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Evaluation and Selection of Defense Solutions for Small, Low-Altitude UAVs

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Abstract- The rapid development and widespread deployment of small, low-altitude unmanned aerial vehicles (UAVs) have provided significant benefits in both civilian and military applications, while simultaneously posing serious challenges to airspace security and safety. The increasing misuse of UAVs for unauthorized intrusion, reconnaissance, or disruption in sensitive areas has driven the need for effective counter-UAV solutions. This paper presents an overview and comparative analysis of existing countermeasures for small, low-altitude UAVs, including surveillance and detection, electronic jamming and control takeover, high-energy neutralization, and physical defense methods. Based on a systematic comparison of technical, economic, operational, and safety-related criteria, the advantages of physical defense - particularly net-based UAV capture are clearly identified. The results demonstrate that physical defense methods provide a safe, cost-effective, and non-lethal solution, especially suitable for training, operational exercises, and the protection of sensitive targets under real-world constraints.

Keywords: Small UAVs; counter-UAV systems; physical defense; net-based capture; non-lethal countermeasures.

I. INTRODUCTION

In recent years, small, low-altitude UAVs have become increasingly prevalent due to their compact size, low cost, high mobility, and ease of deployment. These platforms are widely used in applications such as reconnaissance, surveillance, aerial imaging, small-payload delivery, and military training. However, the rapid proliferation of UAVs has also introduced new security risks, as they can be exploited for unauthorized access, intelligence gathering, or disruptive activities in sensitive areas such as airports, military installations, critical infrastructure, and large public events.

In this context, the development of effective counter-UAV measures tailored to the specific characteristics of small, low-altitude UAVs has become a critical requirement. Such countermeasures must not only be effective in neutralizing UAV threats but also ensure operational safety, legal compliance, and practical deployability in complex real-world environments.

The rapid development of small, low-altitude unmanned aerial vehicles (UAVs) has brought profound changes to both civilian and military domains, while simultaneously posing significant challenges to low-altitude airspace security and safety. Owing to their compact size, low cost, high mobility, and ease of deployment, small UAVs have become increasingly widespread; however, these same characteristics also make them vulnerable to misuse for unauthorized intrusion, reconnaissance, disruption, or threats against critical infrastructure. In response to these emerging risks, many countries have developed multi-layered UAV defense systems aimed at early detection, accurate tracking, and effective neutralization of unauthorized aerial targets. Existing counter-UAV solutions can generally be categorized into four main groups: surveillance and detection, electronic jamming and control takeover, high-energy neutralization, and physical capture. Each group is based on distinct technical principles and exhibits specific advantages and limitations, depending on operational scenarios, environmental conditions, and mission requirements.

A systematic analysis of these approaches is therefore essential, not only to clarify their scientific foundations but also to support the selection, integration, and development of effective counter-UAV solutions. Such analysis is particularly important in contexts where safety, legal compliance, and

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applicability to training and educational environments are of primary concern.

II. SURVEILLANCE AND DETECTION METHODS

Surveillance and detection constitute the first and most critical stage in any counter-UAV system, as the effectiveness of subsequent defensive measures depends directly on the ability to detect and identify targets accurately and at an early stage.

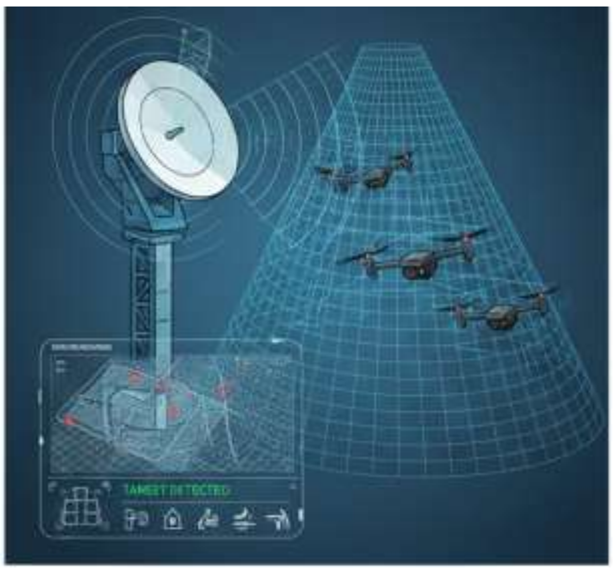

Figure 1. Surveillance and Detection Methods

For small, low-altitude UAVs, detection is particularly challenging due to their small radar cross-section, low flight altitude, and high maneuverability in complex environments. Conventional radar systems often prove inadequate for such targets, prompting the development of specialized sensing solutions. Low-altitude and high-frequency radars have been enhanced to improve resolution and sensitivity to small objects. In parallel, optical and infrared sensors enable UAV detection through visual and thermal signatures, offering high accuracy under favorable weather conditions. Acoustic sensing systems, capable of identifying characteristic UAV engine noise, have also been investigated as complementary detection tools. Current trends emphasize multi-sensor fusion, integrating radar, optical, infrared, and acoustic data to enhance reliability and reduce false alarms. Despite these advances, surveillance and detection systems typically involve high acquisition costs and complex infrastructure requirements, and their performance may be degraded by adverse weather or terrain masking. Consequently, such systems are most effective when deployed as the initial layer in a multi-tier counter-UAV defense architecture.

