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Compact Critical Infrastructure Active Drone Protection System – Conceptual Design

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***Abstract*—The ever growing threat of hostile and unauthorized drones drives the need for counter-action, starting with early detection and reaction. The low cost and availability of small and low flying drones increases both their extensive use in warfare and the accidents with them in civilian settings. Efficient and adequate counteraction requires a detailed study of the threat and a retrospective analysis of potential solutions to the problem.**

***Keywords*—Counter-UAS, drone defense, early warning, radar, electronic warfare, acoustic sensing**

I. Introduction

The use of unmanned or remotely guided aerial threats is not a new phenomenon. As early as World War II, Germany employed the V-1 flying bomb, a precursor to today's cruise missiles and long-range UAVs. Since then, advances in electronics, communications, and navigation have led to the widespread availability of small and highly capable drones. These systems are now used by state and non-state actors alike for reconnaissance, strike, and harassment missions.

The defense against such aerial threats [1] has evolved from visually guided anti-aircraft fire to highly automated, networked systems integrating multiple sensors and effectors. This article reviews that evolution, focusing on early warning and detection, followed by defensive and neutralization methods, and concluding with an analytical synthesis presented in a historical timeline.

A. Detection and Early Warning

Early warning is the foundation of any effective air and drone defense system. [2] The ability to detect, classify, and track aerial threats in sufficient time enables appropriate engagement decisions and efficient allocation of defensive resources.

The first systematic early warning systems emerged prior to and during World War II. Visual observation posts and acoustic sound locators were initially used to detect incoming aircraft. These methods were limited by weather, human perception, and reaction time. The introduction of radar, most notably the British Chain Home system, revolutionized air defense by providing long-range detection and centralized command and control.

Flying bombs such as the V-1 highlighted the challenge of detecting small, fast, and low-altitude targets, a problem that remains relevant in modern drone defense.

Visual detection remains a basic but important layer of early warning, particularly at short ranges. Modern systems augment human observers with electro-optical (EO) and infrared (IR) cameras. These sensors provide high-resolution imagery and thermal contrast, enabling detection and identification of drones against complex backgrounds. Automated image processing and artificial intelligence increasingly support these systems by reducing operator workload and false alarms.

Acoustic detection systems use microphone arrays to capture and analyze the characteristic sound signatures of drone propulsion systems. Such systems can be effective against small, low-flying UAVs that are difficult to detect by radar. However, their performance is sensitive to environmental noise, wind, and terrain, making them most effective as part of a multi-sensor architecture rather than as standalone solutions.

Radar remains the primary long-range detection method for aerial threats. Traditional air defense radars were optimized for large, fast aircraft and missiles, but modern drone threats require high-resolution radars capable of detecting small radar cross-section targets flying at low altitude. Specialized counter-UAS radars have been developed to address these challenges, often operating in X-band or Ku-band and employing advanced signal processing techniques.

Many drones rely on radio frequency (RF) links for command, control, and telemetry. Passive RF detection systems monitor the electromagnetic spectrum to identify known drone communication protocols and locate both the UAV and its operator. These systems are valuable because they do not emit energy and can detect drones even when radar signatures are weak.

No single detection modality is sufficient under all conditions. Modern early warning systems therefore rely

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on sensor fusion, combining radar, RF, EO/IR, and acoustic inputs into a unified situational picture. [4] Advances in data processing, networking, and artificial intelligence have significantly improved classification accuracy and response times, forming the backbone of contemporary counter-UAS architectures.

Era	Early Warning and Detection	Defense Against Aerial and Drone Threats
1930s – 1940s	visual observers, acoustic sensors, early radar	fighter interception, anti-aircraft guns
		interceptor drones

B. Defense and Neutralization Methods

Once a drone is detected and classified as hostile, a range of defensive options is available. These can be broadly divided into kinetic and non-kinetic methods.

Historically, fighter aircraft were the primary means of intercepting aerial threats, including flying bombs and reconnaissance aircraft. Surface-to-air missiles (SAMs) later complemented and partially replaced fighter interception, offering rapid reaction and high engagement probability against high-value targets. While effective against large UAVs, these methods are often impractical or uneconomical against small, low-cost drones. Moreso, they are unaplicable in populated areas – both urban and rural – because of high risk of collateral civilian damage.

