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A Survey of UAVs Detection: From Single UAV to Swarm

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Abstract

During the First World War, the world experienced the innovation of what is called drone, as a tool of espionage. Today we talk about drone swarm, where multiple drones work together to achieve a common goal or task. The use of this type of aircraft has undergone a great evolution and has become a source of problems for countries' security, which incites researchers to look for solutions against drones. There are several detection methods such as acoustic, radar, visual, and thermal detection. Also, there is radio frequency (RF) detection based on the RF communication links of the drone system. All these methods of drone detection facilitate the mission of the fight against drones. This review presents a comprehensive study of single/multi-UAV (swarm) architectures and offers a critical analysis of detection methods, transitioning from a single to multi-drone context. The paper also highlights several potential research directions providing essential datasets related to the detection techniques. In addition to the theoretical literature review, this work paves the way toward the development of practical counter-UAV systems.

A. Introduction

Unmanned aerial vehicles (UAVs) or drones have seen significant market development: The statistics reveal that over 1.7 million drones were registered in the U.S. in 2020. Drones are perceiving significant applications in a variety of fields, including;

- **Cinematography**: drones are currently being used by various filmmakers to ensure aerial filming like never before, enabling a new level of creativity with a bird's eye view [1].
- **Search and Rescue**: drones are used in searching for lost, scattered, or stranded people, especially when human presence is limited
- **Crisis Management**: In case of a terrorist attack or a natural disaster (earthquake floods), UAVs can act as hot spots or base stations, which allows for the collection of short messages sent by affected people
- **Military use**: drones are used in military applications like surveillance, target acquisition, reconnaissance, targeted strikes, force Protection, etc
- **Delivery use**: Today, big companies (DHL, amazon) use drones in delivery. For example, "Amazon Prime Air" was initiated by Amazon to deliver packages of five pounds within thirty minutes at a distance of 10 miles using a drone. Also, DHL started her project "Parcelcopter" to deliver medicine by drones.

In February 2017, a Chinese-made autonomous flying drone taxi named "Ehang 184" was tested in Dubai. It has a top speed of 63 mph and can transport a passenger weighing up to 100 kg. In 2019, Zipline International used UAV medical service to distribute life-saving medicines, blood, and vaccines to 2000 healthcare centers in the south of Ghana.

On the other side, we have drone swarm technologies which allow groups of drones to coordinate with each other, even without direct human control. Drone swarm is used in several fields, such as:

- **Agriculture**: Drone swarm technologies could plant seeds, identify disease outbreaks by surveying large areas, and deploy treatments such as fertilizers to crops.
- **Emergency management**: Responders could use drone swarms to find missing persons and deliver emergency care and supplies during natural disasters. Drone swarms could also help firefighters track & control the spread of wildfires and collect information about damages, access points, and more.
- **Entertainment**: Event organizers have used drone swarms for entertainment as an alternative to fireworks. Doing so can mitigate debris, pollution, fires, and disturbances to animals and humans.

The Federal Aviation Administration (FAA), USA forecasts the number of model UAVs will reach a total number of 1.47–1.63 million in the United States (US) by 2025 also 8 % of americans say they own a drone.

However, there has also been an increase in the usage of UAVs for malicious applications: they can be used to endanger ecosystems and species, violate people's privacy and security, provide moral dilemmas for military usage, interfere with employment markets and economies, and present legal and regulatory issues, as detailed below:

- **Illegal Surveillance and Espionage:** Drones equipped with cameras can be used for unauthorized surveillance, potentially invading individuals' privacy. This can occur in both public and private spaces[2].
- **Criminal Activities:** Criminals may use drones for illegal activities such as drug trafficking, smuggling, or planning and executing thefts. Drones provide means to conduct reconnaissance without direct physical presence
- **Terrorism:** There are concerns that drones could be weaponized and used forterrorist attacks. Weaponized drones have the potential to carry explosives or chemical agents, posing a threat to public safety.

Drone swarms can cause even more harm than a single malicious drone. They may be maliciously used for;

- **Weaponization:** If drone swarms are equipped with offensive capabilities, they could be weaponized for malicious purposes. This could include carrying explosives or conducting coordinated attacks on targets
- **Disruption of Critical Infrastructure:** Malicious actors may deploy drone swarms to disrupt critical infrastructure, such as power plants, communication networks, or transportation systems[3].
- **Airspace Congestion:** Large-scaledeploymentofdrone swarms in urban areas or restricted airspace can lead to congestion and pose a threat to manned aircraft, especially if the swarm's control is compromised.

Face to this security challenge, concerns are derived towards counter-UAV and counter-swarm technology. The target should be detected and identified to respond to this emerging threat, as discussed below [4].

A.1. Related Works

Researchers and professionals have explored different technologies and methodologies to address the challenge of the detection and classification of drones. presents a comprehensive survey on drone detection and defense systems, with an emphasis on RF-based systems implemented using software-defined radio (SDR) platforms. The authors highlighted the importance of RF methods in detecting and defending against drones. They introduced the DronEnd system, which provides a robust drone detection and defense solution, contributing to the overall security framework. Also, acoustic detection was analyzed in which proposes an audio-based drone detection and identification system using deep learning techniques. The authors utilize a dataset of audio recordings of drone activities and apply deep learning algorithms to detect and classify drones. The study demonstrates the effectiveness of deep learning in accurately identifying drones based on their acoustic signatures. The findings highlight the potential of deep learning models in achieving reliable drone detection and identification capabilities. In the authors analyze the radar cross-section signatures of diverse drone models at mm-wave frequencies. Their measurements revealed that larger drones made of carbon fiber are easier to detect, while drones made from plastic and styrofoam materials are less visible to radar systems. This finding suggests that the material composition of drones plays a significant role in their radar detectability.

