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Survey on Anti-Drone Systems: Components, Designs, and Challenges

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ABSTRACT This paper presents a comprehensive survey on anti-drone systems. After drones were released for non-military usages, drone incidents in the unarmed population are gradually increasing. However, it is unaffordable to construct a military grade anti-drone system for every private or public facility due to installation and operation costs, and regulatory restrictions. We focus on analyzing anti-drone system that does not use military weapons, investigating a wide range of anti-drone technologies, and deriving proper system models for reliable drone defense. We categorized anti-drone technologies into detection, identification, and neutralization, and reviewed numerous studies on each. Then, we propose a hypothetical anti-drone system that presents the guidelines for adaptable and effective drone defense operations. Further, we discuss drone-side safety and security schemes that could nullify current anti-drone methods, and propose future solutions to resolve these challenges.

INDEX TERMS Anti-drone, counter-drone, drone detection, drone identification, drone neutralization.

I. INTRODUCTION

Advances in micro air vehicles, also known as drones, take advantage of opportunities in the several industrial domains, from agricultural engineering to military missions [1]. Rapid expansion of the drone industry has surpassed regulations for safe and secure drone operation, which makes them representative means of the illegal and destructive terrors and the crimes [2]. With the introduction of drones into civilian technology, drones are now gaining attention as a threat of safety and security, which leverages the emergence of the anti-drone (or counter drone) technologies. Anti-drone systems are devised to defend against drone accidents or terrorism, and needed to be advanced to cope with the future drone flight systems.

Currently, most of anti-drone systems adopt military grade components to achieve the confirmatory destruction of malicious drones. However, several difficulties apply when locating military grade anti-drone system into civilian areas. Military counter-drone measures typically use jamming systems [3] to disable the target drone control channel. The jammer generates extremely high amplitude of RF signal in the target frequency band to prevent communication. For military scenarios, the site is controlled by the military, and the operator pre-acquires proper field manual for jamming conditions, hence the side effect of jamming can be ignored or managed. However, for non-military applications, RF jamming to neutralize high-speed drones risks temporal paralyze of existing wireless network systems, such as mobile access or wireless sensor networks. Thus, most national regulations prevent non-military use of jamming systems [4], [5], and hence civilian anti-drone systems need to investigate alternative approaches to stop illegal or unauthorized drones. Similarly, anti-aircraft weapons such as missiles are hardly allowed for civilian systems. Except for cases where the national army covers the entire civilian area, such as Iron Dome [6] in Israel, non-military operators need anti-drone strategy without using military grade weapons.

Radar was regarded as a limited solution for drone detection due to inflexible radar cross sections (RCS) [7], but recent radar technology advances enable arbitrary drone detection with acceptable identification rate [8]. Thus, radar is becoming adopted for long range drone detection [9], but its use also suffers from national regulations, such as RF

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license policies [10]. The difficulty and relatively high cost of installing drone detection radars makes civilian counter drone systems look for other drone detection methods, such as vision [11] and RF signal [12] systems.

Civilian drone stopping strategies tend to employ unarmed methods such as hijacking (Section V-A) or capturing (Section V-F) solutions. These methods are technical counterpoint of drone's safety and stability systems, and both sides of methodologies are equally on demand in drone research. As a breakthrough in such a competitive situation, it is essential to refine the anti-drone system in a structural manner in order to cope with the drone's defense mechanism by adaptively responding to the drone's avoidance strategy. To do so, state-of-the-art drone security and safety studies should be evaluated, not only attempt to take advantage of the conventional drone mechanism.

This paper studies non-military anti-drone systems in comprehensive way. Considering recent drone incidents, we specially investigate the requirements for non-military anti-drone systems. We do not only list suitable methodologies, but propose guidelines for anti-drone system design that efficiently merge the components. Finally, we provide milestones to advance counter drone technology against drone security evolution.

A. ROADMAP FOR THIS PAPER

Fig. 1 graphically represents the organization of this paper, with the following details.

Section II discusses anti-drone system motivations and objectives for drone attack cases over the last few decades. Section II-A lists recent non-military drone incidents, highlighting safety and security awareness of malicious drones. Section II-B identifies requirements and breakthrough for applicable anti-drone systems, developing the major criteria to evaluate present system components and design anti-drone system guidelines.

Sections III–V introduce anti-drone components, divided into detection, identification, and neutralization phases, respectively.

Then, Section VI considers actual anti-drone system installations to survey current usage and further system extension requirements. Section VII proposes guidelines anti-drone system design, installation and operation. Sections VII-A–VII-C address detection system deployment, methods to evaluate drone attack situations, and where to neutralize illegal drones.

Section VIII considers future aspects and aims for anti-drone systems. Section VIII-A introduces drone-side safety and security methods against anti-drone technology, which can nullify attempts to detect and neutralize illegal drones. Section VIII-B consequently derives anti-drone development directions to sustain robust defense against malicious drones.

To avoid semantic confusion, each section defines anti-drone terminologies commonly used in the domain. Frequently used in anti-drone terms sometimes have ambiguous scope, e.g. hijacking, spoofing, and jamming. Hijacking and spoofing are often used interchangeably, and jamming sometimes includes drone neutralization methodologies, or only drone communication interruption solutions. Clearly defining these terms helps to avoid contextual conflicts and fit with anti-drone system operator requirements.

To the best of our knowledge, this study is the first one investigating non-military grade anti-drone systems. This paper provides a useful survey for non-military anti-drone system and contributes to future technology developments.

II. ANTI-DRONE BACKGROUNDS

This section considers the motivations and requirements of anti-drone system. Drone industry expansion has increased injudicious, unauthorized, and illegal drone use, causing considerable social and economic damage. We review some major drone incidents worldwide, and derive essential features for emerging anti-drone systems.

A. DRONE INCIDENTS

Drone illegal use and terrorism have recently occurred in various ways. We list and analyze several key incidents to derive appropriate anti-drone system objectives.

1) ILLEGAL FLIGHTS AT AIRPORTS

Gatwick Airport, the second largest airport in the UK, was paralyzed for a day in December 2018, by an illegal drone that breached the runway airspace [13]. Illegal drones have appeared near the airport more than 50 times for almost 15 hours. This happening seemed to be intentional to confuse the airport operations, since these are industrial drones and considerably larger than commercial models. Illegal drones also appeared near Frankfurt Airport, Germany, in May 2019, closely at the aircraft landing area for approximately one hour [14]. In both cases, the drones reached at important locations such as runway or crucial airspace without being detected by any of airport security systems. These incidents occurred large ecnomic loss due to poor detection distance and accuracy, and lack of response[1] procedures against unauthorized or illegal drones.

2) ATTACKS ON PUBLIC INSTITUTIONS

An unmanned aircraft equipped with a C-4 bomb attempted to attack the U.S. Department of Defense and Capitol Hill in September 2011 [15]. Fortunately, the criminal was arrested by the FBI before explosion. This was the first known terrorism using drones and an example of FBI terrorist prevention through tracking and proactive blocking. The case highlights that building an anti-drone system is important in practical terms, but requires cooperation with national organizations such as police and military.

The Russian military defended the first drone fleet attack in January 2018 [16]. Thirteen armed fixed-wing unmanned

[1]We use a term *response* to meaning combined detection, tracking and neutralization.

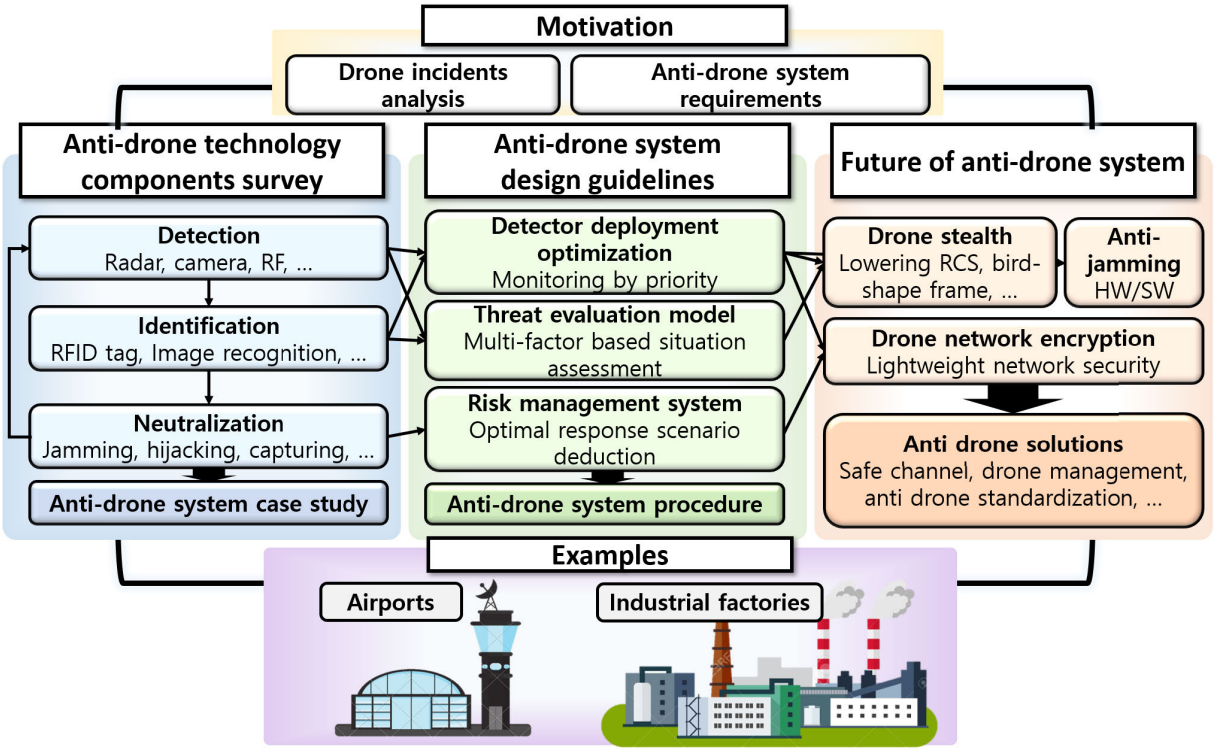


FIGURE 1. Roadmap for this paper.

aircraft deployed to attack Khmeimim Air Force base and Tartus naval installation, but repelled by Russian military radio electronic warfare technology. Ten drones were shot down by missiles, and the other three were blocked by Russian hijacking technology. Several military bases had high level anti-drone systems, but anti-aircraft systems such as missiles cannot be used in non-military site. Thus, anti-drone systems should prepare neutralization technologies without weapons, such as hijacking and capturing.

At Aramco, Saudi Arabia's national oil company, the largest oil refining facilities were burned and shut down by drone attack in September 2019 [17]. Ten drones attacked the facility, carrying 3 kilogram of explosives per unit. The incident caused huge damage to Saudi Arabia's crude oil production and peak price of international crude oil. This attack succeeded due to lack of simultaneous detection and defense systems for multiple drones. However, it is almost impossible to install drone neutralization equipment to completely cover such large number of facilities and enterprises. Therefore, it is essential to prioritize and concentrate anti-drone systems in key facilities.

3) ATTACKS ON SPECIFIC INDIVIDUALS

A small drone containing radioactive materials was dropped on the roof of the Japanese Prime Minister's residence in April 2015 [18]. Not only was the drone able to fly to the Prime Minister's residence, it was left unattended for approximately two weeks. Clearly, there was poor or no drone detection system installed. However, it might have been difficult to install intensive detection equipment due to the circumstances of the location, particularly privacy. Therefore, it is essential to secure various detection methods to fit to the area's requirements.