Anti-aircraft artillery (AAA) have long been used against low-altitude threats. Modern short-range air defense systems integrate rapid-fire cannons and missile launchers with radar and electro-optical fire control, enabling effective engagement of small UAVs. Proximity-fused ammunition and programmable airburst rounds further enhance effectiveness.

Directed energy weapons, including high-energy lasers and high-power microwave systems, represent an emerging class of counter-UAS effectors. Lasers offer precise, speed-of-light engagement with low cost per shot, while microwave systems can disable drone electronics over a wider area. These technologies are increasingly deployed as part of layered defense systems.

An emerging approach involves using drones to counter drones. Interceptor UAVs can pursue and physically disable hostile drones using nets or kinetic impact. Such systems are particularly suited for urban or civilian environments where collateral damage must be minimized.

C. Historical Analysis and Timeline

The evolution of early warning and defense against drones reflects broader trends in air defense: increasing automation, sensor integration, and a shift from purely kinetic solutions to flexible, multi-layered systems. Table 1 summarizes key developments over time.

TABLE I. TIMELINE OF EARLY WARNING AND DEFENSE AGAINST AERIAL AND DRONE THREATS

Era	Early Warning and Detection	Defense Against Aerial and Drone Threats
1930s – 1940s	visual observers, acoustic sensors, early radar	fighter interception, anti-aircraft guns
1980s–1990s	improved radar resolution, early UAV tracking	SAM modernization, limited EW
2000s	RF detection, early sensor fusion	MANPADS, basic jamming
2010s	multi-sensor systems, EO/IR integration	Dedicated C-UAS systems, EW, nets
2020s	AI-enabled fusion, passive RF and acoustic arrays	lasers, high-power microwaves (HPM),

The history of air defense demonstrates that technological change in offensive systems inevitably drives defensive innovation. From the V-1 flying bombs of World War II to today's small, low-cost, and autonomous drones, defenders have repeatedly adapted detection and engagement methods to address new threats. For modern armed forces, counter-UAS is no longer a niche capability but a core element of air defense and force protection. The key lesson is the importance of layered defense: early warning through multiple sensors, rapid decision-making, and the flexible use of kinetic and non-kinetic effectors. As drone technology continues to advance, particularly in autonomy and swarm tactics, successful defense will increasingly depend on integration, automation, and well-trained personnel who understand both the technology and its operational employment.

II. CONCEPTUAL DESIGN OF AN ANTI-DRONE SYSTEM

Based on previous developments [5,6], we suggest a conceptual design of an integrated anti drone system for a typical critical infrastructure site – a controlled area with fixed size. Let us suppose it is a data center, satellite communication relay or a thermal powerplant. For the study, we have fixed the size limiting it to a radius of 1.5 km. Thus the physical layout of the system, as shown on Fig. 1, is:

- Radius: maximum footprint of 1.5 km (all key components within this range).
- Central Command Node (CCN): Buried or hardened structure at the center, hosting the AI-driven fusion & command system.
- Sensor/Effector Layers: Deployed in concentric rings, with overlap and redundancy.

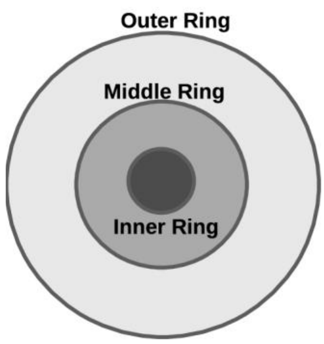

Fig. 1. Sensor Grid Structure.

A. Sensor Grid

Our goal is a 360° multi-elevation coverage with both passive & active sensors and all-weather capacity.

The outer ring is intended for primary early warning. It consists of three parts:

First is an acoustic sensor array: ground mounted microphones to triangulate propeller and engine noise. It works in all weather, though its range would be affected by the wind and the humidity.

The second are the RF (electronic support measures, ESM) Sensors. They detect drone control and telemetry signals and also provide direction finding to identify both drone and operator location. They will works in all conditions.