There are multiple related works about single drone detection. According to our knowledge, there are no dedicated research works about the emerging threats of drone swarms andthedetection techniques of these targets, which is among the scope of this work.

A.2. Scope and contribution

This review is for readers who want to read about the drone system: its composition and principles. Also, by this review, readers can understand the principle of the swarm of drones and know different types of drone and swarm detection. The readers will have a good overview of the RF detection of drones and multi-drones (i.e. swarm) and also a comparison with other techniques of detection.

A.3. Organization of the paper

We have organized this paper as follows: Section 2 provides basic information about drone and drone-swarm systems. Detection systems for single-drone and multi-drone are addressed in Section 3. Section 4 provides technical details about the RF detection of single and swarm drones. Section 5 concludes this review and finally, section 6 provides a Future Roadmap.

B. Single Drone and Drone Swarm Systems

The use of drones is constantly rising in numerous domains because UAVs provide users with a bird's eye that can be used everywhere either as a single or a swarm system.

B.1. Main components

As given in Fig. 1, the drone is a part of a system in which we find:

- **Ground Control Station (GCS):** is based on land and serves as the interface between the drone operator or pilot and the unmanned aircraft during flight. The GCS pilot can control the UAVs during their operations.
- **Flying Segment**: is the flying part (the drone) and it contains a lot of components: flight controller, sensors, motor, etc.
- **Data links:** refer to the communication links that enable the exchange of information between different components of the drone system, including the drone itself and the GCS. These data links play a crucial role in ensuring real-time communication, control, and telemetry during drone operations.
- **Payload:** refers to any additional equipment or cargo that a drone can carry beyond its essential components for flight. Drones can be equipped with various types of payloads to serve different purposes, like cameras, arms, and sensors. coordination A drone swarm is composed of two or more drones, so it keeps these main components as detailed below.

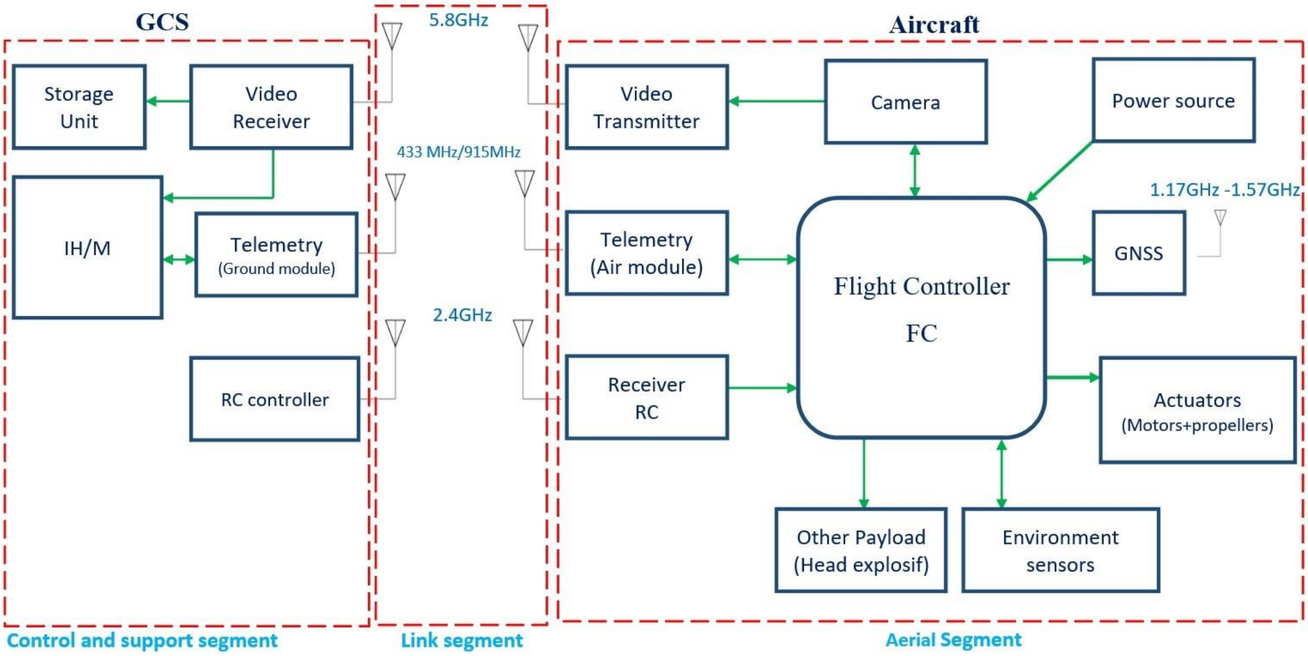

Figure 1. Block diagram of drone system [5]

B.2. Architecture of drone swarm

Traditional UAV swarms use a computer as a GCS running ground control software. The computers are equipped with a transceiver that sends and receives telemetry data from connected UAVs. Telemetry data traditionally includes GPS information, groundspeed, and other parameters collected from payload sensors. The commonly used swarm communicationarchitecturesareinfrastructure-based swarm architecture and ad-hoc network-based architecture.