The Islamic militant group Islamic State (IS) has been using small drones to drop grenades since 2016. IS killed two Iranians in Syria in October 2016 with two ultra-small drones purchased from Amazon [19]. This was considered to be the first case of terrorism using commercial drones, and the case is important in that IS used commercial off-the-shelf drones, establishing that a wide range of drone terrorism was possible because the drones could be easily obtained without requiring expert-level skill to fly them.

Two drones equipped with bombs attempted to assassinate Venezuelan President Nicolas Maduro at a national outdoor event in August 2018, but failed [20]. This was the first attempt to use a drone to assassinate the head of the country. This case of incident highlights the need for anti-drone systems in the cases of temporal events. To cope with these portable scenarios, temporary anti-drone systems require rapid installation and deployment of their equipment.

Various drone incidents using small drones are difficult to detect, regardless of the type of sites, military or non-military. Illegal drones are mainly to paralyze major facilities [13], [14], [17], terrorist attacks [15], [16], or attacks on specific people [18]–[20]. In addition to the listed cases, there are numerous cases of minor accidents such as restricted area invation by unauthorized or illegal drones. The demands on

the anti-drone system to prevent such incidents are exploding worldwide.

B. ANTI-DRONE SYSTEM REQUIREMENTS

From the observations in Section II-A, we summarize core requirements for anti-drone systems as follows.

- **Drone-specialized detection**. Conventional zone security systems include drone-detection equipment such as radars or cameras, but lack the performance and awareness to allow current systems to recognize various drone incidents. When designing anti-drone system with current monitoring equipment, the overall architecture should be revised to detect various drones at sufficient distance to prepare the defense.
- **Multi-drone defensibility**. Some previous illegal drone incidents [16], [17] highlight the potential for a drone fleet attack. Sooner or later, various numbers of (legitimate) flying objects including personal air vehicles (PAVs) would be around the area, which leads to situations where multiple drone threats will need to be simultaneously detected and handled.
- **Cooperation with security organizations**. Seizing and intercepting drone threats such as [15] is the prime way to safely defend an area against unauthorized or illegal drones. In addition to the preemptive investigation, regulatory restrictions and cooperation opportunities with national or public security systems (such as police or military) should be discussed.
- **System portability**. As shown in II-A3, defending an area against unauthorized or illegal drones can vary depending on space and time. Immediate anti-drone deployment can be accomplished with mobilized detection, identification, and neutralization components, which require lightweight equipment and competent wireless networks.
- **Non-military neutralization**. There has only a single successful defense against drone attack reported [17], which was possible by deploying military grade weapons. Although drone jamming has been largely adopted and tested for commercial anti-drone systems, jammers could not stop the physical threat of the uncontrolled drones. Thus, a definitive neutralization methodologies and procedures are required.

Fig. 1 shows a typical anti-drone system comprising multiple subsystems. Anti-drone research domain remains in early-stage development, in contrast with drone stabilization technologies [21]. Solid solutions such as jamming or anti-aircraft weapons provide acceptable results for demands on stopping the drones, but place a heavy burden on regulations and financial budget. Therefore, we focused on approaches that could be deployed for non-military grade facilities, such as civil airports, sports stadia, outdoor/indoor convention sites, etc. Sections III–V list anti-drone system component surveys, and evaluate each considering the above requirements to build an effective anti-drone system. To have global view of the domain from research to product, we comprehensively surveyed vendor catalogues, articles, and white papers as well as research papers.

III. ANTI-DRONE SYSTEM: DRONE DETECTION

Drone detection exploits various features of flying drone. Drones commonly emit heat, sound, and RF signals to communicate with the remote operator. Detection system collects sensor data to confirm the presence of drones in nearby areas. Depending on the measure, it can speficy the drones' expected locations.

Table 1 shows drone detection schemes categorized by sensing technology. The following subsections consider each detection strategy and explore the basic mechanism and technical limitations.

A. THERMAL DETECTION

Physical components such as motors, batteries, and internal hardware radiate significant amount of heat, which can be recognized by thermal cameras [26]. Many studies have proposed detecting target drones by their heat signatures. Andraši *et al.* [22] proposed a drone detection scheme to detect thermal energy emitted by the drone during flight. Wang *et al.* [56] employed a convolutional neural network to enhance the system performance and accurately detect target drones from thermal images. The Spynel [23] product from HGH Infrared Systems detects infrared from the object heat, enabling 360° surveillance.

Thermal detection has advantages in terms of weather resilience, identification availability, and lower cost than radar based systems. However, the practical detection range (51 m [22]) is considerably shorter than most other approaches, hence enhancing granularity of detection scheme or improving resolution of thermal imaging camera are major challenges.

B. RF SCANNER

Drones controlled by an operator usually exchange specific messages as RF signal containing sensor output, flight commands, etc. RF scanner technologies capture wireless signals and determine the existence of drones in the target area. Signal intelligence (SIGINT) and communication intelligence (COMINT) are primitive models for RF based drone detection. Al-Sa'd *et al.* [28] designed a drone RF signal learning and detection system using a deep neural network with multiple hidden layers to categorize detected drone types and flight modes. Although classification accuracy decreases with increasing number of classes (drone types), detection accuracy is acceptable. Da-Jing Innovations (DJI) released Aeroscope [57], a detection system that collects DJI drone control data at around.

As discussed above, the major disadvantage for RF based detection is that it cannot detect drones that do not exchange RF signal continuously, such as the ones in autonomous navigation. In addition, since RF scanner detects the drones by signal analysis, drones using unknown control protocols

TABLE 1. Drone detection technologies.

Feature	Sensing devices	Advantages	Disadvantages	Detection range	References
Heat	Infrared camera	• Less affected by weather • Long range	• Low accuracy	1–15 km	[22]–[27]
RF signal	RF receiver	• Obstacle-free • Detect the drone operator	• Unable to detect • Autonomous flight	3–50 km	[12], [28]–[33]
Physical object	Radar	• Less affected by weather • Long range	• High expense • Regulations on RF license • Vulnerable to obstacles	1–20 km	[34]–[40]
Visibility	Optical camera	• Low expense • Miniaturized • Identification	• Highly affected by the weather • Vulnerable to obstacles	0.5–3 km	[41]–[46]
Acoustic signal	Acoustic receiver	• Compatible with RF based sensors • Miniaturized	• Extremely low detection range • Low accuracy • High signal detection complexity	$<$ 0.2 km	[47]–[55]

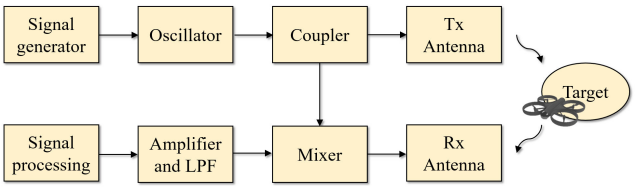


FIGURE 2. Frequency modulated continuous wave (FMCW) mechanism.

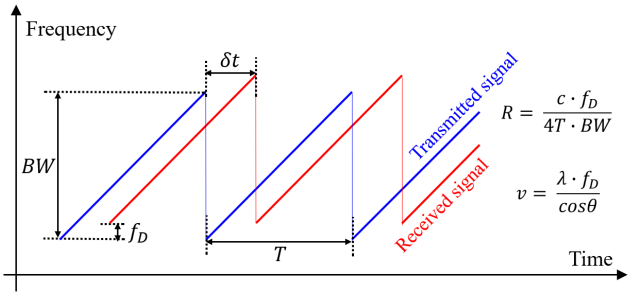


FIGURE 3. Distance and velocity determination by FMCW.

or different frequency bands [12] are challenging to detect. Nevertheless, most drone detection systems use RF scanner, due to its long range and low cost, while combining with other methodologies.

1) RADAR BASED DETECTION

Radar detects physical objects and determine its shape, distance, speed, and direction by sensing reflected Radio signals. In contrast with RF scanner, radar measures time-of-flight for the reflected signal, whereas RF scanner demodulates the signal itself. Continuous-wave radar characteristically measures target velocity using range and Doppler information.

Fig. 2 shows a typical radar based detection system. Frequency modulated continuous wave (FMCW) radar and coherent pulsed Doppler radar retain and track transmitted and received signal phases to estimate distance and velocity. In Fig. 3, FMCW radar derives distance R from speed of light c; and multiple measurements of δt; Doppler frequency shift f_D; and bandwidth BW. Then, the velocity of object can be calculated from c, wavelength λ, and angular deviation θ [58].

Radar surveillance and tracking uses several frequency bands [59], [60], which we summarize below.[2]

- Ka, K, and Ku bands, above 18 GHz, very short wavelength. Used for early airborne radar systems, but uncommon today except maritime navigation radar systems.
- X-band, 8–12 GHz. Used extensively for airborne systems for military reconnaissance and synthetic aperture radar.
- C-band, 4–8 GHz. Common in many airborne research systems (e.g. CCRS Convair-580 and NASA AirSAR [61]) and spaceborne systems (e.g. ERS-1 and 2 and RADARSAT [62]).
- S-band, 2–4 GHz. Used for Russian ALMAZ satellites and weather radar.
- L-band, 1–2 GHz. Used for US SEASAT and Japanese JERS-1 satellites and NASA airborne systems.
- P-band, 300 kHz to 1 GHz. Longest radar wavelengths, used for NASA experimental airborne research systems.

Radar is also classified into 2D and 3D by the type of the phase array antenna [63]. 2D radars adopt passive electronically scanned array antennas (PESAs), which control beam steering by electric field phase applied to each array element, providing relatively large detection range while wideband utilization is not possible. 3D radar commonly uses active electronically scanned array antennas (AESAs), which control beam steering and shape by the electric field gain and phase of each element. Although AESAs have relatively short detection range, they can self-correct errors and support wideband detection. Several studies have implemented 3D radars, e.g. [64]. The main difference between 2D and 3D radar is that 3D radar can estimate the altitude of target objects,

[2]This paper refers to nominal frequency range for each band, and specific frequency ranges differ from international/national workgroups.

whereas 2D radar acquires limited information of z-axis through auxiliary systems [65], [66]. 3D radar is desirable for anti-drone systems, but 2D radar with other methods can be a better solution from the view of large-scale monitoring and cost efficiency.

Although radar has been widely adopted for military and civil surveillance systems [67], early drone detection systems were skeptical about using radar, due to extremely low drone RCS [68]. Liu *et al.* [34] proposed multi-channel passive bistatic radar (PBR) to improve radar detection granularity, correcting the drone's location by extended Kalman filter (EKF) and global nearest neighbor (GNN) approaches. Several drone detection studies proposed high resolution FMCW radar with various improvements, including phase interferometry, functional modes, and various bands [35], [69], [70].

Radar based drone detection offer longer detection range and constant observability compared with RF scanner, but there are some detection availability and regulatory limitations. Radar cannot distinguish a drone from obstacles if the drone hovers in one position or flies at low speed. Thus, combining radar and other technologies (camera, RF scanner, etc.) is strongly recommended. Radar systems also continuously emit high power RF signals, so nation permission is required for frequency bands and installation locations. In particular, facilities that already operate radars, such as airports [71] may have difficulty installing additional radars due to RF interference issues. Partial spectral overlap between radar and radio waves can cause bad signal interference and poor performance of both radar and the network. Several studies investigated mutual interference between radar from military or other government/private organizations and radio access networks such as 5G to ensure coexistence [72]–[75]. Administrator should consider these RF circumstances in anti-drone system installation.

C. OPTICAL CAMERA DETECTION

Similar to thermal camera detection, optical cameras for drone detection have been widely investigated for anti-drone application. Sapkota *et al.* [42] exploited histogram of oriented gradients features to detect drones from captured images, and Jung *et al.* [76] proposed a video based drone surveillance system to monitor large 3D spaces in real time. Drone detection equipment based on optical cameras provide extremely low cost and less regulatory limitations than previously discussed ones, enabling fine-grained tracking system via dense deployment. However, the shortcomings including relatively short ranges, high weather dependency, and impermeability to obstacles force the fusion with different sensing systems. Widely adopted military electro-optical/intra-red (EO/IR) systems combine optical cameras and infrared sensors for drone detection [77].