The third component is a low-power bistatic radar with mutiple recievers along the perimeter and one or two transmiters in the middle

The middle ring is at 0.8 km radius. It consists of two layers:

Multi-Function Active Electronically Scanned Array (AESA) Radar. It is the main tracking radar. It consists of multiple small panels on towers/buildings for 360° coverage. This radar is capable of weather filtering (rain/snow clutter suppression).

Electro-Optical/Infrared (EO/IR) Pan-Tilt-Zoom (PTZ) Turrets. They mount high-resolution day cameras and thermal imagers on elevated masts. Thermal vision is effective in fog/light rain but degrades in heavy rain/snow. It is used for visual confirmation and tracking.

The inner ring (>0.3 km) encompasses the critical asset itself. It includes a close-in motion sensors and LIDAR on rooftops. The LiDAR provides high-precision 3D tracking in clear conditions, though is severely degraded in fog/rain. Also, optional are close quarter unauthorized RF, WiFi and Bluetooth signals.

The command post is centered around Sensor Fusion AI ("Sentinel Core"). Its task is to fuse all sensor inputs in real-time, creates a single, confident track. It also should use weather data (both on-site station and external) to weight sensor reliability dynamically (e.g., to rely more on radar and less on EO/IR in fog).

B. Countermeasure Effector Matrix

Our goal is to achieve a scalable effector response from soft kill (and forensic study) to hard kill with absolute minimum collateral damage.

First effector layer is non-kinetic soft kill. It is priority in collateral damage sensitive zones like urban area and close proximity to airports. It includes:

- Spoofers/GPS Simulators. They can take control of or misguide GPS-dependent drones.
- Directional RF Jammers. Located at the middle ring, they employ focused beams to disrupt control, GPS, and telemetry links. Their power level is adjustable to minimize area effect (crucial in urban settings).

Second layer is hard-kill and includes kinetic and directed energy (DE) effectors.

- High-Power Microwave (HPM) Emitters. Mounted on quick-swivel platforms at the inner ring perimeter. They cause area effect to fry electronics of drone swarms, working line-of-sight, in all-weather.
- Laser Defense Pods (30-50 kW). On stabilized towers, they are silent, low-cost-per-shot and precise. Effective against single drones, though their performance degrades in heavy fog, rain, or snow (hight atmospheric attenuation).
- Interceptor Drone "Nests" take the form of 4-6 vertical launch tubes sheltering high-speed quadcopters or fixed-wing interceptors. Equipped with nets, blades and relying on kinetic impact collision capability. They are launched autonomously for beyond-visual-line-of- sight (BVLOS) engagements, especially useful in complex terrain (urban canyons) or against maneuvering targets.
- MANPADS are not integrated into a closed loop. They are held in armory to be used by trained operators under strict rules of engagement against larger high-risk threats.

C. Command and Control (C2) unit

It sits in a central hardened location, possibly underground, somewhere in the inner ring. Central to its operation is the AI Battle Manager. It constantly maintains situational awareness, evaluating every threat and suggesting the best and most adequate response. It, mandatory, operates under control of a human operator (Human-in-the-Loop). He authorizes lethal engagements (except in a pre-authorized ‘war mode’). The communications sceme is shown on Fig. 2.

All the system employs closed loop communications in two layers:

- Layer 1 is the primary fiber network. Its topology is structured as dual counter-rotating rings following the perimeter road/internal paths. Nodes terminate at each major sensor/effector site (radar towers, laser pods, command bunker). Fiber technology is multiplexing (CWDM/DWDM) to carry multiple data channels (sensor data, video, control signals) on a single fiber pair.
- Layer 2 is the Wireless MESH Overlay. Its purpose is to enhance resilience through redundancy: to allow for immediate fallback if fiber is severed. It also provides connectivity to mobile elements interceptor drones (when airborne/returning) and MANPADS teams. It allows rapid deployment – temporary sensor connectivity during during maintenance. It is build on military-grade MIMO radios with frequency-hopping/AES encryption. Should operate in

bands less likely to be jammed by own systems.