B.2.1 Infrastructure-based swarm architecture

The infrastructure-based architecture , given in Figure 2, consists of a GCS that receives telemetry information from all drones in the swarm and sends commands back to each UAV individually. In some cases, the GCS communicates back to individual drones in real-time, sending commands to the flight controllers on board each UAV. In other cases, a flight operation is pre-programmed aboard each UAV, which is simultaneously operated while the GCS is simply used to observe the systems. These UAV swarms are considered to be semi-autonomous as they still require direction from a central control to complete an assigned operation. Infrastructure-based swarm architectures are dependent upon the GCS for the coordination of all drones. This dependency causes a lack of system redundancy.

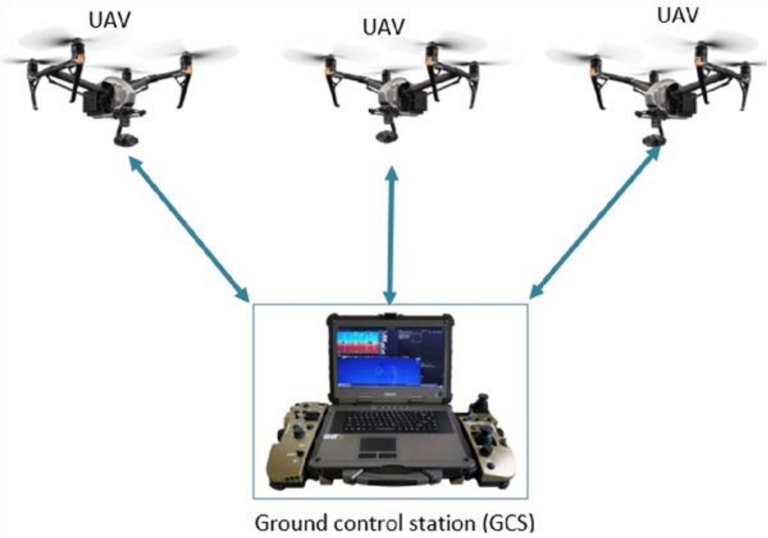

Figure 2: Block diagram of infrastructure (GCS) based swarm architecture[6]

B.2.2. Flying ad-hoc network (FANET) architecture

FANETs is a group of UAVs communicating with each other with no need for an access point. But at least one of them must be connected to a ground base or satellite, as given in Fig.3. UAVs carry out their missions without humanhelp.Awirelessad-hocnetworkisawirelessnetwork that does not rely on existing infrastructure to establish the network. Instead, nodes are dynamically assigned and reassigned based on dynamic routing algorithms. Various configurations of ad-hoc communication networks have been proposed in M2M communication systems [7, 8, 9, 10, 11, 12, 13].

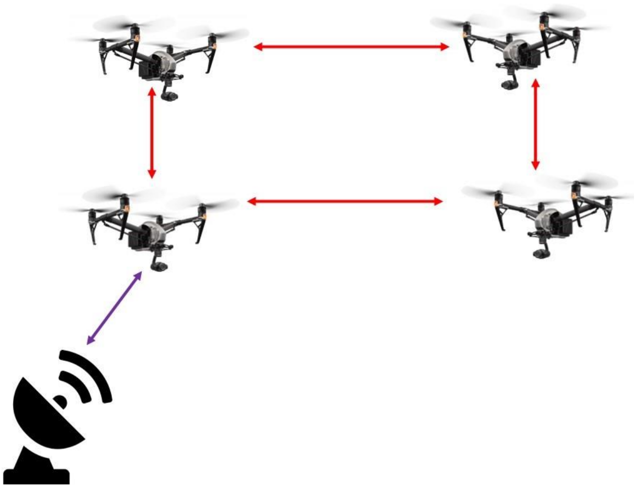

Figure 3. Communication architecture of UAV swarm based on FANET [12, 6]

B.2.3. UAV-to-UAV drone swam architecture

In this architecture, the telemetry of each UAV is communicated to every other UAV via cellular mobile infrastructure, as shown in Figure 4. Decisions are distributed among the UAVs, and the infrastructure is purely used to transmit data. Furthermore, UAV payloads containing computational power sufficient to coordinate decisions based on the realtime telemetry data received from connected UAVs shall be deployed. This allows for distributed decision-making based on formal logic, machine learning, and other distributed control algorithms.

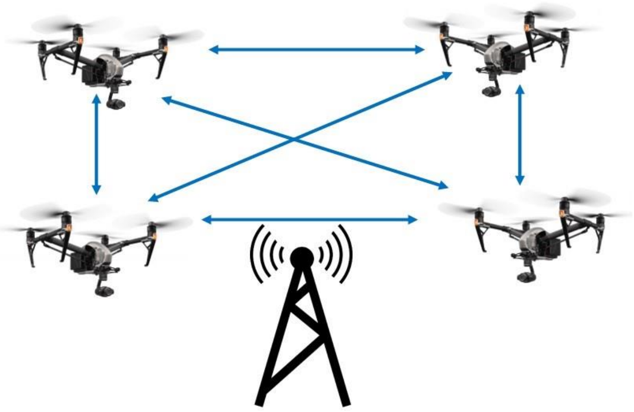

Figure 4. UAV to UAV drone swarm architecture [12, 6]

The comparison between these three architectures of drone swarm is given in table 1.