D. ACOUSTIC SIGNAL DETECTION

Drone detection sensing acoustic signal emitted from the motors [78] directly exploits an inherent drone feature. Kim *et al.* [47] proposed plotted image machine learning and k-nearest neighbors, achieving 83% and 61% accuracy, respectively. Aside from short detection range, direction measurement and drone tracking are remaining challenges.

Fig. 4 compares drone detection components with respect to their functionalities and detection ranges. As shown in the figure, radar achieves high amount of minimum detection range, due to its inherent mechanism [79]. Most vendors propose hybrid drone detection systems for availability, accuracy, and installation flexibility. Some vendors provide automatic systems combining both detection and neutralization, commonly targeting and jamming, but the jammer use is highly limited in most countries. Thus, non-military systems need to fine-tune a wide range of requirements including jamming limitations, relevant existing radar installations, and drone neutralizing techniques considered in more detail in Section VII.

Table 2 presents the availability of drone detection technologies for problems that may interfere. The table and Fig. 4 explicitly show that each method cannot perfectly satisfies current requirement of anti-drone system. To break this limitation, drone detection system should be designed in a cooperative way that combines the clues from multiple equipment. To do this, not only each method should be improved to enlarge the cover area in Fig. 4, multiple mechanism should be combined as a hybrid system, considering the security requirement of defending area. For instance, RF scanner has big advantages in both range and functionality, except for the limitation that can only be used for commercial drones. Thus, RF scanner is acceptable in large scale area for detecting hobby drones flying in illegal. Meanwhile, the drone-sensitive spots where precise tracking of any flying objects is essential, such as airstrips or nuclear piles, must be equipped with detection components including vision, radar, and acoustic. To cope with non RF-detectable drones such as terrorist drones, high security area should locate versatile detection methods for preventing drone concealment technologies (Section VIII-A). In Section VII, we address some guidelines to deploy drone detection system with examples.

E. HYBRID DETECTION SYSTEM

Sections III-A–III-D show that using a single detection method inevitably results in drone detection blind spot, which makes it difficult to successfully neutralize illegal drones. Most vendors install hybrid drone detection systems that employ sensor fusion technology and joint hardware control. We discuss some cases of their hybrid schemes.

- **Radar + vision**. Radar and optical (or thermal) cameras provide excellent complementarity for drone detection. Vision based detection can easily track drones by controlling image zoom, tilt, and focus, but struggles with dynamic control over the target area; whereas radar detection provides omnidirectional wide area scanning with low drone identification and low scan frequency. Thus, radar scans the target area, and vision system

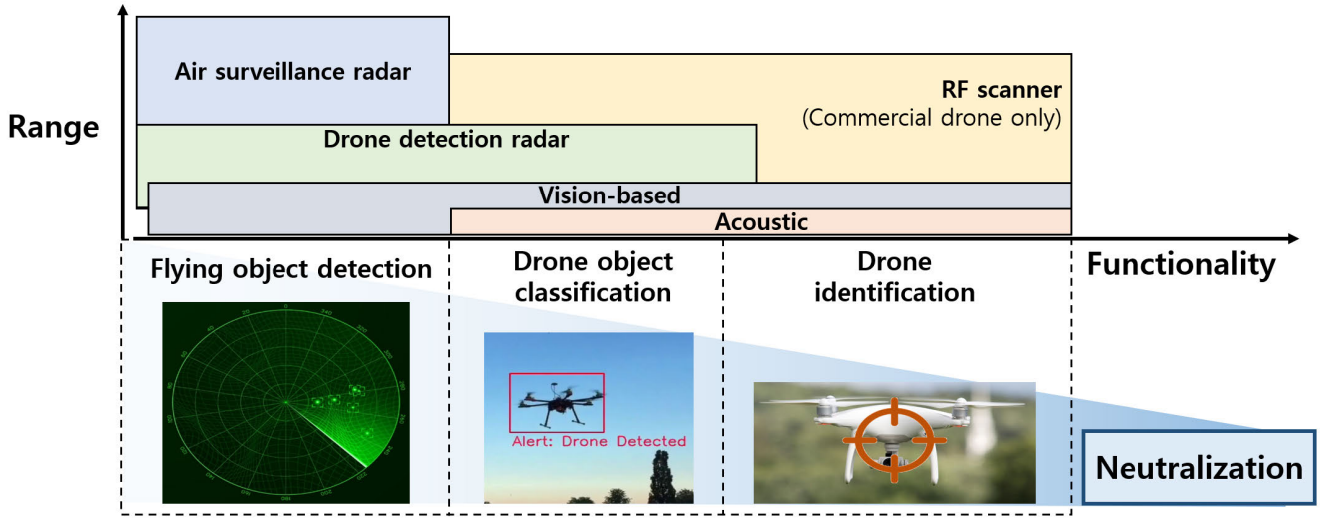


FIGURE 4. Detection method classification with respect to functionality and range.

TABLE 2. Detection technology availability.

Method	Physical obstacles	Unknown communication	Unusual shape	Low speed
Thermal detection	Unavailable	Available	Unavailable	Available
Optic camera	Unavailable	Available	Unavailable	Available
Radar	Unavailable	Available	Detectable, Not identifiable	Unavailable
RF scanner	Available	Unavailable	Available	Available
Acoustic	Available	Available	Partially available	Partially available

controls external and internal camera parameters to accurately investigate suspicious points. This combination dynamically compensates for each other's flaws, and hence many vendors adopt this structure [80]–[83].

- **Multiple RF scanners**. RF scanners can detect drones and additional information (type, control commands, and so on), but not always their location. If the drones are controlled only by pulse position modulation (PPM) or pulse width modulation (PWM) messages, they may not emit location information on an RF channel. Fig. 5 shows multiple RF scanners receiving RF message and calculating drone locations by traditional RF localization schemes [49]. Since RF scanners are generally cheaper than equivalent coverage of radar systems, some vendors dominantly use multiple RF scanners instead of radar [84].
- **Vision + acoustic**. Combining vision and acoustic sensors is a traditional sensor fusion technique to improve detection accuracy [49], [85]. Vision based detection struggles to distinguish unfamiliar drone shapes, and acoustic based detection achieves low performance in noisy environments. The complementary design is effective in terms of weather resilience, environmental resilience, and detection accuracy, hence [81], [83] products commonly employ this design.

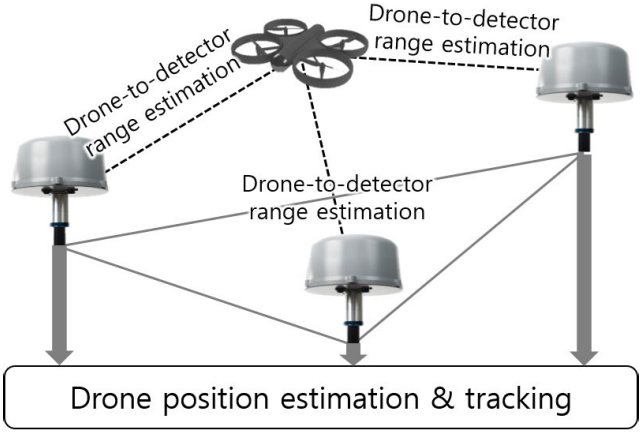


FIGURE 5. Drone position tracking by multiple RF scanners.

Table 3 lists several commercial anti-drone system components. Various detection technology combinations are available to achieve similar 3–5 km detection range. Multiple systems can be installed, e.g. [82], with reliable and

TABLE 3. Hybrid detection systems.

Vender	Model	Radar	RF scanner	Camera (Infrared, optic)	Acoustic	Detection range (indicated)	References
ELTA	Drone guard	✓	✓	✓		4.5 km	[80]
Aaronia AG	AARTOS DDS	✓		✓		5 km	[82]
Advanced Protection Systems	Ctrl+Sky	✓	✓	✓	✓	3 km	[81]
CerbAir	CerbAir Fixed, Mobile		✓	✓		3 km	[86]
Rodhe and Schwarz	ARDRONIS		✓			3 km	[31]
Drone Shield	DroneSentinel	✓	✓	✓	✓	3.5 km	[31]

low-latency networks. Thus, finding an efficient detection configuration for the target area is an essential step for constructing a robust anti-drone system.

IV. DRONE IDENTIFICATION

Before listing identification systems, we clarify *detection* and *identification* terms used in this paper to avoid confusion. Drone detection refers to systems that observe a flying (or stationary) object and determine if the object is a drone, whereas drone identification refers to determining if the detected drone is illegal and hence should be neutralized. For example, a minimal radar system may barely accomplish drone detection, since it cannot distinguish between drones and similar sized birds without an additional prediction scheme or auxiliary equipment (e.g. vision cameras) as discussed in Section III-E. Identification should be performed accurately, robustly, and promptly; particularly where the target area utilizes drones or permits legal use of leisure drones. The identification system should cooperate with the detection system to defend the target area without false neutralization.

Ideally, drone identification should *passively* identify the legality of drones through identification tags attached to them that periodically broadcasts their information, such as RFID tags. However, comprehensive attachment of tag can be discussed nationally or internationally, and has currently just begun. Furthermore, unintended or inexperienced control of legal drones can also be a threat to nearby facilities. Thus, any anti-drone system should include *active* identification solutions to determinate hazard level for detected drones, by tracking and estimating flight paths, and collecting specific information such as drone model and detailed properties that violate safety regulations. As described in Section 4, some detection systems can also provide identification functionalities, such as DJI aeroscope [57], or fine-grained detection network which can track the flight path. This section discusses active and passive drone tracking and path estimation solutions, mainly based on vision techniques.

A. DRONE TRACKING AND FLIGHT ESTIMATION

To distinguish detection methods, we focus on theoretical and systematic location estimation schemes for flying drones. Most systems use vision information to improve drone tracking, using conventional image processing or machine learning (convolutional neural networks). Path estimation systems also use neural networks or various filters over the tracking results to determine the drone movements. Xie *et al.* [87] improved the particle filter algorithm to more precisely estimate drone location from measured azimuth, elevation, and distance between the drone and the detection equipment, and modelled drone constant acceleration. Son *et al.* [88] proposed an optical flow based tracking method to track fast and small drones. The authors combined a recursive filter to detect tracking failures caused by fast positional changes and perform retracing. Xue *et al.* [89] proposed a multi-layer neural network for drone path estimation which approximates any continuous function in a specified space to estimate dynamic non-linear drone movement, and determined the network parameters. Drone tracking and position (or motion) estimation may be insufficient to judge drone legality, but it is essential to estimate how much drone motion could threaten the defense area. We introduce path-based drone threat assessment in Section VII-B2.

B. RFID BASED IDENTIFICATION

Radio frequency identification (RFID) has been widely adopted for identification and real-time location systems (RTLS) in recent decades [90]. Active RFID system is a promising drone identification approach due to low cost and lightweight system design. Buffi *et al.* [91] proposed an RFID based drone identification system over large areas, to distinguish between licensed and unlicensed drones. The major challenge is range extension and security concerns. High speed drones may not give a short range RFID system sufficient time to identify them. Spoofing RFID signal can also deceive the system and allow malicious drones to trespass over the defended area. Thus, security schemes for RFID drone identification systems [91] and long-range active RFID communication [92] should be further studied.

