Counter-UAS Framework

## (Part 1, Surveillance)


### Abstract

*Unmanned Aircraft Systems (UAS), commonly known as drones, have witnessed substantial global proliferation in the past decade. Their constructive applications hold the promise of being a useful, yet critical component in creating a more efficient society with the enhancement of safety, efficiency, and facilitating advancements in various domains, ultimately contributing to our modern daily lives. However, the escalating dependence on computer and communication technologies renders, especially small, UAS susceptible to various threats, posing risks to public safety, national security, and individual privacy. Addressing these concerns necessitates the development of innovative technologies designed to detect, track, identify, and eliminate UAS in a manner that upholds safety, security, and privacy. A Counter-Unmanned Aircraft System (C-UAS) is defined as a system or apparatus capable of legally and securely incapacitating, disrupting, or assuming control over an UAS. Recent years have witnessed significant research endeavours aimed at detecting and eliminate drone threats. Detection methodologies encompass acoustic, visual, passive radio frequency, radar, and data fusion techniques, while neutralisation strategies encompass physical capture and jamming approaches. This paper, delving into the realm of small drone surveillance, is the opening segment of a three-part series aims to envision a C-UAS framework; it provides an exhaustive review of existing literature in the domain of UAS surveillance, delineating the challenges associated with countering*


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*unauthorised or unsafe drone operations, and evaluating the trajectory of detection to prepare against UAS-induced threats. Therefore, the fundamental objective of this paper is to offer a comprehensive surveillance baseline for a structured vision to a C-UAS framework, thus fostering a research community dedicated to the secure integration of drones into the airspace system.*

*Keywords: anti-drone, counter-UAS, drone sensing, drone neutralisation, drone surveillance*

## Introduction

The term *"no man's land"* is primarily known from history books and is closely associated with the tumultuous period of World War I. In this no man's land, an area which essentially sprawled between the opposing powers' trenches, soldiers only set foot when ordered to launch an attack, facing minimal chances of survival and constant exposure to the dangers of small arms and artillery fire.[2] Derived from the analogy of no man's land, envisioning a "no drone's sky" swaps the land for the sky, the soldier for the small drone, and the artillery fire for neutralisation techniques, ultimately creating a hostile space for adversarial and unlawful UAS activity.

The motivation behind formulating such a dire analogy lies in the recognition that small, unmanned aircraft systems (UAS), commonly referred to as drones, pose significant threats to both civilian and military entities,[3] as highlighted in recent episodes of the Russo–Ukrainian War[4] and the Israel–Palestine conflict.[5] Noting this challenge in Hungary, Government Decree 448/2023 (X. 3.) formally recognises small drones operating near critical infrastructure as genuine and emergent threats, emphasising the need for their surveillance and neutralisation. Within this context, advanced Counter-UAS (C-UAS) multi-spectral technologies are increasingly becoming the focus of interest, representing innovative approaches to the challenge, envisioning integrated solutions across multiple domains incorporating various sensors from active radars, through passive electromagnetic interceptors to acoustic sensors, all seamlessly connected to the neutralisation element via a dedicated command and control infrastructure. Additionally, the potential of cyber capabilities holds promise for countering mini-drone threats, although current solutions are still in their infancy, and these solutions demand advanced expertise, relatively rare skillsets, and expensive tools.[6]

Nonetheless, even though we have witnessed a significant progress in countering drones lately, the evolving threat landscape continues to present new challenges.[7] Rapid advancements in materials and the widespread availability of commercial off-the-shelf (COTS) technologies, including additive manufacturing, long-lasting batteries, and commercial navigational aids, have improved relatively cheap drone platforms with

[2] Chen 2010.
[3] Palik 2013.
[4] Faragó 2022.
[5] Freilich 2023.
[6] Shukla 2023.
[7] Krajnc 2018.

characteristics like high manoeuvrability and minimal signal-to-noise ratio (SNR).[8] Consequently, more advanced detection and tracking solutions are necessary to counter these evolving threats. In response to this rapidly evolving threat landscape, procurement rules for both military and law enforcement agencies have undergone significant changes. The traditional concept of time-to-market has started shifting to time-to-operation considerations.[9] Tender processes have expanded to include field trials and live competitions, highlighting the importance of availability over reliability in addressing these dynamic challenges. Therefore, the primary objective of this three-part study is to provide a comprehensive survey of the current body of literature pertaining to UAS surveillance, neutralisation and finally envisioning a C-UAS framework. It also aims to address the challenges associated with countering adversarial small UAS and evaluate emerging trends in detection and neutralisation methods, with the ultimate goal of cultivating a research community dedicated to the secure integration of UAS into the airspace system and supporting the adoption of Counter-UAS measures that align with legal obligations.