Table 1. Comparison between drone swarm architecture

Drone swarm architecture	**Merits**	**Limitations**
GCS-based swarm architecture	-Coordination and Oversight: A GCS allows centralized coordination and oversight of the entire drone swarm. -Simplified Communication: single point of communication, simplifying the control and communication infrastructure. -GCS provides real-time monitoring of each drone's status, sensor data, and mission progress. -Operators can make informed decisions based on up-to-date information.	-There may be communication bottlenecks as the number of drones in the swarm increases. High traffic can lead to delays and reduced responsiveness. -Drones in a GCS-based architecture may have reduced autonomy since they rely on continuous communication with the GCS. -Jamming Vulnerability: Centralized communication makes the entire swarm vulnerable to jamming attacks. Disrupting communication with the GCS can compromise the control and coordination of the drones.
Flying ad-hoc network (FANET) architecture	-FANETs are highly adaptable to changes in the environment and can be scaled easily by adding more drones. -This flexibility is advantageous in dynamic scenarios. Reduced Dependency on Central Control. -Drones in a FANET can establish multiple communication paths, enhancing redundancy. -FANETs empower individual drones to make decisions based on local information.	-FANETs operate in a dynamic and changing network topology, which can lead to challenges in maintaining stable communication links. Factors such as interference, signal attenuation, and environmental conditions can impact communication. -Decentralized communication in a FANET may introduce security vulnerabilities. Drones communicating directly with each other could be more susceptible to certain types of attacks, such as jamming or eavesdropping. -Drones in a FANET may have a limited global view of the entire swarm. This can affect decision-making, especially when drones need to consider the overall swarm behavior for coordinated actions

UAV-to-UAV drone swarm architecture	-Autonomous Decision-Making: UAV-to-UAV architectures often allow for decentralized control, enabling each drone to make autonomous decisions based on local information. -UAV-to-UAV communication is adaptable and scalable. New drones can be easily integrated into the swarm, and the architecture is flexible in dynamic environments. -Individual drones have a higher level of autonomy, making decisions based on local sensor data.	-Direct UAV-to-UAV communication may have limitations in terms of range, especially in environments with obstacles or interference. Maintaining reliable communication links over longer distances can be challenging. -UAV-to-UAV communication may be more susceptible to certain security risks, such as eavesdropping or interference, compared to a more centralized communication architecture.

B.3. Key Principles of Drone Swarms

A drone swarm is a group or cluster of UAVs that operate collaboratively to achieve a common objective. Drones in a swarm share information, coordinate their movements and work together. Swarm behavior often involves decentralized control, where each drone makes decisions based on local information and interactions with nearby drones. They communicate with each other to share data, coordinate movements, and maintain awareness of the overall swarm's status

The key principles of a drone swarm include:

- **Autonomy**: Each drone in the swarm is equipped with sensors, communication devices, and onboard computing power, allowing it to operate autonomously without human intervention. They can make decisions, adjust their flight paths, and adapt to changing conditions in real time.
- **Communication**: Drones in a swarm must communicate with each other to share information, coordinate their actions, and maintain formation. Communication can be achieved through a combination of wireless protocols, such as Wi-Fi, Bluetooth, or proprietary mesh networks.
- **Coordination**: The swarm relies on algorithms and coordination mechanisms to ensure that drones work together harmoniously. These algorithms may include leader-follower models, consensus algorithms, or decentralized decision-making processes.
- **Distributed Control**: Rather than having a central controller, each drone plays its role in the swarm with a certain level of autonomy. Decentralized control ensures that the swarm remains flexible and resilient, as there's no single point of failure.
- **Swarm Intelligence**: Swarms can exhibit swarm intelligence, where the collective behavior of the group emerges from the interactions of individual drones. This allows for problem-solving, decision-making, and adaptation based on the collective knowledge of the swarm.
- **Adaptive Algorithms**: Drones in a swarm often use adaptive algorithms that allow them to respond to changing conditions and obstacles in real time. These algorithms may involve obstacle avoidance, path planning, and dynamic formation control.

Protocol refers to a set of rules and conventions that dictate how individual drones communicate and coordinate with each other to achieve common objectives. The choice of communication protocols is crucial for the effective functioning of the swarm.as we said in drone sarm we have differnt connectivity mode so we have also different protocole as decentralized protocols,coordination protocolsand wireless communication protocols. After this details about componentsofswarmandconnectivity,iwilldetaildetection techniques of this target. So we can say that the detection of drone swarm or single drone can be with different methods shown in next section.

C. Detection systems

The malicious use of drones is on the rise, leading to an increase in security concerns and potential threats. As a result, the need for effective detection and protection mechanisms to safeguard against these UAV-related attacks has become essential [14, 15]. This section synthesizes existing research findings on the detection of malicious drones.

C.1. Single drone detection

Face to single UAV attacks, there are different detection methods:

- **Radar detection**: Radio Detection and Ranging (Radar) is a technology commonly used for detecting and tracking objects in the airspace, and it is also employed for the detection of drones. Radar systems work by emitting RF signals and analyzing the signals reflected off objects in their vicinity [16]. The conventional radar signal processing techniques have the limitation of accurate distinction of mini UAVs from birds due to their smaller radar cross-sections(RCSs) Advanced commercial solutions utilize radar sensors to identify and counteract malicious UAVs, as illustrated in Fig. 5. These radar sensors are seamlessly integrated into systems by Dedrone company.