In addition to identification, positioning RFID-tagged drones has also been widely studied for drone tracking. Choi *et al.* [93] proposed a differentiated method for indoor localization by attaching Ultra High Frequency (UHF) RFID tags to UAVs and installing a number of passive tags over the target area, connected to the system. This solution exploits

interference between UAV and ground tags, which can be detected by measuring the received signal strength indicator (RSSI). The system first measures the tag's RSSI variance, and then dynamically estimates drone future location by finding the spot with greatest signal interference comparing with pre-measured variances. Locating wired passive tags over large areas may be cost-intensive, but position estimation in a coarse distribution of the ground tags can extend the available area.

C. AUTOMATIC DEPENDENT SURVEILLANCE - BROADCAST FOR DRONES

Automatic dependent surveillance - broadcast (ADS-B) has been adopted for aircraft Air Traffic Control (ATC) systems [94]. ADS-B in aircraft periodically broadcasts general navigation information via long range RF signal, and anonymous ground users and the other aircraft can utilize it for situational awareness and self-separation. The major difference with RFID system is the broadcasting message content: ADS-B messages contain identification and navigation information for the aircraft, which is standardized, such as altitude, GPS, identification number of aircrafts, etc. ADS-B has been recently applied to drones [95], [96] for surveying flight information within the target area. Conventional ADS-B systems are too large for smaller drones, so smaller ADS-B modules are required. The Ping2020 family [97] by uAvionix is an off-the-shelf product for drone-level ADS-B, which can be attached to the drone flight controller (e.g. Pixhawk [98]) and broadcast flight information through the RF channel. Currently, Ping2020 has somewhat higher price than expected (US 2000 per Ping2020i [99]), which blocks large-scale deployment. Low production cost and nation-wide drone registration systems can construct wide area drone identification infrastructure for continuous and robust identification.

Drone identification phase can be flexibly configured from drone-to-others authentication to threat analysis. However, anti-drone system should clarify each logic that determines whether or not to neutralize drones to cover any type of drone intrusion. This determination should have firm criteria from the detection results, national or international regulations, and auxiliary identifiaction tools. Then, according to the determination, the proper level of neutralization scheme must be in accordance with the law. As an intermediate step, identification system must be defined as a determination tools that provide zone-safe and regulatory-safe solution in given circumstances.

V. DRONE NEUTRALIZATION

We use the term *Drone neutralization* as a component of anti-drone system which refers to operations that suppress the threatening drones' movements. We classify the neutralization methods as destructive and non-destructive. This classification is valid since it not only presents technical difficulty, but also availability within civil regulations. Destructing the illegal drones are currently prohibited in many countries, so non-destructive ways are preferred in several public constitutions. We address in more detail non-destructive methods, to achieve high utilization of anti-drone systems in the worst cases.

Mostly, confirmatory methods such as jamming are preferred to prevent secondary crises (landing/crash and/or operational failure). Jamming is confirmatory and also non-destructive, but as discussed above, causes temporary communication paralysis across the target area. Thus, recent approaches attempt to individually disturb the target drones, considering their operation features. Table 4 lists several common drone neutralization solutions each of which is discussed in the following subsection.

A. DRONE HIJACKING

The terms *hijacking* and *spoofing* are often used interchangeably in anti-drone domain. We clarify meaning of the terms in this paper for readability. Drone hijacking means that a defending operator stake control of the target drone regardless of the methodology. Drone spoofing means that the operator generates a fake signal to prevent the target drone from moving as intended by the original controller. The main difference between hijacking and spoofing is post-attack behavior. The original controller cannot control the drone after hijacking, whereas spoofing signals can be used to hijack drones.

The reason for this definition is mainly the need for control deprivation. Usurping the original operators' control could include jamming or hacking before the anti-drone system obtains actual control. Thus, hijacking could be technically and regulatorily challengeable, but it is more robust then spoofing after successful deprivation. In any case, both should be investigated and for confirm defense.

Most drones establish a tightly coupled or paired connection with the operator, and hijacking focuses on breaking this pairing. Trujano *et al.* [115] proposed a system to break the pairing using a jamming signal and instantly re-attach to the attacker's controller to take control. Donatti *et al.* [100] proposed a drone hijacking system by increasing RF signal amplitude. The authors considered drone control packet decoding schemes and validated the proposed system with a prototype. Drone hijacking is an ideal approach in terms of safe capture or landing, and facilitates follow-up investigation. However, extending coverage and measures, e.g. autonomous flight, drone communication protocol, etc., are major challenges.

B. DRONE SPOOFING

Spoofing the drone signal can be used to hijack drones or confuse their flight routes. Drones generally control their location and altitude from the operator's RF signal, but use sensor outputs to determine current status. GPS signals are key data to determine current drone position in manual or autonomous flight. Noh *et al.* [101] proposed a system to generate fake GPS signals to deceive the drone's GPS receiver, and make the drone mistakenly calculate its position. The authors aimed to secure hijacking related to the GPS failsafe mode of the drone internal system and quietly send the drone

TABLE 4. Drone neutralization technologies.

Destructive	Name	Advantages	Disadvantages	References
Non-destructive	Hijacking	• Enable safe landing	• Only available for drones using known protocols	[100]
	Spoofing	• Wide availability • Includes autonomous and manual flight	• Difficult to control • Possibly nullified by manual control	[101]
	Geofencing	• Simultaneous response • Easily extended	• Only available for communicable drones • Modified or disabled by drone operators	[102]–[104]
	RF jamming	• Simple, instant procedure • Effective for drones using unknown protocols	• Can affect nearby facilities • Not effective for autonomous drones	[105], [106]
	Capture	• Available for follow-up investigation • Ground and aerial solutions available	• Difficult to target and hit • Possible damage during landing/crush	[107]–[111]
Destructive	Laser	• Long range • Confirmatory destruction	• High maintenance and operation cost • Generally unsuitable or unavailable for non-military facilities	[112]
	Killer drone	• Low maintenance and operation cost • Possible simultaneous response to multiple drones	• Hard to target and hit • Deregulation for public drone flight required	[43], [113]
	Anti-aircraft weapons	• Confirmatory destruction • Long range neutralization	• High maintenance and operation cost • Generally unsuitable or unavailable for non-military facilities	[114]

to a specific location. Simple spoofing techniques that distract drones can take advantage of several types of sensors, which may be cooperatively combined. Deceiving drone sensors can be achieved following a wide range of approaches regardless of the communication protocol, but in the absence of separate safety measures for areas outside a certain range, accidents such as crash landing may occur due to unpredictable drone operator control.

C. GEOFENCING

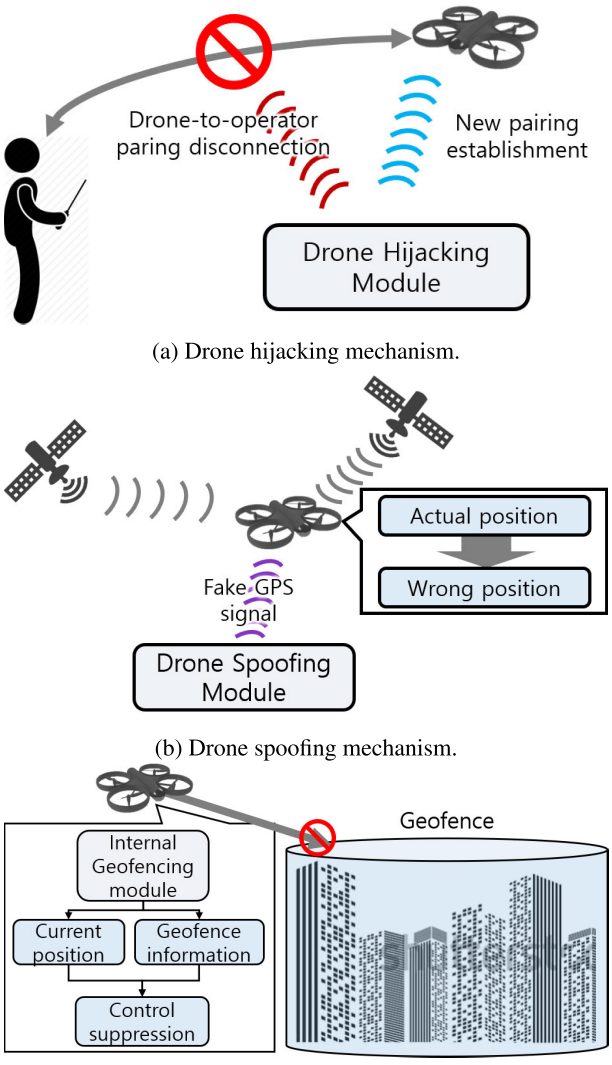
Geofence based drone neutralization systems prevents target drones from approaching a specific point. Various methods have been studied to block the trespassing drones, including the techniques discussed in Sections V-A and V-B. However, the most generally adopted and implemented approach is that the drone self-determines whether or not the drone lands from its current location [116]–[118]. Geofence technology for drones is classified into two types [118]. Dynamic geofence propagates information regarding restricted flight zones, and static geofence uses a flight permission information repository that any drone can access. Most commercial drones with common flight control stacks, e.g. PX4 [119] and ArduPilot [120], have internal auto-landing modules for safety. This method effectively prevents hobby drones from invading unlicensed areas, but cannot defend a modified or remodeled drone – disabling automatic landing systems built into the drone controller. Since the system relies on the drone's internal navigation logic, malfunctioning drones may allow trespassing into the secured area. Further preemptive geofencing studies are required to address these limitations, which may utilize spoofing and hijacking techniques.

As discussed in Section I, drone neutralization terminologies are somewhat confused due to the variety of mechanisms and their consequences. Fig. 6 summarizes representative non-destructive drone neutralization mechanisms, and Fig. 7 shows their technical relationships. The hijacking, spoofing, and auto-landing sets ($\mathcal{H}$, $\mathcal{S}$, and $\mathcal{G}$, respectively) refer to top tier scheme classifications. Each intersection refers to neutralization scheme collaborations, e.g. [100] for $\mathcal{H} \cap \mathcal{S}$, and [101] for $\mathcal{S} - \mathcal{H} - \mathcal{G}$. Thus, anti-drone system designers can evaluate redundancy of neutralization deployments by this approach. Anti-drone systems must prepare compositive systems including $\mathcal{S} \cup \mathcal{H} \cup \mathcal{G}$ to cope with highly secure drones, such as high-level anti-hijacking systems.

D. DRONE JAMMING

Drone jamming focuses on paralyzing radio communication between the target drone and controller by strongly interfering RF signals, which can be any kind of empty packet signals within a targeted frequency range. The general purpose is to make the target opponent fall into an uncontrolled state where they cannot exchange external communication signals [121]–[123]. Jamming technology can be classified into various types by the different objectives and coverages. We introduce some representative classification criteria.

1) The jamming system can be classified into directional [105] or omnidirectional [106] jamming by the operating direction. The former focuses on a specific direction, and the latter can jam all direction.
2) Stationary jamming is when the jamming system is installed at a fixed location, such as a strategic location or base station, whereas mobile jamming is when the system is operated from portable devices such as handheld or vehicle mounted [124], [125].
3) Narrow or wide jamming is distinguished by the system bandwidth [126]–[128].



(a) Drone hijacking mechanism.

(b) Drone spoofing mechanism.

(c) Geofence mechanism for drone.

FIGURE 6. Typical non-destructive neutralization mechanisms.

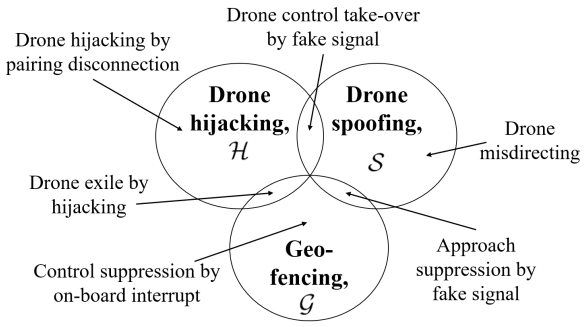


FIGURE 7. Non-destructive drone neutralization scheme relationships.