## The etymology of drone surveillance

The catechism of comprehending the environment, accurately interpreting sensations, understanding the principles governing the material world, and delimiting the bounds of perception, consequently influencing surveillance capabilities, has perennially concerned mankind. Rooted in Western philosophy, this quest harks back to Plato's Theory of Forms, also known as the Theory of Ideas. According to Plato, every perceptible projection in the realm of (visual) sensory experiences emanates from the higher domain of ideas, a concept elucidated in the Allegory of the Cave.[10] These ideas epitomise the real, eternal, unalterable, and immaterial attributes of the thing-in-itself, accessible through the faculties of the human mind. The Platonic concept ιδέα (idea) traces its origins to ἰδέειν (seeing), symbolising the human capacity to deduce and abstract *a priori* existing categories and ideal archetypes from raw sensory input. Employing logic and mathematical formulations, one can encapsulate and approximate the realm of ideas, and this approach may propose a novel way of understanding the different forms of small drone surveillance techniques presented in this paper: radar, acoustic, optical, and data fusion.

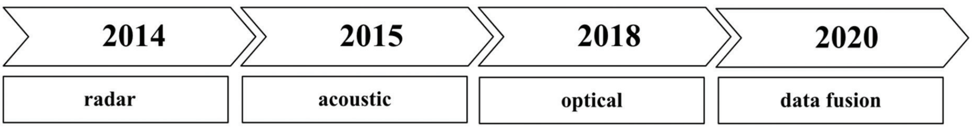


*Figure 1: Advancement of UAS surveillance technologies*
*Source: compiled by the author*

[8] Song et al. 2017.
[9] Jahangir–White 2021.
[10] Ross 1976.

The developmental trajectory of UAS detection technologies is illustrated in Figure 1. Subsequent sections delve into the specifics of each UAS detection technology, offering a comprehensive exploration of their respective advantages and disadvantages. The term "surveillance" in this context serves as an umbrella term, encompassing the integral components of detection, identification, and tracking.

## Radar surveillance

Radar technology possesses distinctive advantages in detecting airborne objects, offering day and night operational capability, weather independence, and concurrent measurement of range and velocity. Nevertheless, traditional radar systems primarily target medium- and large-sized aerial objects with Radar Cross-Section (RCS) larger than 1 $m^2$, posing challenges in the detection of small-sized and low-speed UAS.[11] This challenge arises from the slow speed of UAS, necessitating efforts to develop new radar models or enhance the resolution of existing systems. To address this, two categories of radar-based UAS detection technologies are explored: active and passive radar surveillance.

### *Active radar surveillance*

Enhancing the resolution of conventional radar systems for Unmanned Aircraft Systems (UAS) surveillance typically involves two strategies: utilising higher frequency carriers and employing multiple input multiple output (MIMO) beamforming radio front-ends. In pursuit of shorter wavelengths, X-band and W-band frequency modulated continuous wave (FMCW) radars designed for UAS detection are explored in its respective paper.[12] These solutions incorporate a bi-static antenna, ultimately converting received signals into a digital quadrature stream for subsequent processing, while leveraging ultra wide band (UWB) signals with a 24 GHz carrier has been demonstrated feasible.[13] The optimal carrier frequency for UAS detection radar, recommended to exceed 6 GHz (K-band), incorporates alternative approaches that employ multiple antennas to construct MIMO front-ends.[14] Notably, showcasing the detection of a small hexacopter using a 32 by 8 element L-Band receiver array, achieving notable sensitivity against micro-UAS.[15] Similarly, introducing a ubiquitous FMCW radar system operating at 8.75 GHz (X-band) with a PC-based signal processor, exhibiting the capability to detect a micro-UAS at a range of 2 km with an excellent range-speed association.[16] In another example, a K-band radar system with 16 transmitting and 16 receiving antennas forming 256 virtual antenna elements

[11] Károly–Sághi 2021.
[12] Park–Park 2017.
[13] Nakamura–Hadama 2017.
[14] Krátký–Fuxa 2015.
[15] Jahangir–Baker 2016.
[16] Duque De Quevedo et al. 2018.