Figure 5. Radar brands on the Dedrone platform[17]

- **Acoustic detection**:Acoustic sensors detect the sound generated by drones. The distinct noise produced by drone propellers or motors can be picked up by specialized microphones, allowing for audio-based drone detection. An example of such a detection system is shown in Figure 6 [18]

Figure 6. The acoustic sensor of the SKY CTRL antidrone system [19].

- **Electro-Optical/ Infrared detection(EO/IR)**: Observation is astraightforward method of detectingdrones. Security personnel or automated surveillance systems can visually identify drones in the airspace. However, this method is limited by line-of-sight and is dependent on lighting conditions. Dedrone has developed a specific camera for UAV detection called the PTZ camera. It has a pan function, tilt function, and zoom function. Thanks to the powerful zoom, even small drones can be detected from a long distance. Optical sensors make it possible to visually verify drone incursions. High-resolution video can provide security providers with visual evidence of a drone's payload, allowing them to respond to the observable threat. Fig.7 provides a complete counter UAV system that is based on EO/IR imaging sensor for detection, it also performs classification and RF jamming There are many reported EO-based UAV datasets; imagebased related works are given in [20, 21, 22, 23], and video-based materials can be found in [24].
- **Thermal detection**: This technology identifies and tracks the heat signatures emitted by drones. Since, like other objects, drones emit infrared radiation that thermal cameras can capture. This capability is valuable in various applications, including security, surveillance, search and rescue, and environmental monitoring.

- **RF-detection**: RF analysis involves monitoring the radiofrequencyspectrumforsignalsemittedbydrones. This can include communication signals between the drone and its operator, as well as signals from onboard systems. RF detection is a promising solution for identifying and tracking drones Furthermore, the RF passive detection method has the advantage of low cost, license-free, long-range distance coverage, and early warning capability [25]. A complete counter UAV solution based on RF detection and neutralization is presented in Figure 8.

The detection and tracking of small UAVs are challenging due to various limitations imposed by different detection techniques. These limitations include small RCS, noise environment constraints in acoustic detection, visibility conditions, and size constraints in optical detection. RF detection of drones offers the advantage of being able to detect small UAVs under low visibility in noisy environments without the need for line-of-sight conditions. In table 2, we resume these detection methods and discuss their principles and their limitations.

C.2. Drone Swarm Detection

Swarm detection presents much greater challenges than single-drone detection. The following is a summary of the swarm detecting methods [28]:

- **Radar-Based detection**: Detecting a swarm of drones using radar involves the use of radar systems designed to identify multiple small and fast-moving targets simultaneously
- **Radio frequency Sensing**: UAV operations rely on the Radio communication (RC) link between the operator and the UAV for control commands and data relay. Moreover, swarms rely on inter-UAV communication using RF links. These RF signals can be detected. Furthermore, multiple deployments would be required for geo-locating its exact position using triangulation algorithms. For example, multiple high-gain directional antennas which can be co-mounted to provide Omni-directional performance with high accuracy directional estimates wideband operations from a few kHz to 18 GHz frequency range[29].
- **Electro-Optical (EO) & Infrared (IR) Sensors**: A combined optical, IR, and Laser range finder configuration could provide day and night operational capabilities, high accuracies for engagement, identification of the class/model of multiple UAVs and instant damage assessment after an engagement is required. Different configurations of EO/IR sensors for surveillance and engagement assistance functions could provide performance improvements. A high update rate rotating EO/IR sensor with laser range finderbased surveillance will provide 360-degree azimuth coverage. Multiple co-mounted sensors for different elevation angle coverage can be considered. A gimbal-mounted or weapon-aligned EO/IR sensor with a laser range finder can provide engagement assistance by providing the fine tracking parameters and identification of the acquired UAV threat. A visual dataset called UAVSwarm is presented in [30] to detect and track UAV swarms based on a large number of UAV swarm videos.

Table 2. Summary of Single Drone Detection Techniques

Techniques	**Strengths**	**Weaknesses**
Radio Frequency	-Real-time analysis for the detected radio communication between UAV and its controller. -Low cost and simple architecture and elements: Antennas, Processors, RF sensors. -Common frequency bands are around 2.4 and 5.8 GHz Covering a long detection range. -Referring to RF datasets and integrating with machine learning algorithms are advanced ways to enhance detection, localization, and precise classification.	The RF-based detection technique applies only if the UAV is remotely controlled. However, it does not apply to autonomous UAV detection [26]
Radar	-Transmitting radio signals, then receiving and analyzing the echo radar signals. -UAV's detection, Doppler-based tracking, classification, and localization are based on the analysis of the reflected radio signal. -Active sensor and data processing modules with high-range detection and accurate localization. -Machine learning algorithms and techniques' integration for better performance and results. -Less noise and applicable in different weather conditions (fog, dust, rain, etc.). -Analyze acoustic signals coming from UAV's engine or propeller blades. Acoustic sensors/microphones arrays combined with data acquisition and signal processing modules. -Acoustic fingerprint analysis, features extraction, classification, and localization UAV's identification and distinction from otherobjects. -Effective in a short distance. -Acoustic dataset and machine learning techniques integration for higher performance (detection and classification).	- UAVs with small radar cross-sections are difficult to be identified and classified. - The detection of acoustic noise emitted by UAVs is low; thus,the acoustic technique requires a network of sensors deployed around sensitive places. - It's affected by the nearby noise sources and weather.
Electro-optic	-Imaging and motion line of sight detection. -Ability to track autonomous UAVs. -Controlling false alarms with advanced integration with other methods/algorithms/machine learning.	-High-cost equipment. -Detection performance can vary with different environmental conditions and weather. -Using different electro-optics is required, and the fusion of video streams is required to cope with UAVs' environment and type/size. This increases the cost of the solution [27]