4) GPS jamming aims to cause the drone GPS system to malfunction [129], [130]), whereas communication jamming aims to interrupt communication between the drone and controller [131]–[133]).

Exceptionally, there are other jamming approaches targeting specific network layers (e.g. L1 [134], L2 [135] or L3 [136]). However, since drones generally do not follow conventional communication protocols, we will not describe these approaches in details. Jamming can also be implemented by degrading the target communication quality [137]. However, anti-drone systems aim for complete drone neutralization, hence jammers that only reduce drone performance were not considered in this paper.

Jamming is a simple, robust, and wide-range solution with low failure risk, hence most anti-drone systems adopt jamming as their major neutralization scheme [84]. However, since jamming techniques mainly uses electromagnetic signals, they can have significant unintended impacts, including TV broadcasts, telecommunication, or even the air traffic system. Thus, most countries strictly prohibit jamming technology in public. The USA Federal Communications Commission strictly forbids use of any radio jamming system at consumer level [4], and the UK Office of Communication also restricts jammers for any purpose interfering with radio communication [5]. Many countries provide guides to use jammers, but they have very strict legal constraints. Therefore, there is almost no practical jamming technology possible for civilian users. Thus, non-military grade anti-drone systems should generally be designed without jammers.

E. KILLER DRONES

We use the term *killer drone* to mean legal drones that track target drones and attempt to damage them [43]. To distinguish killer drone from drone capture, we limit the killer drone scope to solutions that physically strike invading drones. Killer drones require reactive and real-time decision making regarding incoming drones, high accuracy drone flying path estimation [87], [89], and outstanding physical durability and mobility [113]. Using drones to damage illegal drones is very early stage technology, and requires considerable patience for adoption into commercial anti-drone systems. Swarming killer drones with distributed intelligence [138] and precise tracking systems [87], [89] could be a promising solution for drone fleet multi-faceted attacks. Similar to jamming and radar, scrambling killer drones is subject to regulatory restrictions [139], but can be mitigated by policy changes and technical maturity in drone management systems [140].

F. DRONE CAPTURE

Drone capture approaches physically bind the target drone with various tools, generally some type of net or similar rather than military ammunition. We divide drone capture systems into two groups depending on the capture mechanism.

- Terrestrial capture systems [109], [111] are human-held or vehicle-mounted, and are available in wide range of net sizes and numbers of rounds.
- Aerial capture systems [107], [108], [110] are installed on defender drones, with restraint to the amount and size of net bullets. Aerial capture provides much more precision and response speed than terrestrial capture due to drone mobility, but high requirements for tracking

accuracy and speed raises the possibility of neutralization failure.

This classification comes from the entire difference in the implementation phase of each. Terrestrial capture system should consider the coverage of each device and the optimal spots for safe capture. Furthermore, improvement strategy is to increase the effective range of the devices, which has a higher balance between the cost and the performance than aerial case. On the other hand, aerial capturing devices have a higher tradeoff at weight and the performance due to the limited load of the drones. In addition, aerial capturing system mainly considers the traceability of the drone itself; the flight performance and the formation strategy of the drones are key issues of the system. It is not desirable to determine which ways are correct, so both approaches should be investigated in the future.

As drone detection mechanism utilizes the features of drone operation, drone neutralization also exploits them and invokes unintended operation. However, not all neutralization methods always meet the anti-drone system administrators' goal, and may vary from case to case. Thus, multiple neutralization schemes should be prepared in one package and increase the successful rate of each. It is also important to continuously follow up the drone-safe technologies such as anti-spoofing and anti-hijacking, each of which was originally suggested without malice. In addition, anti-drone system should be able to plan its neutralization, considering the effective range of the scheme and the estimated flight path, detailed in Section VII-C.

VI. ANTI-DRONE SYSTEM USE CASES

Recently, most installation examples of officially released anti-drone systems are in airports and prisons, or temporary but important meetings. Current security systems tend to install a drone detection sensor package but are not integrated with identification and neutralization phases. Rather, they rely on human guards carrying drone neutralization equipment, hence are vulnerable to rapid and elaborate attacks from high technology drones. This section introduces some practical use cases for current anti-drone system installations and addresses remaining requirements for public safety against illegal drones. Table 5 summarizes the use case details.[3]

A. ANTI-DRONE SYSTEMS AT AIRPORTS

After drone incident [13], Gatwick International Airport installed a military grade anti-drone system [141] using the British army's laser based destructive system [112]. Northwest Florida Beaches International Airport is a coastal airport, and installed a detection system to detect both bird and drone incursions [142]. Copenhagen International Airport is one of the most population intensive airports in North Europe, and hence deployed the Mydefense anti-drone system [143], developed by Denmark. Muscat Airport in Oman installed the German AARTOS anti-drone system [82], [151], characterized by scalability of the defense area up to 50 km to meet large airport requirements.

Airports are densely populated facilities with high injury risk in the event of an airplane accident, hence national security agencies tend to deploy military grade defense systems. Anti-drone systems are expected to increase gradually as international airports in each country develop further from their current pilot systems. However, radars are widely used for air traffic management (ATM), so many airport cases are limited to non-radar components. It is essential to deploy sufficient alternative solutions to ensure safety against unauthorized drones, including vision and sound based approaches.

B. ANTI-DRONE SYSTEMS IN OTHER FACILITIES

Various non-airport anti-drone systems have been implemented against illegal drone intrusion. Suffolk Prison deployed a drone detection system to prevent smuggling prohibited items, such as drugs and mobile phones [144]. New York's Mets City Field installed a drone detection system to protect against unlicensed broadcast of the matches [145]. Zhejiang University independently developed and deployed anti-drone system named ADS-ZJU, with sensor fusion and automatic jamming technology [84]. PyeongChang Olympics Stadium deployed interceptor drones to capture illegal drones [146], and temporary drone detection systems were deployed the at University of Nevada, Las Vegas (UNLV) during US presidential debates [147], Davos during the World Economic Forum [148], and Buenos Aires during the G20 summit [149]. Israel has developed the Drone Dome anti-drone system [150] covering the whole country.

C. REMARKS

The use cases considered here indicate that anti-drone systems are currently installed where real drone threats, such as smuggling or terrorism, are expected. This implies that anti-drone system design remains introductory and relatively primitive compared with actual drone incident urgency. A generalized and diverse strategy for anti-drone system design is urgently required. Considering the high mobility and accessibility of drones, anti-drone systems must be installed on large scales to prevent sporadic drone incidents. However, existing anti-drone systems are generally military grade and only installed in important facilities, hence other sites are vulnerable to drone attacks and may need appropriate anti-drone systems according to national regulations. Furthermore, majority of anti-drone systems include only drone detection and alert systems with identification and neutralization stages are performed by people, mostly soldiers. Integrating detection, identification, neutralization schemes, and automating the overall system would greatly improve anti-drone system accessibility and reduce the labor costs. Section VII proposes some guidelines for efficient anti-drone system design.

[3]We only included confirmed information from authorized media.

TABLE 5. Anti-drone system use cases.

Location	Model	Temporal	Detection	Neutralization	Purpose	Reference
Gatwick International Airport	AUDS		✓	✓	Safety against drones	[141]
Northwest Florida Beaches International Airport	DroneWatcher		✓	✓	Safety against drones	[142]
Copenhagen International Airport	Mydefence	✓	✓	✓	Safety against drones	[143]
Suffolk Prison			✓	✓	Preventing smuggling	[144]
Mets City Field			✓		Protection of broadcasting rights	[145]
Zhejiang University			✓	✓	Safety against drones	[84]
PyeongChang Olympic Stadium		✓	✓	✓	Safety against drones	[146]
University of Nevada, Las Vegas	DroneTracker	✓	✓		Drone terrorism defense	[147]
Davos	DroneTracker	✓	✓	✓	Drone terrorism defense	[148]
Buenos Aires	Drone Guard	✓	✓	✓	Drone terrorism defense	[149]
Israel	Drone Dome		✓	✓	Drone terrorism defense	[150]

VII. ANTI-DRONE SYSTEM GUIDELINES

Comparing with military installations, non-military facilities are significantly disadvantageous to defend against illegal drones legally and technically. Rapid advances in imbedded systems make drones continually get smaller and faster in obstacle-rich 3D space [69], [152], with enormously increasing payload capability. Most countries regulate drone use for industrial and market applications, and require urgent implementation of a systematic and rigorous drone defense system at major facilities. Several drone attacks were reported in the 2010s, not only for military bases [13]–[16], [18], [20]. Non-military drone intrusion can cause considerable economic damage, but applying ideal anti-drone systems in overall area is almost impossible not only due to budget constraints, but also workforce. Furthermore, excessive response to hobby drones can impose considerable capital redundancy, and still may be vulnerable to subsequent serious attacks.

Utilizing the surveys in Section III–V, this section proposes a guideline for designing non-military anti-drone systems, including where to deploy the equipment, what method should be chosen at neutralization, and how to define integrated response procedures.

Given the scope of this paper, we do not consider amendments to legislative provisions regarding drone and defense system permits, etc.

A. DETECTOR DEPLOYMENT

An ideal drone detection system could form a comprehensive deployment of high-performance devices with high density, but system management and installation must be considered to operate a cost-efficient drone defense system. The system must also be able to intensively monitor critical points where catastrophic accidents such as massive explosions or top secret leaks could occur. Furthermore, increased detection accuracy is essential to obtain as much information as possible by combining multiple detection methods (Section III-E). We propose a superpositioning strategy for drone detectors considering relative importance of the areas. First, we categorize detection methods by quantitative and qualitative features, and show deployment examples for an airport and industrial facility.

1) DETECTION EQUIPMENT CATEGORIZATION

Table 6 shows the categorization scheme that we proposed. We considered not only the technical mechanism of detection, but also detailed specifications related to detection performance, such as operating angle and installation method. The main objective is to improve the detectability of high priority areas; hence we set the criteria that differentiates existing detection systems. For example, radar based detection has technical specifications at product level, such as directional/omnidirectional, stationary/non-stationary, detection range, and whether the drone is identified.[4] On the other hand, if a detection system combines multiple sensors (e.g. vision+acoustic, Section III-E), new type should be created to reflect differentiated detection performances. Categorizing available equipment according to features rather than methodology means the system can deploy detection systems in terms of various metrics, which lays the foundation of detection system abstraction.

2) AREA PRIORITY CLASSIFICATION

Understanding the features and characteristics of defense area is essential for optimal drone detection deployment. The proposed approach analyzes defense area spatial usage and classifies area priority into several levels. Classification criteria reflects the main purpose of defense against drones, which generally effects civilian and major property safety.

Figs 8 and 8b describe a fictitious airport and industrial plant, respectively, as classification examples.

We mainly considered safety risks for airport passengers in the airport classification. The most threatening airport situations would be the one that drones cause aircraft crash at takeoff or landing, which could result in massive human casualties [153]. A relatively small drone can harm a flying

[4]There are technical differences between the radars that can detect a drone-size object (low RCS) and identify the drone [35], [69], [70].

TABLE 6. Detection equipment categorization criteria.

Types	Directionality	Identifiability	Detection range (unit: km)			Stationary	Examples
			< 1	$[1, 3]$	> 3		
Type 1				✓		✓	Omnidirectional radar
Type 2	✓	✓		✓		✓	EO/IR camera
Type 3		✓			✓	✓	RF scanner
Type 4	✓			✓			Portable (vehicular) radar
Type 6	✓	✓	✓				Human eye (baseline)

airplane if it enters the jet engine or damages the wings, particularly during take-off or landing. To prevent this, the runway and surrounding surfaces must be closely monitored, and any abnormal condition quickly propagated to control aircraft takeoff and landing. We exploited International Civil Aviation Organization (ICAO) regulations regarding obstacle limitation surfaces [154] to prioritize areas within the airport.