demonstrates UAS detection even in a non-stationary clutter environment at a range of approximately 150 m.[17] The generation of a substantial volume of data for further processing is a noteworthy aspect of MIMO systems, prompting the author to employ the data cube and classifier concept to determine the presence and location of an incoming UAS.[18] In addition to employing a simplified multiple input single output (MISO) approach for UAS detection, other studies have shown the feasibility of utilising random sequence radar in the sub X-band, indicating potential cost-efficient solutions for UAS detection.[19]

Advancements in computation introduce the software-defined radio (SDR) based multi-mode radar, characterised by its small size and high configurability.[20] Nevertheless, the operational performance of software-defined radar (SDR) is closely tied to the capabilities of the backend processor; as demonstrated in an earlier research, the feasibility of UAS detection is tested through the presentation of two distinct implementations of FMCW radar and an implementation of continuous wave noise radar, revealing that the analogue implementation exhibits a superior updating rate and SNR.[21] The primary drawback associated with active radars is their reliance on specially designed transmitters, posing challenges in deployment and vulnerability to anti-radioactive attacks.

### *Passive radar surveillance*

Passive radar technology represents a unique paradigm in radar systems, deviating from the conventional need for dedicated transmitters. Instead, it harnesses existing radiation sources, such as ubiquitous cellular signals, to effectively illuminate the surrounding space. Within the domain of Micro-Doppler effects, passive radars can be broadly categorised into two fundamental types: single station passive radar and distributed synthetic passive radar.[22]

The single-station variant operates by leveraging a singular illumination source, and the analysis of variations in received signals facilitates the discernment of the presence and characteristics of UAS. An illustrative example entails the utilisation of a Wi-Fi-based passive radar explicitly designed for the detection and two-dimensional localisation of small aircrafts, representing a direct emulation of active radar principles.[23]

Distributed synthetic passive radar, on the other hand, involves distributed stations leveraging existing telecommunication infrastructures as sources of illumination to enhance small UAS detection capabilities. Two primary approaches manifest within this category: cellular system-based solutions and digital video broadcasting (DVB) system-based solutions.

17 Klare et al. 2017.
18 Jian et al. 2018.
19 Sacco et al. 2018.
20 Kwag et al. 2016.
21 Stasiak et al. 2018.
22 Ghazalli et al. 2021.
23 Martelli et al. 2017.

Within cellular system-based solutions, innovative approaches include utilising reflected Global System for Mobile Communications (GSM) signals for UAS location and tracking.[24] Another method involves the reception of 3G cellular signals reflected by the UAS for tracking, exploiting the Doppler features of the signal.[25] Furthermore, the investigation involves the deployment of 5G mm-wave radar infrastructure to detect small Unmanned Aircraft Systems (UAS), with captured signals being uploaded to the cloud for hazard analysis;[26] a comparable passive radar array system employs the orthogonal frequency division multiplexing (OFDM) echoes of UAS initially transmitted by nearby base stations.[27]

In the realm of digital video broadcasting system-based solutions, the utilisation of digital television signals as effective sources of illumination for passive drone detection radars has been explored. Significant research efforts have yielded the design and testing of passive drone detection radars, with a noteworthy emphasis on mirroring active radar methodologies;[28] micro-Doppler effects are employed for UAS classification, and experiments involving propeller-driven micro-Doppler signatures alongside machine learning underscored the distinguishability between plastic and carbon fibre propellers.[29]

Despite the promising potential of passive radar technology in leveraging ambient radiation, a notable challenge lies in the substantial passive surveillance efforts or the need for multiple receivers to achieve satisfactory detection accuracy. Nonetheless, if effectively addressed, challenges related to resource management, non-line of sight (NLOS) radar operation, noise mitigation, and big data management, passive radar technology holds the promise of significantly enhancing the safety and security of urban environments and critical infrastructure.

## Acoustic surveillance

Utilising acoustic sensors for UAS detection involves capturing UAS sound, identifying and tracking these vehicles through audio analysis. Deployed around restricted areas, acoustic sensor arrays periodically record audio signals, which are then transmitted to ground stations for feature extraction and UAS detection. Traditionally, power spectra or frequency spectra are analysed to identify UAS sounds, with some studies employing advanced techniques.