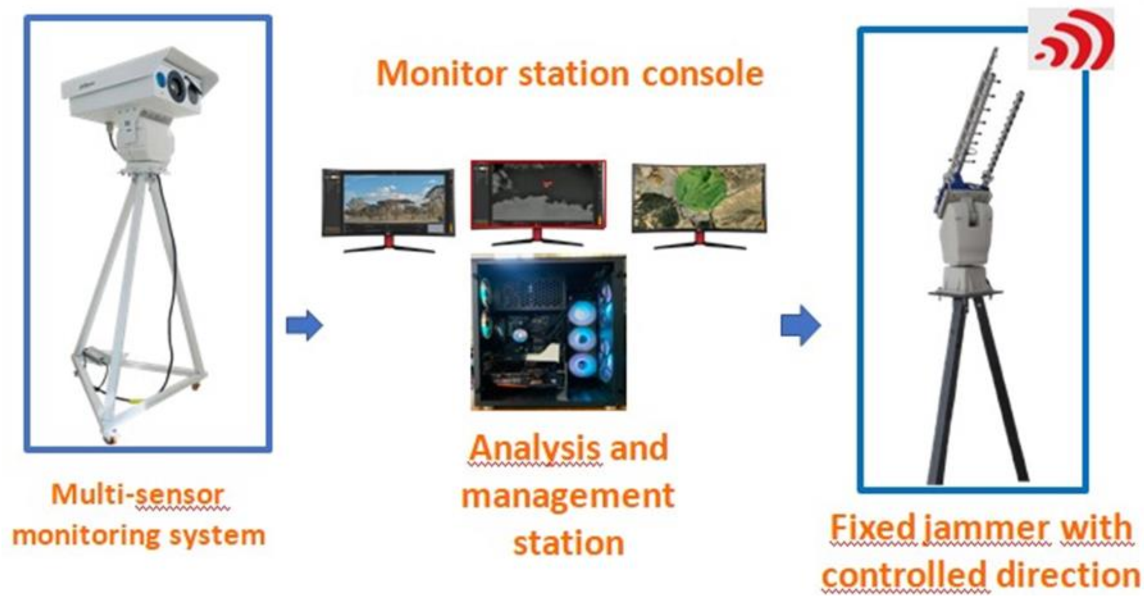

Figure 7. The Integrated Air Defense System against mini-UAVs

Figure 8: Complete CsUAS Kill-Chain Solution for the ACE Mission [17]

- **Acoustic Sensors**: Acoustic sensors unlike EO/IR sensors are not limited by line-ofsight or the size of targets for detection. Distributed shortrange acoustic sensors with directional acoustic scanning capability could provide effective coverage for a larger area. The Library of acoustic signatures of different UAVs could be used to correlate with the input signal for detection and identification. Algorithms and array microphone system characteristics could be studied to provide background noise mitigation and performance enhancement. An array of high-gain microphones with wider coverage using multibeam/electronic scanning would be best suited.

- **LIDAR sensors**: LiDAR, which stands for Light Detection and Ranging, is a remote sensing technology that uses laser light to measure distances and create detailed, threedimensional maps of the environment. LiDAR sensors contributevaluablecapabilitiestoenhancesituationalawareness and security. In table 3, we discuss the merits and limits of these swarm detection techniques.

Table 3. Strengths and weaknesses of different detection techniques of drone swarm

Techniques	Strengths	Weaknesses
Radars	• Well-established technology with all-weather operations • Target identification/classification capability • Large number of target detection and tracking capabilities	• Limited line of sight (LOS) for low-altitude UAVs • Low radar cross-section (RCS) of UAVs due to smaller non-metallic bodies • Challenging to distinguish from large background clutter or birds due to low speeds
Radio Frequency (RF) Sensing	• Low complexity and established technology • Longer distance operations possible • All-weather robust operations without performance degradation from clutter or other flying objects like birds	• Not effective against autonomous UAVs • Multi-path reflections can degrade measurement accuracies • Prior knowledge and dataset of emissions required
Electro-Optical (EO) and Infrared (IR) Sensors	• Target identification/classification capability • Large number of target detection and tracking capabilities • Laser range-finding equipment for range detection	• Provide 2D images • Limited by weather conditions/background temperature • Susceptible to positions of objects (horizon) • LOS is required
Acoustic Sensor	• Not dependent on LOS or the target's size, orientation, or flight profile • Supports day and night operations	• Range is limited • Vulnerable to ambient noise
LiDAR	• Provides 3D representation • Detecting an object in a complex background • High-resolution detection is possible • Provides target Doppler information	• Limited by weather conditions • LOS is required, and the detection range is short • Expensive technology

D. Technical Details about RF detection

In many circumstances, RF detection may be chosen over alternative approaches for the following reasons:

- **Wide Applicability**: RF detection can be used to detect a wide range of drones, regardless of their size, type, or purpose. This versatility makes it suitable for a broad spectrum of applications.
- **Regulatory Compliance**: In some regions, regulations may favor RF detection methods as a means of ensuring that drones comply with airspace regulations. RF detection can help enforce no-fly zones and altitude restrictions.
- **Passive Detection**: RF detection is typically a passive method,meaningitdoesn’trequireactivecountermeasures or engagement with the drone. This makes it a non-invasiveandlessconfrontationalapproach,which can be important in certain contexts.
- **Long Detection Range**: RF detection systems can detect drones at relatively long ranges, allowing for early identification and response. This is valuable in scenarios where early warning is critical. The data/video/control communication signals between the remote controller/control station and Mini/Micro UAVs are captured by RF receivers and processed [14].