- Class I included airplane gliding and landing areas with altitude range to drone-identifiable altitude, for the highest priority of protection.
- Class II included navigation safety facilities and population intensive areas that could result in massive human injury.
- Class III included areas that could have short and long term impact on airport operation and ATC in the event of attack. This considers social and economic risks of drone-aircraft collisions, which could temporarily paralyze ATC facilities, or cause airport shutdown.
- Class IV included areas protected by automatic drone guidance systems such as Geofencing (Section V-C), and boundaries where drones should turn back, such as conical and horizontal airport surfaces.

There are no global regulations relevant to area designation for the industrial factories. Therefore, we considered both safety and security of the facility.

- Class I included areas with the highest potential for large-scale incidents, such as explosion from drone crash.
- Class II included population intensive areas, similar to the case for the airport.
- Class III included security sensitive areas to prevent drones from breaching confidentiality.
- Class IV included remaining and detectable outer perimeter areas, to proactively detect and respond to drone intrusions.

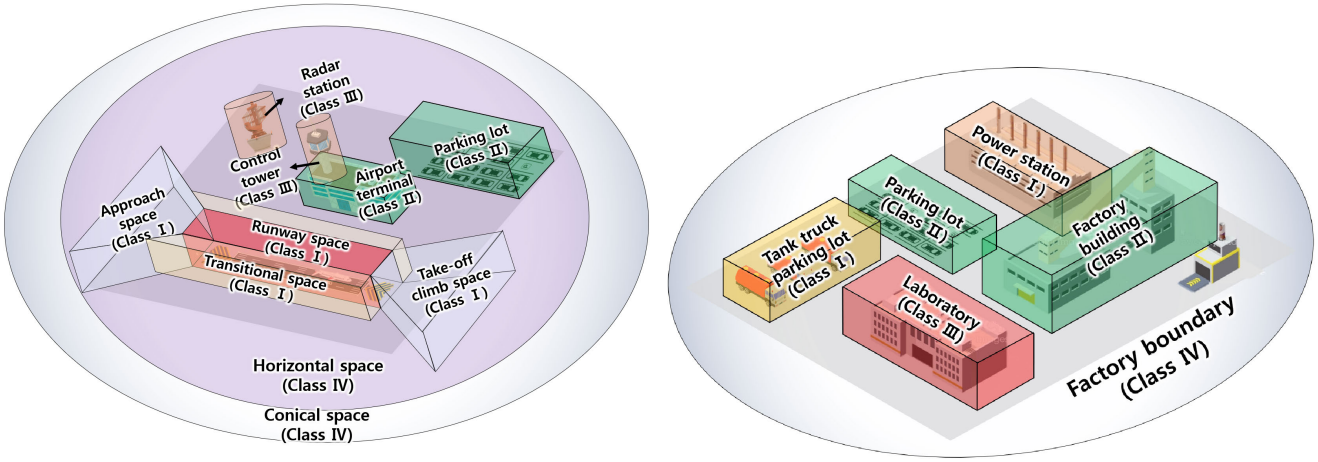
Fig. 8 shows priority assignments for the airport and factory examples. Various areas were scaled for visibility; Class IV space was actually much larger than the sum of Class I to III. The system can indicate where to focus detection resources to minimizes potential damage caused by a drone incident. Note that lower class areas do not mean that these areas represent a weak point. The main goal of this classification was not to reduce the likelihood of detection in low-risk areas, but to effectively expand the detection network in cost restraint.

3) ABSTRACT FORMATION

From detection categorization and priority classification, we show example drone detection deployments using the abstracted detection equipment. Fig. 9 shows deployments for the airport and industrial facility cases. Figs. 9a and 9b show two-dimensional views of the sample areas (left side), indicating area classes, for visibility and better structural understanding. The right side of the figures show results for 3 types of stationary equipment arranged in the defense area. Type 3 equipment has wide surveillance range and hence is installed at the center of the defense area to include as many essential areas as possible; whereas type 2 equipment is directional, hence devices were placed on entry surfaces on both sides of the runway, and two others on the runway and airport terminals considering the arrangement of Class III facilities.

Real installations will have many more things to consider when determining physical location of the equipment, such as radio frequency bands, spatial margins with wireless equipment in the target area, etc. Representative considerations are as follows.

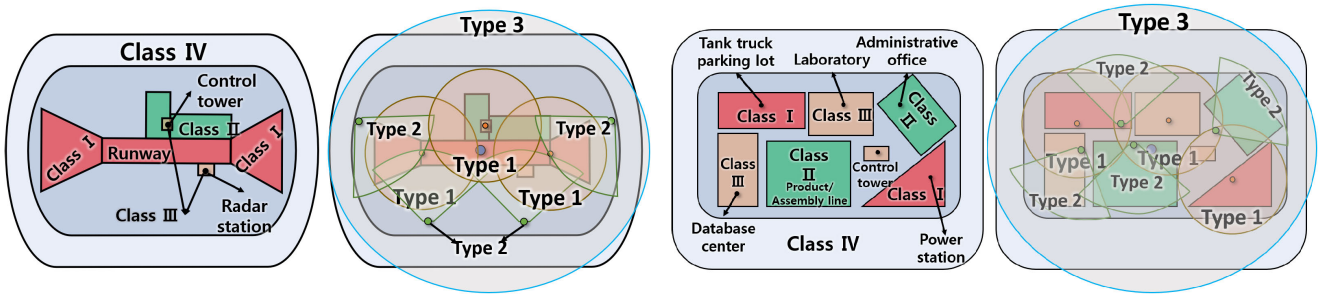
- **Radio wave environment**. In the case of drone radar, it is necessary to investigate the risk of reducing detection rate due to radio interference between the drone radar equipment and nearby existing radars, and check frequency bands employed. Most countries set regulations on installing new radar sites [155], in terms of frequency band and spatial distancing, hence prior consultation with relevant institutions (e.g. US Federal Communications Commission (FCC)) is required.
- **Legal operator boundaries**. National regulations related to anti-drone solutions (particularly radar, camera, RF jamming, and killer drones) should be considered prior to deployment. The system designer should also check legal right to arrest drone owners and public regulations regarding destroying or damaging the drones, to ensure system installation cost is more effective while accomplishing the security requirements.
- **Physical environments**. Fig. 9 shows that existing facilities can block radar scanning, vision, etc. The



(a) Priority classification map of airport.

(b) Priority classification map of industrial factory.

FIGURE 8. Priority classification examples according to drone threat level.



(a) Deployment scenario of airport.

(b) Deployment scenario of factory.

FIGURE 9. Detection system deployment scenario.

anti-drone system designer should carefully locate selected detection devices considering building and surrounding terrain profiles. Acoustic detection devices should not be placed around noisy environments, and wired or wireless networks should be optimally configured to collect results from multiple detection systems.

- **Radio interference**. RF interference with existing radio based systems (weather or aviation radar, ATC components, etc.) must be concerned before installing the drone detection radar, which could detrimentally impact overall RF equipment performance. Discussions regarding interference between 5G access networks and drone radar [73] should also proceed nationwide.

The main objective for the proposed deployment was sustainable design for drone detection devices' configuration, which could be semi-permanently employed by abstraction. The deployment process could be applied when new detection equipment was introduced or protection priorities changed. Future work on this scheme should be an autonomous algorithm for selecting and deploying the detection devices considering installation cost and system features. Optimal placement of drone detection network can be obtained with the proper objective function and efficient algorithm design, which greatly improves security against illegal drone incursion within a given budget.

4) AIRSPACE PRIORITY CLASSIFICATION

Civilian hobby drones can achieve over 3 km maximum height [156], by the lack of the awareness of drone regulation. Area priority classification effectively protects a specific target area, but it is necessary to classify large areas by priority to expand protection range to the national airspace and prevent accidents of various aircraft types, such as PAVs. Thus, we suggest an airspace priority classification, based on ICAO regulations [157]. Wide-spread concerns about drones in operating airspaces have raised the awareness for suitable drone regulation [158]–[160]. Airspace is defined across a wide area and it is difficult to cover with conventional local anti-drone systems, hence large-scale airspace drone defense system should be constructed with global (or national) drone identification infrastructure (Section IV), containing long-range identification and detection equipment.

Fig. 10 shows space priority classification according to ICAO airspace classification criteria. Airspaces above

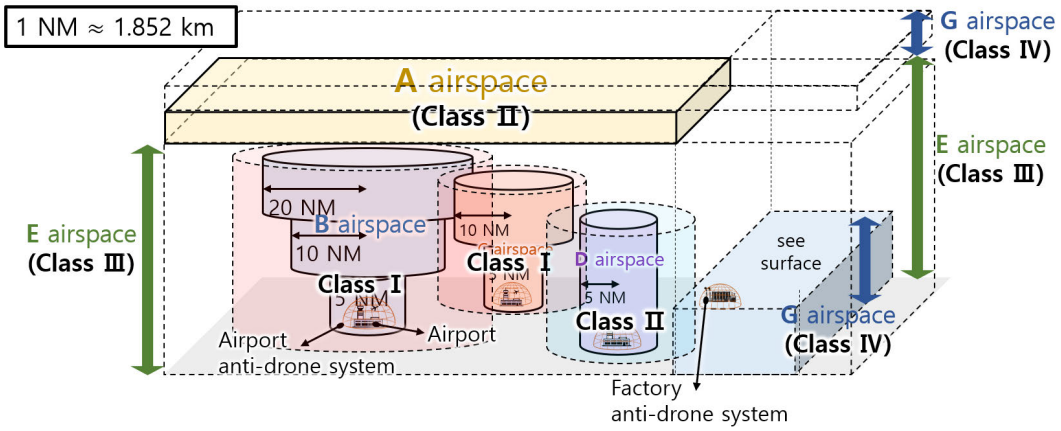


FIGURE 10. Airspace priority classification.

airports (B to D) are usually shaped as a stack of cylinders with larger radius at higher altitude, reflecting airplane flight and landing paths. However, drones draw landing and takeoff trajectories relatively freely, so we allocated a large cylindrical area near the airspaces. We designated Class I areas to large and busy airports (B and C), and Class II areas to relatively small airports (D). Airspace A includes airplane flightpaths, and hence we allocated these to Class II since drone collision at this airspace could cause forced landing or worse. We set airspace E to Class III due to human accident risk, and airspace G to Class IV for preemptive drone monitoring.

The hierarchical configuration with local anti-drone systems such as in airports and factories will provide a global view of widespread provocation of drones, and enable cooperative tracking and neutralization. Every country has different airspace regulations [161], and some countries do not use some of their airspaces, so the system designer should reflect nationwide potential threats and geographical features.

B. THREAT LEVEL ASSESSMENT

When a drone illegally approaches, it is mostly unavailable to identify who or what the drone belongs to or it intends to do. Thus, anti-drone system should be able to assess the potential threat of unknown drones from the defender's point of view. We can obtain an exemplary threat model from drone detection results as a numerical value R. We can determine R with

$$R = (R_{object} + R_{path})^{R_{time}}, \tag{1}$$

where R_{object}, R_{path}, and R_{time} refer to threat levels induced by the drone, drone flight path, and remaining response time, respectively. We set maximum R_{object} and $R_{path} = \alpha$ and β (constants), respectively, and $R_{time} = 1$.

In our model, R quantifies the likely damage that would occurs if the observed drone actually attacked in a certain area, considering the currently measured factors. R_{object} represents the physical impact from the drone crash, and R_{path} the estimated damage for a given crash point. Powering factor R_{time} indicates how much the damage realized, and R becomes the realized damage of the observation when R_{time} is maximized to 1.