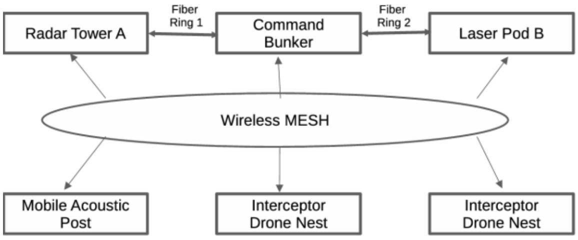

Fig. 2. Site Communication Diagram

All the internal communications remain within the 1.5 km site radius.

III. Physical and Mathematical Modeling

In the outer perimeter we envision acoustic sensors, RF detectors and a bi-static radar with several emitters and receivers.

A. Equations Describing Detection Parameters

The range of the acoustic sensors is governed by the equation for the sound pressure level, where one clearly sees how the effective range reduced in high wind [7]:

$$S_{pl} = 20\log_{10}(R/R_0) + a_a R + W_n(w,q) + P_t(T) \quad (1)$$

Here S_{pl} is the sound pressure level, a_a is the atmospheric loss quotient, R and R_0 are the distance and the reference distance, $W_n = 10\log_{10}[1 + (w/5)^2|\cos\theta|)]$ takes account of the wind losses according to the wind speed w and wind direction angle q. are the turbulence losses dependent on the temperature (absolute temperature T). In moderate winds, the first term in Eq. (1) dominates.

The power received by the bi-static radar [8] receiver – in dB to mW – is governed by the following equation:

$$P_r\,[\text{dBm}] = (P_t + G_t + G_r + 20\log10(\lambda) + \sigma_b) / \quad (2)$$

$$(F_t + F_r - 20\log10(4\pi) - 20\log10(R_t) - 20\log10(R_r)$$

$$- L_t - L_r - L_p - 10\log10(k\, T_s B_n)\,),$$

where P_r is the received power level, P_t is the transmitted power, $G_{t,r}$ are antenna gain coefficients at the transmitter and receiver, σ_b is the bi-static radar crossection, $F_{t,r}$ are the transmitter and receiver propagation factors, k is Bolzmann constant, T_s is system noise temperature, B_n is bandwidth noise level and $L_{t,r,p}$ are, respectively, transmitter, receiver and processing losses.

B. Effector Efficiency Equations

Laser Irradiance at target [9] is given by

$$I_{target} = (P_{laser}\, \eta_{trans}\, \eta_{atm}) / \quad (3)$$

$$(\pi\cdot(\theta_{div}\cdot R)^2)\,,$$

where $\eta_{atm} = \exp(-\beta\cdot R)$ is atmospheric transmission quotient, $\beta = \beta_{clear} + \beta_{fog} + \beta_{rain} + \beta_{snow}$.

Typical values for λ=1.06 µm are:

- Clear: β=0.1 per km
- Fog: β=10-100 per km
- Rain: β=0.2-2 per km (depending on rain rate)

Laser Kill Criterion is $I_{target} > \Phi_{kill}$ where Φ_{kill} depends on target material (plastic: ~1 kW/cm², metal: ~10 kW/cm²).

Jamming efficiency [10] is governed by:

$$J / S = (P_j\, G_j\, G_r(\theta)\, \lambda^2\, R_t^2) / \quad (4)$$

$$(P_t\, G_t\cdot G_r(0)\, \lambda^2\, R_j^2\, L_j)$$

Where R_t = is the from drone to operator, R_j is the range from the jammer to the drone and $G_r(\theta)$ is drone antenna gain pattern (which usually nulls at certain angles).

C. Overall System Effectiveness

Effectiveness of the system [11] is governed by the following integral:

$$E_{system} = \int[\alpha\, P_{detect}(t) + \beta\, P_{intercept}(t) - \gamma\, P_{collateral}(t)]\, dt\,, \quad (5)$$

where α, β and γ are weight quotients, and $P_{detect,\, intercept,\, collateral}$ are corresponding probabilities for detection, interception and collateral damage.

In the case of swarming drone attack [11, 12], the probability for attack neutralisation is

$$P_{(swarm\ neutralized)} = 1 - \sum_{\{k = 0 \text{ to } m\}} [C(n,k)\cdot(1 - P_{single})^k\, (P_{single})^{\{n-k\}}] \quad (6)$$

Where the single drone probability P_{single} depends on interceptor type (laser vs interceptor vs HPM).