D.1. Related RF detection works

To gain an understanding of the trends in current research, it was first necessary to construct a database of related studies. The two most popular research databases were used, Google Scholar and Scopus. IEEE and MDPI databases were also examined. In table 4, we provide recent

Table 4. Related works about RF detection related works about RF detection with a technical overview.

Papers	Date	technical overview
[31]	2024	This paper sheds light on the current challenges and limitations of drone classification by RF signatures, and suggests avenues for future research.
[14]	2024	This paper presents RF detection of drones and gives the system architecture of an experimental work and analysis.
[32]	2023	This paper presents the history of You Only Look Once (YOLO) and provides an overview of case studies of the application of YOLO in several industry sectors and the detection of UAV’swith YOLO.

[33]	2022	This review provides a comprehensive overview of drone RF detection techniques, classification models, and recent advances in this field.
[34]	2022	The study examines how deep neural networks can be used to improve drone classification by leveraging RF data.
[35]	2019	This study focuses on the use of machine learning to detect drones based on RF signals, examining different classification approaches.
[36]	2019	This paper builds a novel open-source database for the RF signals of various drones under different flight modes and tests the developed database in a drone detection and identification system designed using deep neural networks.
[37]	2018	The article discusses the importance of drone sensing in 5G networks and proposes spectrum sensing techniques specific to this application

D.2. Principle

RF-based detection focuses on the characteristics of the RF signals. Actually, UAVs have distinctive RF characteristics due to the different vendors' unique transceiver circuit design, frequency band/bandwidth choice, modulation techniques, etc. RF-based analysis can therefore help detect and classify these targets. In fact, drones communicate with the remote control using one or multiple radio links: one from the remote to the drone for control, and two from the drone back to the remote: one for sending the video feed, for those equippedwithacamera,andanotheroneforoptionaltelemetry data. Usually, drones operate on different frequencies, but most commercial drones operate in Industrial, Scientific, and Medical (ISM) frequency bands of 433 MHz and 2.4/5.8 GHz. The simple power detection in these bands will not work due to the presence of other legitimate users in the same geographical area. Therefore, most of the modern RF detection systems provide the detection and identification of special and unique signals related to the targets.

RF detection based on drone-commanded communications, as the name suggests, focuses on identifying and tracking drones by monitoring the signals generated by the drones themselves as they communicate with their operators or remote pilots. This approach is advantageous for several reasons:

- **Real-Time Monitoring**: This approach provides real-time information about the presence and location of drones. By continuously monitoring the RF signals used for drone control and telemetry, it allows for immediate response and situational awareness.

- **Minimal False Positives**: RF detection based on drone commands can be highly accurate, as it focuses on identifying specific communication protocols and signals associated with drones. This minimizes false positives and reduces the chances of misidentifying other objects or signals as drones. RF detection involves several key concepts: Spectrum Analysis: RF detectors continuously monitor the electromagnetic spectrum for signals that fall within the frequency range used by drones for communication. The analysis includes scanning various frequency bands to identify the presence of RF signals associated with drones.
- **Signal Characteristics**: Drones communicate with their controllers using RF signals, and these signals exhibit specific characteristics. RF detectors look for patterns in signal frequency, modulation, and other parameters to distinguish drone signals from background noise and other RF sources.
- **Frequency Hopping Detection**: Some drones use frequency hopping spread spectrum(FHSS)or other techniques to hop between different frequencies during communication. RF detection systems must be capable of rapidly scanning and tracking these frequency hops to maintain continuous surveillance.
- **Signal Strength Measurement**: RF detectors measure the strength of detected signals. Sudden changes in signal strength or the presence of unusually strong signals can indicate the proximity of a drone.
- **Direction Finding**: RF detection systems can incorporate direction-findingcapabilitiestodeterminethedirectionfrom which the drone signals are emanating. This information helps in locating the position of the drone.
- **Database of Drone Signatures**: RF detection systems can maintain a database of known drone swarm RF signatures. This database includes information about the unique RF patterns associated with different drone models and communication protocols.

D.2.1. UAV RF detection using SDR platforms

Researchers have explored the use of software-defined radio (SDR) platforms for the detection of drones based on radio frequency (RF) signals. In this paragraph, we synthesize and integrate the findings from several studies to explore the current state of research in SDR-based drone detection and the construction of a dataset of drone RF signals.