Eq. (1) can be made more flexible by parameterization. For example, R_{object} could be set to a constant if the detection network only provides the drone position. Since derivation of R_{object} requires detailed drone information, constant R_{object} can produce wide R range through the remaining parameters R_{path} and R_{time}. The derivation of each parameter is as follows.

1) THREAT LEVEL BY OBJECT

Ideally, the drone's physical threat level is defined by its physical properties such as kinetic energy, but the collected information can be limited. Thus, we model the derivation of R_{object} with complex conditions. Basically, kinetic energy is determined by drone mass or weight (maximum takeoff weight) and speed, where $K = \frac{1}{2}mv^2$. Detecting drones with RF scanners can provide detailed information, such as model name and weight, from a predefined database. This allows us to infer the drone's bare bone weight and potential payload, providing an estimate for increased threat level if detection device catch the payload of explosives.

Table 7 shows an example physical threat level classification scheme considering drone characteristics that can be obtained through the detection systems. We referenced criteria for classifying threat level from the kinetic energy at [162] and noise at [163]. Most factors can be determined once the drone's commercial model is identified, including the mass, and the threat level can be more accurately derived. Otherwise, the system approximates drone weight from the size and default density from the database. Low noise drones are classified as higher threat since noise can help humans track and evacuate drones easily, and reduce the damage.

Table 8 describes how to calculate the threat level according to drone physical characteristics, where values were obtained from Table 7, and N_{drone} refers to the number of

TABLE 7. Drone classification by physical features.

	Level 1	Level 2	Level 3	Level 4
Kinetic energy (J)	< 1400	$[1400, 7000]$	$[7000, 14000]$	> 14000
Noise level (dB)	> 80	$[60, 80]$	$[40, 60]$	< 40
Loaded objects	None	Vision camera	Lightweight weapon Identifiable object	Explosives unidentified object
RF scannable	Scannable		Not scannable	

TABLE 8. R_{object} derivation.

	Weight	Calculation
Kinetic energy	$W_{kinetic}$	$R_{object,kinetic} = (observedkineticenergy) \div 14000J \times W_{kinetic}$
Noise level	W_{noise}	$R_{object,noise} = (1 - (observednoiselevel) \div 80dB) \times W_{size}$
Loaded objects	W_{loaded}	$R_{object,loaded} = (level)/4 \times W_{loaded}$
RF scannable	$W_{scannable}$	$R_{object,scannable} = \begin{cases} 0, & \text{if scannable} \\ 1.0W_{scannable}, & \text{if unscannable} \end{cases}$
Total	α	$R_{object} = \max(\alpha, (R_{object,kinetic} + R_{object,noise} + R_{object,loaded} + R_{object,scannable}) \times N_{drone})$

swarming drones. This score is not an absolute range for R_{object}, and the system administrator can change the weights on demand. Partial threat factors from size, energy, scanability, and loaded objects are calculated and then summed to obtain the object-wise threat level. The overall threat level of a drone swarm is derived by multiplying the object-wise threat level to N_{drone}. If the drone is not detected by RF scanner or the system experiences difficulty in accurate determination of some parameters, the safest option is to conservatively set any uncertain parameter to its maximum value to induce strong response.

Examples of $\mathbf{R_{object}}$. Let

$$W_{kinetic} = W_{noise} = W_{loaded} = W_{scannable},$$

and two DJI Phantom 4 drones weighing 1.3 kilogram are approach at 72 km/h, 70 dB noise, without additional transport. Then $R_{object} \approx 0.134\alpha$, which is relatively low. However, if the drone approaches major facilities, such as runways or civilian-intensive spots, the comprehensive threat level is set higher. R_{object} then used to calculate the total threat level $\alpha + \beta$ in addition to R_{path} and R_{time}.

Similarly, if an unknown drone with approximate size $800 \times 700 \times 400$ mm approaches at 60 km/h, 80 dB noise, with a lightweight weapon, then $R_{object} \approx 0.453\alpha$. This case is considerably higher than for the two DJI Phantom 4 drones, mainly due to loaded weapon and lack of scannability. This case of threat level is valid since the drone may intend a terrorist attack, and be unable to neutralize by geofence or hijacking.

2) THREAT LEVEL BY FLIGHT PATH

We adopt the defense area analysis of Section VII-A to determine drone threat level in various cases. In example of airport, threat level is low if the drone is flying around airport conical space, and the system can observe automatic landing behavior or prepare delayed but safe neutralization methods, e.g. capture. However, if the drone approaches near the runway, where it could impose severe damage, the system determines the increased threat level and can prepare immediate, confirmatory, risky, or expensive neutralization methods, e.g. jamming or firing, as appropriate. Multiple neutralization methods are required to efficiently cope with various drone attack situations. If risky options, e.g. jamming, are not permitted, then the system should have an emergency hotline to related agencies, such local police or military bases.

Based on area priority classification, we determine potential threat levels for each area. Table 9 shows an example derivation for each class's potential threat, T_i, where $i = 1 \ldots 4$. First, the system derives a numerical value for each drone incident, and checks if the incident can happen in the each area. Then it calculates the sum of incident values of each area, and divides by the largest sum to obtain coefficients for T_i, where $T_1 = 1$, and finally multiply each coefficient by β to derive T_i. Thus, we quantify the expected damage from a successful drone attack for each area class.

Threat level for the drone's flight path can be determined from the potential threat levels for each area, applying higher levels when the drone path includes high-priority areas. Let $\overrightarrow{F}$ be the aggregated drone flight direction (unit vector), measured from tracking data over some period, and $\overrightarrow{F_{d,i}}$ be the unit vector from its current location to the nearest Class i point, as shown in Fig. 11. $\overrightarrow{F}$ and $\overrightarrow{F_{d,i}}$ can be calculated from drone tracking data and the drone threat level R_{path} is

$$R_{path} = T_c + \sum_{i \in \mathcal{S}, i \neq c} (\overrightarrow{F_{d,i}} \cdot \overrightarrow{F}) w_d T_i, \tag{2}$$

where $\mathcal{S}$ is the set of area indices; c is the section containing the drone; and

$$w_d = \frac{1}{1 + \exp(d - \frac{D}{2})}, \tag{3}$$

where d is the distance between the drone and area of interest and D is the system's maximum detection range. w_d indicates

TABLE 9. Potential threat derivation according to priority classification (airport).

area class	Damage types						Coefficient	T_i
	Airplane crash (120)	Human casualty (100)	Airport paralysis (60)	Facility explosion (80)	Facility damage, civilian injuries (20)	Other damage (10)		
Class I	Y	Y	Y	N	Y	N	300/300	1.0β
Class II	N	Y	Y	Y	Y	N	260/300	0.867β
Class III	Y	N	Y	N	Y	Y	210/300	0.667β
Class IV	N	N	N	N	Y	Y	30/300	0.1β

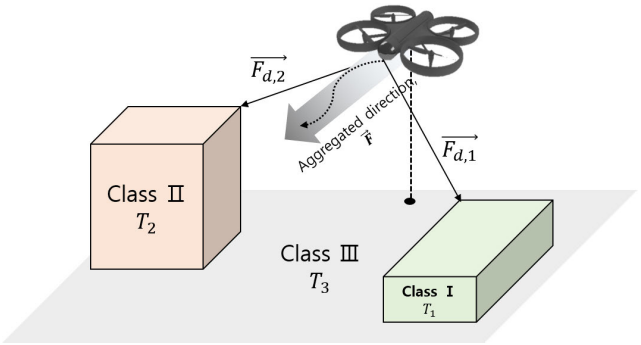


FIGURE 11. R_{path} determination for illegal drone flight direction.

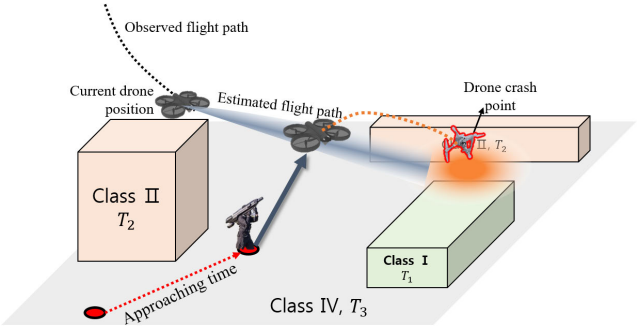


FIGURE 12. Risk model for drone neutralization.

a weight of threat with respect to a specific area, which increases when the drone approaches to the area. In sum, R_{path} increases if the drone approaches high priority areas, hence the proposed system can differentiate threat levels between (for example) a drone circling the airport conical space and one rushing toward a runway.

3) THREAT LEVEL BY AVAILABLE TIME

Response time affects anti-drone neutralization method selection. We employ time-wise threat as a weight to enable the system to respond to emergency situations. However, estimating available response time is challenging due to uncertainty regarding the illegal drone's purpose. Therefore, we modeled R_{time} assuming the worst case of active drone attack from factors collected by the drone detection and tracking system. R_{time} can be expressed as

$$R_{time} = \min\left(\frac{t_{avg}}{D_{critical} \div |\overrightarrow{v_{drone}}|}, 1\right), \tag{4}$$

where t_{avg} is the average response time for the available neutralization methods; $D_{critical}$ is the minimum distance to a critical point; and v_{drone} is the average drone velocity. R_{time} is generally larger than the expected time to prevent tardy system response. Critical area can be assigned by using the proposed area classification method (Section VII-A2) or any other useful system. The denominator in (4) expresses the remaining response time, hence the system should deploy fast and effective neutralization methods as $R_{time} \to 1$. Similar to R_{path}, R_{time} should be updated periodically as drone neutralization progresses to immediately react to changing situations.

C. RISK MANAGEMENT

With few exceptions, neutralization carry the possibility for further damage. For example, a promising neutralization technology is the drone capturing gun [109], [111], which fires a large net bullet to wrap the flying drone. However, successful neutralization means the captured drone immediately fall to the ground, potentially causing additional damages such as explosion or human injuries. Thus, it is essential to decide *where and when* to neutralize the incoming drone, considering the risk from drone neutralization. We propose an approach to search an optimal position to intercept the drone after the threat assessment in Section VII-B.

To derive the risk model for drone neutralization, we consider a simple scenario employing the drone capturing gun, as shown in Fig. 12. Suppose a drone is flying across the defense area, with current location $\overrightarrow{d_t}$ and estimated flight path $\overrightarrow{e(t)}$. The selected neutralization device is located at $\overrightarrow{k_t}$, and moves toward the estimated drone route with speed v. The system intends to intercept the drone at position $\overrightarrow{p}$, and estimated response time t_{resp} is

$$t_{resp} = \frac{|\overrightarrow{p} - \overrightarrow{k_t}|}{v}. \tag{5}$$

The capture gun fires the net at $\overrightarrow{e(t_{resp})}$, hitting the drone if it is within the device's effective range D_{eff}, and the drone

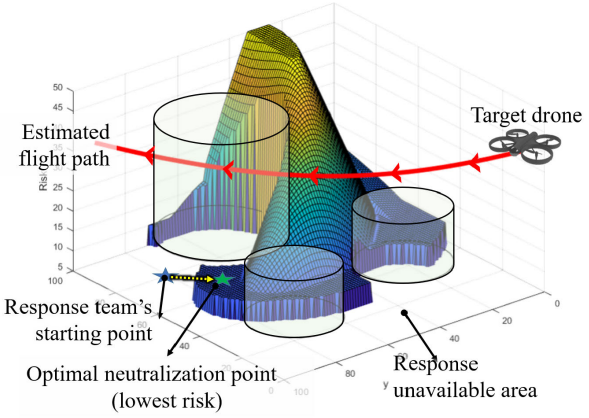


FIGURE 13. Estimated risk from drone flight path and neutralization point.