Researchers have investigated linear predictive coding for the discrimination of UAS engine audio signal patterns from other ambient noises, despite sensitivity to weather conditions;[30] concurrently, in other papers have devised a real-time UAS sound detection and analysis system, showcasing its proficiency in acquiring real-time

[24] Zemmari et al. 2014.
[25] Chadwick 2017.
[26] Solomitckii et al. 2018.
[27] Xiaoqi et al. 2016.
[28] Liu et al. 2017b.
[29] Zhao–Su 2018.
[30] Vilímek–Buřita 2017.

sound data and recognising UAS sounds.[31] Noteworthy also that in another method, Euclidean distance and scale-invariant feature transform (SIFT) have been applied to differentiate UAV engine sound signatures from background noise, showcasing effectiveness despite processing efficiency challenges.[32]

Acoustic sensors, valued for their lightweight, cost-effectiveness, and ease of assembly, are instrumental in constructing arrays for UAS detection. An approach utilising a 24-microphone acoustic sensor array calibrated with time difference of arrival (TDoA) showed promise in tracking UAS flight paths but encountered limitations in scalability and calibration accuracy.[33] Another study enhanced UAS localisation by deploying two arrays of four microphone sensors, addressing multipath effects with a Gauss prior probability density function.[34] Advanced acoustic sensors, leveraging 2 to 4 cameras for sound strength distribution, demonstrated effectiveness in computing UAS locations both indoors and outdoors.[35] Additionally, an audio-assisted camera array captured video and audio signals simultaneously, employing histogram of oriented gradient (HOG) and Mel-frequency cepstral coefficients (MFCCs) features for object classification.[36]

Innovatively, machine learning has been introduced to classify UAS from audio data. Support vector machine (SVM) analysis of mid-term UAS engine sound signatures created a distinctive signal fingerprint, enabling precise UAS distinction in specific scenarios.[37] Another approach transformed UAS presence detection into a binary classification problem, employing Gaussian Mixture Model (GMM), Convolutional Neural Network (CNN), and Recurrent Neural Network (RNN) techniques, exhibiting effectiveness within short input signal durations.[38]

While current acoustic-based UAS detection technologies achieve precise recognition and localisation, the inherent limitations of acoustic approaches hinder large-scale deployment.[39] The integration of machine learning holds promise for enhancing small UAS detection performance in acoustic sensing, presenting a significant avenue for future research.

## Optical surveillance

Vision-based Unmanned Aircraft System detection technologies primarily centre on image processing, utilising videos and cameras to capture images of intruding UAS. Computational methods at ground stations analyse videos and pictures to identify the presence of UAS. Conventional approaches heavily depend on image segmentation methods, using the differential between UAS and the environment in images

31 Kim et al. 2017.
32 Jang et al. 2018.
33 Case et al. 2008.
34 Chang et al. 2018.
35 Busset et al. 2015.
36 Liu et al. 2017a.
37 Bernardini et al. 2017.
38 Jeon et al. 2017.
39 Gajdács 2022.

to discern UAS presence in restricted areas. Several studies tackle the challenges of separating UAS from the background and distinguishing UAS from flying birds.[40] In contrast, contemporary image segmentation methods employ neural networks to directly recognise UAS appearances. A novel approach employs a thermal camera for UAS detection, coupled with a neural network for identification.[41] Another research introduces a lightweight, fast algorithm capable of operating on embedded systems like Nvidia Jetson TX1, enabling small UAS identification in motion.[42]

A real-time vision-based UAS detection system combines FPGA-based and GPU-based platforms, emphasising power efficiency and processing speed.[43] Various convolutional neural networks were compared, demonstrating that the Visual Geometry Group (VGG 16) network with Faster R-CNN achieves superior performance.[44] Strategies, like combining images to create synthetic datasets, aim to enhance convolutional neural network training for improved UAS detection.[45] Convolutional neural networks also address the challenge of distinguishing UAS from birds, outperforming policy-based approaches in accuracy and efficiency.[46] Efforts employing infrared cameras aim to identify UAS by detecting heat variations, but challenges arise due to the significant impact of battery heat on detection results.[47] Dynamic vision sensors, capturing propeller rotation frequency, efficiently distinguish UAS from birds.[48] Vision-based approaches exhibit potential efficiency in specific scenarios, with the evolution of deep neural networks enhancing image processing capabilities. Real-time trials highlight their efficiency, yet challenges persist in implementing these algorithms across diverse environments. Robustness, adaptability, and precision are critical requirements. Robustness is essential for coping with rapid environmental changes, while mitigating image distortion caused by weather changes through multi-level image processors. Handling UAS mobility variations, distinguishing UAS from birds accurately, and improving overall detection and mitigation efficiency are ongoing challenges.