A drone detection system designed to autonomously detect and characterize drones using RF wireless signals was investigated in [38]. The study explored the feasibility of the approaches using WARP and USRP software-defined platforms. This work provided initial insights into the potential of SDR-based drone detection systems. In a subsequent study [39], the authors further examined the feasibility of inexpensive RF-based detection of drones by identifying physical signatures in the drone’s RF communication. The researchers explored whether the physical characteristics of the drone, such as body vibration and body shifting, could be detected in the wireless signal transmitted by drones. This study highlighted the potential for leveraging physical characteristics in RF communication for drone detection. Also, different drone detection and defense systems were surveyed in [40], with an emphasis on RF-based systems implemented using SDR platforms. Furthermore, [41] presented a drone detection sensor with a continuous 2.400 GHz-2.483 GHz operational frequency range for detection methods based on passive RF imaging techniques. This work contributes to the development of cost-effective SDR platformsfordronedetection,highlightingtheimportanceof continuous frequency coverage in RF-based drone detection systems.

A prototype for RF-based detection using a universal software radio peripheral (USRP) E312 is presented in [42]. The presented system is limited by the 56 MHz bandwidth of the SDR platform considered in this work. Also, the DroneDetectdataset[43]isrecordedusingtheSDRplatform Nuand BladeRF which has the same bandwidth limitation. In fact, the radio control (RC) signals used to communicate with UAVs have a wide bandwidth that reaches 80MHz. This challenge is solved in the DroneRF dataset, a radio frequency (RF) based dataset of drones operating in various modes, which is described in [44]. The collection includes recordings of RF activity obtained from three distinct drones and recordings of background RF activity without drones. Two National Instruments USRP-2943 (NI-USRP) software-defined radio reconfigurable devices were used to capture the data using RF receivers. Given that each RF receiver has a maximum instantaneous bandwidth of 40 MHz, both of them were activated simultaneously to record the frequency band (i.e. 80 MHz) of a technological spectrum, such as WiFi. Another dataset of drone radio frequency emissions, DroneRFa, is constructed in [45]. This dataset monitors communication signals between drones and their controllers using a software-defined radio device (USRP2955) which is characterized by its 80MHz bandwidth. The signals include nine different types of flying drone signals in an outdoor setting, fifteen different types of drone signals in an indoor setting, and one background signal type for reference.

While the existing research has made significant strides in the development of SDR-based drone detection systems, there are still several knowledge gaps and potential future research directions that warrant attention. Firstly, the integration of machine learning and deep learning techniques with SDR platforms for drone detection could enhance the accuracy and efficiency of detection systems [46]. Additionally, the construction of multimodal datasets acquired from RF and vision-based sensors could facilitate the development and testing of robust drone detection algorithms Moreover, future research could explore the development of hardwareaccelerated real-time spectrum analyzers with fast sweep features based on cost-effective SDR platforms, which could further improve the capabilities of RF-based drone detection systems Furthermore, the use of multichannel SDR platforms for mobile applications could expand the scope of drone detection in diverse operational environments

Overall, the literature on SDR-based drone detection and dataset construction of drone RF signals using SDR platforms has made significant progress, with various studies exploring the feasibility of RF-based drone detection and the development of cost-effective SDR platforms. However, there are still ample opportunities for future research to enhance the accuracy, efficiency, and versatility of SDRbased drone detection systems, paving the way for more robust and reliable solutions to address the challenges posed by drone misuse.

D.2.2. UAV RF detection using osciloscope

Several research works have exploited datasets of RC. drone signals that have been captured using high-resolution oscilloscopes. The authors in focused on drone presence detection and classification using physical signatures in the drone's RF communication. The study has used a dataset of recorded signals using a high-frequency oscilloscope, indicating the importance of this equipment in capturing drone RF signals for detection and classification purposes. Also, the Cardinal RF (CardRF) dataset is presented in [47]. Bluetooth, Wi-Fi, UAV controllers, and UAVs all sent out RF signals that were gathered. Both beyond line of sight and visible line of sight are used to gather signals. The data collecting process and its underlying assumptions are described based on the Aerial Experimentation Research Platform for Advanced Wireless (AERPAW) project. Furthermore, MPACT Lab Drone RC RF Dataset, presented in [48], includes the RF signals from several brands and models of drone remote controllers. A low-noise power amplifier, directional grid antenna, and high-frequency oscilloscope make up a passive RF surveillance system that records and intercepts these signals.

E. Conclusion

This review has presented essential information on drones and drone-swarm systems. We have also provided a comprehensive synthesis of the existing research on single drone and drone swarm detection.

Particularly, RF detection is detailed in this work providing a crucial discussion of the existing datasets. Moreover, research findings are provided and potential research directions are highlighted. The review is structured to cover the key insights from each study, while also addressing knowledgegapsandsuggestingfutureresearchdirectionsfor the advancement of SDR-based drone/multi-drone detection systems.

F. Future Roadmap

In our ongoing study in RF detection field, we are using SDR Platforms, particularly the USRP X310 one. It provides several benefits in the fields of signal processing, research, and wireless communications. This platform supports multiple input, and multiple output (MIMO), has a wide frequency range, high bandwidth, modular design, real-time signal processing, and support for open-source software. To significantly enhance detection accuracy and sensitivity, we intend to explore the fusion of RF data with information captured by radar and Electro-Optical/Infrared (EO/IR) sensors. Additionally, we plan to develop machine learning (ML) models that leverage the combined sensor data for advanced drone/swarm classification and identification. Finally, we will investigate the potential of SDR platforms for RF jamming as a potential means to neutralize malicious drones.

G. References

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