D. Geometry Aspects of Acoustic Detection

Acoustic detection range strongly depends on the type of the source and the site location, as the latter forms the background noise environment. Different drones and locations are reviewed with the help of Table 2 [13].

TABLE II. AVERAGE DRONE VS TYPICAL SPR IN GIVEN ENVIRONMENT

Drone Type	SPL at 1 m [dB]	Rural (40 dB)	Urban (60 dB)
		Range of Detection* **[m]**	
big fixed-wing, petrol engine	115	~5600	~560
small fixed-wing**	100	~1000	~100
big quadcopter	95	~560	~95
small quadcopter	90	~320	~30

**average range; ** electric power;*

Table 2 clearly shows that small drones could easily sneak undetected within meters of installations in urbanized environments. Moreover, electric powered fixed-wings are, in fact, powered gliders that could turn on and off motor in flight, which makes them very dangerous.

If incoming drones are detected by an array of distributed microphones, both the time differences and SPR levels allow for not only detection and warning but for threat localization. In the simplified case of only two microphones, simultaneous detection allows both for time-of-arrival (TOA) and power level localization. For this simplified case, at TOA difference τ (in seconds) means that the sound source can be at any location along a hyperbola with an equation

$$x^2 / (\delta/2)^2 - y^2 / ((\delta/2)^2 - 1) = 1 \qquad (7)$$

where $\delta = \tau c$ is the corresponding distance offset. c is the speed of sound (~ 343 m/s). The foci of the hyperbola in Eq. (7) are taken at $x = \pm 1$ $y = 0$. and On the other side, with the same foci, if the sound pressure ratio is $1/k$, the range ratio is k, thus the locus possible locations takes the shape of an Apollonian circle with ratio k, with the following equation:

$$(x + (1 + k^2)/(1 - k^2))^2 + y^2 = (2k/(1 - k^2))^2 \qquad (8)$$

Intersection of the hyperbola and the circle is the sought-after location, as shown above on Figure 3. The actual sign and the sound pressure ratio indicate the right quadrant and the correct point of the detection.

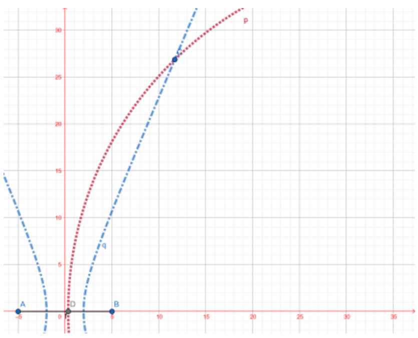

Fig. 3. Intersection of detection hyperbola (blue dash-dot) and Apollonian circle (red dot). Stronger detection and first arrival indicate correct side (according to the bisector).

Addition of third microphone or the use of directional cardioid microphones could indicate the correct quadrant of the localized drone.

In case of a microphone array, multiple detection curves will improve the accuracy as well give 3d localization capacity.

E. Wind Effects on Acoustic Detection Range

Wind changes the acoustic detection range for drones an these changes are significant with strong winds. Drones are much easily detected upwind than downwind. Acoustic detection range was modeled according to (1). A simplified model was drafted, which takes into account the effects of constant wind over a relatively flat landscape. The effects of the wind are given by the following formula:

$$R_{detection} = R_{calm} \exp[(w/w_{cut\_off}) \cos(q - q_{wind})] \qquad (7)$$

where the detection range in direction q (from 0^0 to 360^0) is maximum in upwind direction (q_{wind} is the wind speed direction), w is as above the wind velocity and is w_{cut_off} is the cutoff velocity at wich there is no detection downwind (it is dependent on the sensor system).