## Data fused surveillance

The process of data fusion involves integrating diverse data sources to produce more consistent, accurate, and informative information than any individual source can provide. This approach has the potential to generate fused data that is not only more informative but also more synthetic than the original inputs. By leveraging the strengths of various methods, data fusion aims to yield a combined result that is robust, accurate, and efficient, overcoming the limitations of single approaches, particularly in specific scenarios related to Unmanned Aircraft Systems detection.

40 Dong–Zou 2017. Christnacher et al. 2016.
41 Sineglazov 2015.
42 Briese et al. 2018.
43 Perschke et al. 2018.
44 Saqib et al. 2017.
45 Aker–Kalkan 2017.
46 Coluccia et al. 2017.
47 Andraši et al. 2017.
48 Hoseini et al. 2017.

Upon reviewing the advantages and disadvantages of individual approaches, three categories of research in data fusion for UAS detection emerge: multiple-sensor data fusion, multiple-type sensor data fusion, and multiple sensing algorithm fusion.

### *Multiple-sensor data fusion*

Different types of sensors possess distinct advantages and drawbacks in small UAS detection scenarios. To address the limited detection range of single approaches, specific sensor types are designed to overcome inherent limitations. For instance, an acoustic sensor array deploys distributed sensors to record audio, analysing the sound spectrum to locate UAS. In signal processing, adjusting the weight of each sensor enhances location accuracy. Another example involves RF-based detection with omni-directional antennas, enabling the tracking of UAS trajectories and the determination of malicious intent. Combining multiple sensors of the same type improves accuracy and functionality, extending detection range geographically.[49]

### *Multiple-type sensor data fusion*

In scenarios where increasing the number of sensors does not mitigate the drawbacks of single sensors, researchers explore combinations of different sensor types. Fusion of acoustic and radar sensors, for example, has shown more precise UAS detection. Deploying sensors with varying detection ranges, such as passive RF receivers, cameras, and acoustic sensors, enhances accuracy in different field zones.[50] Despite the promising performance, the deployment and configuration of such systems require specific expertise and pose challenges.

### *Multiple sensing algorithm fusion*

Efficiency and accuracy in small UAS detection remain challenging, prompting the exploration of combining multiple sensing algorithms. Activated sensors deliver information to ground stations, triggering relevant algorithms based on detection status. Unsupervised approaches, as demonstrated in one study, extract features of signals from various acoustic sensors, employing support vector machine and K-nearest neighbours (KNN) algorithms for UAS detection.[51] Balancing the weight of each sensing algorithm and establishing reasonable schedules for their activation present ongoing challenges.

In data fusion schemes, researchers may consider platform integration, wherein sensors are deployed on various platforms to enhance mobility; however, challenges

[49] Böniger et al. 2016.
[50] Müller et al. 2018.
[51] Klochko et al. 2019.

encompass maintaining consistency in detection results and balancing the weights of different approaches to achieve optimal outcomes.[52] The data fusion approaches demonstrated advantages over single methods, emphasising the need for further research to optimise their implementation in diverse scenarios.

## Conclusion

The comprehensive introduction of small drone surveillance methodologies reveals a dynamic landscape marked by technological advancements and challenges. Radar surveillance, with active and passive variants, showcases potential, but further research is needed to optimise active radar technologies in order to detect small drones. Acoustic surveillance emerges as a cost-effective alternative, leveraging machine learning applications that exhibit potential for enhanced performance, while optical surveillance, dependent on image processing and neural networks, holds promise but necessitates ongoing refinement to ensure adaptability. Emerging as a unifying approach, data fusion demonstrates the potential of combining diverse data sources for a robust UAS detection method, with the versatility of multiple-sensor data fusion, multiple-type sensor data fusion, and multiple sensing algorithm fusion underscoring the imperative for comprehensive and resilient UAS detection solutions. In short, radar-based small UAS detection demonstrates superior performance, though challenges arise concerning deployment costs and technical expertise; the ongoing pursuit involves developing light, energy-saving, and affordable radar elements that facilitate easy deployment and maintenance.

Conclusively, this comprehensive study offers insights into existing small UAS surveillance methods, underscoring the importance of adopting a holistic approach to envision a Counter-Unmanned Aircraft System framework. As we advance to Part 2, concentrating on neutralisation methods, and Part 3, envisioning a comprehensive C-UAS system, the necessity of synergistic integration becomes evident.

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[52] SONG et al. 2018.

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