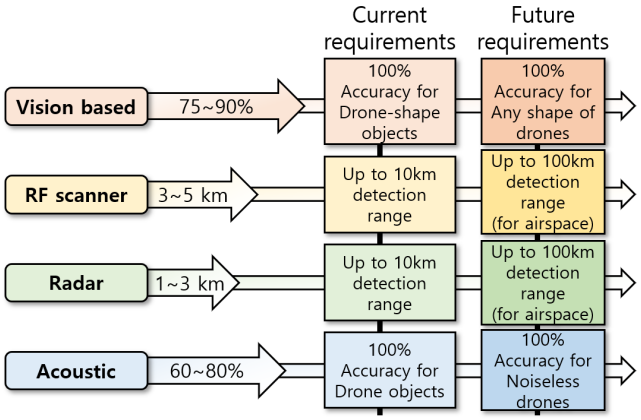


FIGURE 14. Advances and requirements for detection technologies.

subsequently falls to the ground at some crash point $c(\overrightarrow{d_t})$, a probability distribution of coordinates. The expected total risk $r(\overrightarrow{p})$ can be derived from the associated potential threat level for crash or collision for each possible crash coordinate, derived from the spatial threat assessment (Section VII-B2),

$$r(\overrightarrow{p}) = \oint_{\mathcal{C}} S(\overrightarrow{c}) p_{crash}(\overrightarrow{c}), \tag{6}$$

where $\mathcal{C}$ is the set of possible crash points; $S(\overrightarrow{c})$ is the potential threat for location $\overrightarrow{c}$; and $p_{crash}(\overrightarrow{c})$ is the crash probability for $\overrightarrow{c}$.

Thus, $c(\overrightarrow{d_t})$ and D_{eff} must be already known to derive an estimated response risk. Smaller crash point clusters imply larger area of low $r(\overrightarrow{p})$ values, and larger D_{eff} implies larger available response area. $c(\overrightarrow{d_t})$ and D_{eff} are strongly related to the particular neutralization system selected, and hence are essential parameters to evaluate neutralization performance.

Fig. 13 shows a simple drone flight simulation coded in MATLAB to verify the proposed risk model validity. We formed a (100, 100, 100) simulation space, with estimated flight path from (5, 5) to (100, 90) and 3 designated areas with potential threats levels {50, 30, 20}. The drone response team (device and carrier) were initially located at $\overrightarrow{k_t} = (80, 80)$ and $r(\overrightarrow{p})$ distribution was represented as a three-dimensional mesh. As shown, $r(\overrightarrow{p})$ is a dynamic value depending on selected neutralization points. In particular, the neutralization method was unavailable for some of the nominally available area due to range limitation. Then, the optimal operation point can be approximately (60, 80) with lowest risk. Designing risk model can determine where to deploy the neutralization process with lowest risk in dynamic situations.

VIII. ADVANCES IN DRONE TECHNOLOGY

Before the anti-drone system get spotlighted as the security solution for drone incidents, drone researchers rather studied the security solutions for the drones to defend against the malicious attacks [164]. Drones are now widely acknowledged as potential weapons, and anti-drone technologies have been widely studied to defend against malicious drone attacks. However, anti-drone and drone-safety domains are complementary, similar to hacking and network security. This section discusses drone-side defensive technologies and propose future directions for anti-drone systems.

A. ANTI-DRONE NULLIFICATION TECHNOLOGIES

Drone defense solutions have evolved in part to avoid risks from expanded industrial drone use. Increased drone automation and vastly improved stability have greatly improved drone security, and hence many current anti-drone solutions can fail to defend against modern drones. We consider several drone safety systems that could potentially cause anti-drone system failure in terms of detection and neutralization. We replace the concerns about drone identification technology with [165], which solves the existing problems of remote drone registration systems.

1) DRONE DETECTION AVOIDANCE

Disturbing the detection sensor or minimizing drone frame features are the main detection avoidance approaches, also called drone stealth techniques [166]–[168]. Most stealth techniques focus on lowering the frame RCS. Already, some micro-UAVs (e.g. CrazyFlies [169]) are effectively undetectable at sufficient range to allow eavesdropping or spying on confidential facilities, and if the drone is equipped with encryption modules, RF scanners may not detect its approach. A fleet of drones can construct a high security network using advanced micro-computers and lightweighted security schemes [170], [171] that would be impossible to crack until the drones completed their invasion. Indeed, RF scanners may become obsolete unless cracking technology catches up with encryption schemes or adopt working quantum computing devices. Meanwhile, Oh *et al.* [167] proposed a noiseless drone design to avoid acoustic detection, and particular drone shapes can significantly reduce camera detection accuracy [172], [173] since vision systems identify drones by shape.

Drone detection technology struggles with rapid drone evolution in terms of size, speed, shape, and noise. Fig. 14

compares the advances in stealth technologies future requirements for detection technology, based on detection accuracy and range from Section III, required performance from Section II, and future objectives for drone technologies. Current detection solutions grant limited safety against invading drones. Rather, cooperation with dense and large-scale drone identification networks may be better approach to determine if the flying object is harmful or not. It means, detection system should observe wide types of flying suspicious objects, regardless of feature, and let identification system decide to neutralize each. If so, then drone detection can act as a tracking system, another essential role in drone response.

2) DRONE NEUTRALIZATION AVOIDANCE

There are many drone neutralization techniques (Section V), and hence safety solutions also vary. Anti-jamming is the complementary solution for jamming systems. Drone jamming is currently a major neutralization choice despite of the high risk and strict usage regulations due to simplicity, immediateness, versatility, and wide range. Although most drones can fly autonomously, breaking the connection between invading drone and its operator may prevent illegal attempts such as confidential information acquirement. However, jamming the licensed drone bands may be ineffective against modified drones using other bands [174] or multiple bands [175]. Although wideband jamming appears a clear and robust solution, operational cost and risk should be carefully considered along with regulatory restrictions.

Non-destructive methods (Section V) tend to assume a detected drone's operation method, such as what protocols employed and whether a drone is automated. Hijacking only works for manually controlled drones and is ineffective against self-navigating drones. Similarly, although spoofing can misdirect or kidnap target drones, vision based navigation [176], [177] may avoid GPS-spoofing. Destructive methods, such as killer drones or drone capture, have wide potential to neutralize the drones but may struggle with high-speed obstacle avoidance capabilities [178]–[180]. Thus, anti-drone systems should derive universal, robust, and precise strategies for drone response scenario, as discussed in Section VII-C.

B. ANTI-DRONE SYSTEM ADVANCES

Current anti-drone systems are under pressure to establishment safety and security against drones, which remains challenging. Subsequent sections list constructive approaches for anti-drone systems to achieve drone defense, from global philosophy to specific methodologies. Since the proposed statements require longer time than expected because of the regulatory issues instead of technological difficulties, national or world-wide discussions also be actively processed to avoid the global threat of drone incidents.

1) SYSTEM STANDARDIZATION

As discussed above, technical competition between drone and anti-drone industries causes rapid new product developments while beating the opposite side of systems. Thus, viable anti-drone systems must be capable of continuous updates, which means components must be easily replaceable and compatible with sustainable architecture. Anti-drone system component standardization is essential, such as a form of high-level architecture [181], to allow advanced component designs to be quickly evaluated and adopted in the empirical environment.

2) SAFE CHANNEL IN JAMMING

Because of the technical difficulties in other neutralization methods, jamming is still the last bastion of the anti-drone system. To reduce the risk of the use and maintain a network of anti-drone systems and target facilities, the available channel for the defenders, named *Safe channel*, should be required. The safe channel can be designed by the ultra-low band RF or the other mediums, such as visible light [182] or acoustic signal [183].

3) LARGE-SCALE DRONE MANAGEMENT

Most countries have drone regulations [139], but drone incidents still occur. Thus, fine-grained and strong policies are required for drone defense. Currently, anti-drone systems have difficulties identifying and responding to illegal or intrusive drones, so strict drone management regulations, such as installing hardware identification devices on drones, could help reduce the burden on the system.

IX. SUMMARY AND CONCLUSION

This paper discussed non-military grade anti-drone systems. Our findings can be summarized as follows.

- **Drone detection**. Modern detection solutions guarantee a certain level of drone detection accuracy by integrating multiple detection systems. Each methodology has performance limitations in terms of detection range, functionality, weather dependency, etc., so the anti-drone industry tends to construct hybrid detection systems. However, administrators should analysis the defense area to design optimal detection systems and improve drone detection efficiency. From the survey, we suggested a guideline for installing anti-drone detection system considering efficiency and priority. The proposed guidelines include abstract classifications for detection equipment, priority classification for defended areas, and actual system deployment examples for airports, industrial facilities, and airspaces. Detection system should be tightly coupled with fine grained drone identification networks to provide viable drone tracking and neutralization solution.

  To sum up, considering current performance of detection technology and capability of the drones, each mechanism should be improved in terms of range and accuracy to track the drones with advanced stealth functions. In addition, sensor fusion technology must compensate for the flaws in each method while increasing

cost efficiency. Meanwhile, anti-drone system designers should make their own layout of the detection system and map it to the actual equipment that matches their requirements. This coexistence of designers and developers can lead to the technical advances in the drone detection system.

- **Drone identification**. Empirical adoption of drone identification systems is earlier stage than detection and neutralization systems due to requiring regulatory cooperation, such as drone registration policies. Attaching active transponders to drones, similar to conventional airplanes, is currently under consideration. Drone identification networks will become more important than detection alone to overcome evolving drone technologies. Airspace provisions can be further subdivided to prepare for the emerging PAV industry, and anti-drone systems must be phased in to defend against legitimate aircraft.

  In short, drone identification technology will play an important role in future anti-drone systems. Considering the rapid evolution in drone technology and the high attention in anti-drone, drone identification system should clearly determine whether or not to neutralize the observed aircraft. False positive or false negative of identification can result in the entire failure of the defense. Proper amendments in drone regulation such as identification tag are essential to construct reliable identification system. With authentication and regulations, we claim that drone identification can be more specific like detection/neutralization procedures.
- **Drone neutralization**. Drone neutralization schemes exploit various drone features, including flight mechanisms and communication systems. Neutralization methods can be mainly classified as destructive or non-destructive. However, most non-destructive methods may be quickly obsolete due to robust drone security and navigation solutions. Although drone jamming remains the most popular choice for current systems, its inherent aggressiveness and anti-jamming developments strongly suggest the necessity for alternative approaches. Geofencing for drones may prevent unintended accidents from legitimately authorized drones, but deliberate attacks may need to be defended physically, e.g. killer drones or drone capture.

  In summary, anti-drone systems should include multiple neutralization solutions and utilize them appropriately to improve defense reliability. Specially, destructive and non-destructive methods should be separately treated in system design, and must be carefully selected. Our guideline that assesses drone threat level from relevant measured parameters and subsequently derives safe neutralization scenarios could be an abstracted procedure for future anti-drone systems.

Designing anti-drone systems without incorporating military grade weapons and complying to national regulations remains early stage and exposes vulnerability to drone incidents. Current anti-drone systems have well-formed detection, identification, and neutralization stages, but more accurate and effective systems are required to cope with high-speed, high-security, and three-dimensional attacks. We proposed guidelines for designing versatile, available, and sustainable anti-drone to defend against various drone attack scenarios. Our proposals address the direction to resolve technical and structural difficulties for anti-drone system design, and cope with the advances in drones' defense mechanism. We expect this anti-drone system survey contributes to expanding the drone-safety zones without requiring weaponry.

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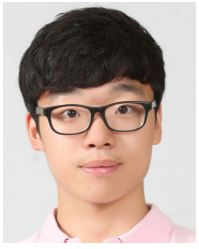

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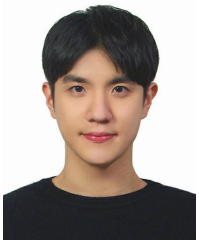

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