A typical situation is shown on Fig. 3

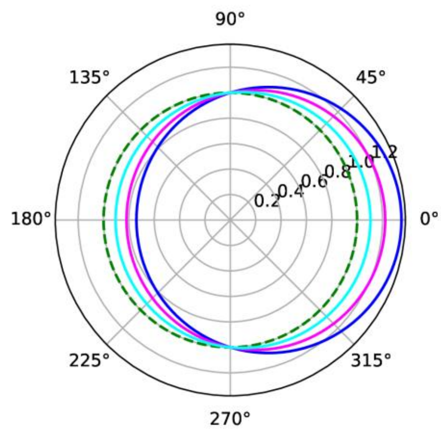

Fig. 4. Relative changes of the maximum acoustic detection range with wind speed at standard conditions (Air temperature 300 K, air pressure 0.9 bar, humidity 60 %). Wind blows from the East (wind speed at 180^0). Dotted line is the normalized range at $w = 0$. Consecutively, cyan, magenta and blue lines are at w = 0.1, 0.2 and 0.3 w_{cut_off}.

The analysis show that if the calm detection range is 800 m, with wind coming straight from the East the detection zone starts to shift upwind, while the range downwind seriously shortens.

IV. Concept System adaptability to location and environment

System deployment in urban areas requires emphasis on stealth and low collateral impact. In remote and rural areas the emphasis is on maximum engagement range and large area denial.

A. Deployment Location

The preferred sensors in urban environment are passive RF, acoustic and electro-optical ones. Only AESA radars will work using urban-mode filters. Effectors for urban settings are jammers, interceptor drones and lasers. MANPAD use is restricted. For physical integration the sensors end effector pods could use rooftop mounting on existing buildings.

In rural area, the deployment will allow for full power radar use in combination with long range EO/IR cameras. The full spectrum of effectors is enabled with HPM and lasers for hard kill and interceptor drones and MANPAD teams for long range engagement. The physical integration requires dedicated towers and masts in combination with perimeter fencing.

B. Weather Impact on Performance

Various cases of weather influence on anti-drone system performance are shown on Table 3.

TABLE III. ALL WEATHER PERFORMANCE REFERENCE TABLE

Condition	Sensor Impact	Effector Impact
Clear	All sensors optimal.	All effectors optimal.
Strong wind	Acoustic range reduced. Drone flight unlikely, but possible.	Interceptor drones grounded. Laser accuracy needs compensation. Projectiles affected.
Fog or Low Cloud	EO/IR (thermal) still works; visual impaired. Radar unaffected. LiDAR severely degraded.	Lasers attenuated. RF/Jamming, HPM, and kinetic effectors unaffected.
Rain or Snow	Heavy precip clogs radar & obscures EO/IR. RF/Acoustic unaffected.	Lasers significantly attenuated. Kinetic effectors (guns, projectiles) effective. HPM effective.

The table shows that system defaults to Radar/RF fusion core in bad weather. Multi-spectral fusion ensures continuity. Only the layered mix ensures all-weather capability. Thus, one layer's weakness is covered by another.

C. Deployment Concept for Example Sites

The Design Concept envisions three core type of sites – a data center, a satellite ground station and a power plant.

- Data Center: Focus on roof-top HPM & lasers to protect server halls. Jamming is used cautiously to avoid disrupting own communications.
- Satellite Ground Station: Careful siting of RF jammers to avoid interfering with own satellite links. Emphasis on directional, frequency-avoidant jamming.
- Power Plant (e.g., Substation): Robust perimeter defense. HPM use carefully evaluated against potential electromagnetic effects on own grid equipment.

This scenarios are typical, but not limiting so it is possible to adapt the design to different setting.

V. Conclusion

Stemming from the historical analysis of the development of the dialectic threat-response contest, we suggest a conceptual design of a anti-drone protection system. Its purpose is to enhance the resilience of critical infrastructure sites through hardening their security systems.

The suggested system is compact and self-contained. It fits within 1.5 km radius with resilient fiber optic and MESHNet communications. Its adaptive software-defined settings allow for adjustment to urban or rural areal, weather, and site type.

The envisioned response is tailored and scalable it ranges from warning to jamming to soft-kill to hard-kill with escalating force. The system has all-weather capacity with no single point of failure. The sensor/effector redundancy is spread across spectra. The collateral-damage risk is controlled strictly as the system prioritizes non-kinetic means, uses precise kinetics and limits MANPAD use to rural area outsite settlements.

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