III. ELECTRONIC JAMMING AND CONTROL TAKEOVER METHODS

Electronic jamming and control takeover methods are based on disrupting or manipulating the communication links between a UAV and its ground control station, as well as its satellite navigation signals.

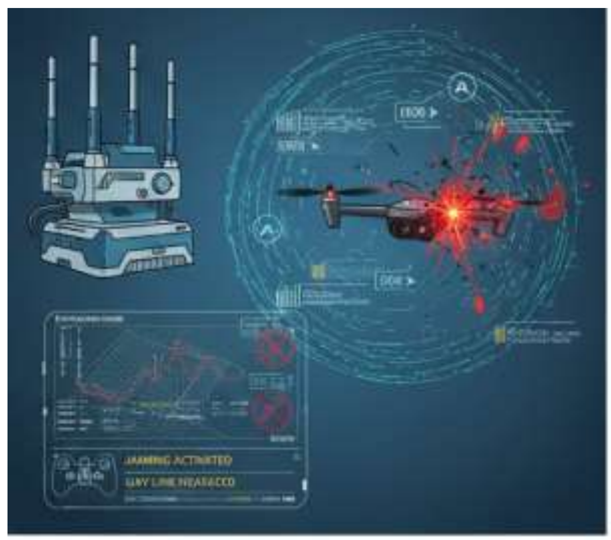

Figure 2. Electronic Jamming and Control Takeover Methods

By transmitting interference signals, counter-UAV systems can interrupt command-and-control channels or navigation data, causing the UAV to lose stability, return to its launch point, land automatically, or enter an uncontrolled state. A key advantage of this approach is its ability to neutralize UAVs at relatively long distances without physical contact, thereby reducing the risk of collision or secondary damage. In certain cases, control takeover techniques may allow defenders to assume command of the UAV, enabling intelligence gathering and technical analysis. However, the effectiveness of jamming-based methods strongly depends on the UAV's communication protocols, frequency bands, encryption levels, and anti-jamming capabilities. Modern UAVs equipped with autonomous flight modes or advanced anti-interference algorithms can significantly reduce the effectiveness of such measures. Moreover, the use of electronic jamming may inadvertently affect other communication systems operating in the same area, necessitating strict control of transmission power and operational range to ensure safety and regulatory compliance.

Table 1. Comparison Based on UAV Neutralization Effectiveness

Method	Neutralization Capability	Effective Range	Remarks
Surveillance & Detection	Not applicable	Long	Early warning only
Electronic Jamming / Control Takeover	Medium–High	Medium–Long	UAV-dependent
High-Energy Neutralization	Very high	Long	Destructive effect
Physical Defense (Net Capture)	High	Short	Direct mechanical restraint

IV. HIGH-ENERGY NEUTRALIZATION METHODS

High-energy neutralization methods employ concentrated energy sources, such as high-power lasers or directed microwave systems, to damage or disable critical components of UAVs.

Figure 3. High-Energy Neutralization Methods

These approaches offer rapid response capabilities and the potential to engage targets at long ranges, making them suitable for scenarios requiring immediate threat neutralization. Laser systems can directly damage structural elements, sensors, or control modules, while directed microwave weapons are capable of disrupting or destroying onboard electronic circuits.

Despite these advantages, high-energy systems are associated with substantial acquisition and operational costs, as well as demanding power supply and infrastructure requirements. The performance of laser-based systems is particularly sensitive to atmospheric conditions, with effectiveness significantly reduced in rain, fog, or dusty environments. Furthermore, these methods are inherently destructive, preventing the recovery of intact UAVs and posing potential risks of unintended collateral damage. As a result, high-energy neutralization is generally less suitable for training, educational applications, or densely populated civilian areas where safety considerations are paramount.

Table 2. Comparison Based on Safety and Collateral Risk

Method	Operational Safety Level	Collateral Damage Risk	Comments
Surveillance & Detection	Very high	None	No physical impact
Electronic Jamming / Control Takeover	Moderate	Possible	Interference with other systems
High-Energy Neutralization	Low–Moderate	High	Fire, debris, secondary hazards
Physical Defense (Net Capture)	Very high	Very low	Non-lethal approach

V. PHYSICAL ENTRAPMENT METHOD

Physical entrapment is a counter-UAV (C-UAV) methodology centered on the deployment of mechanical apparatuses to achieve direct kinematic control over a target, most notably via net-projectile systems.

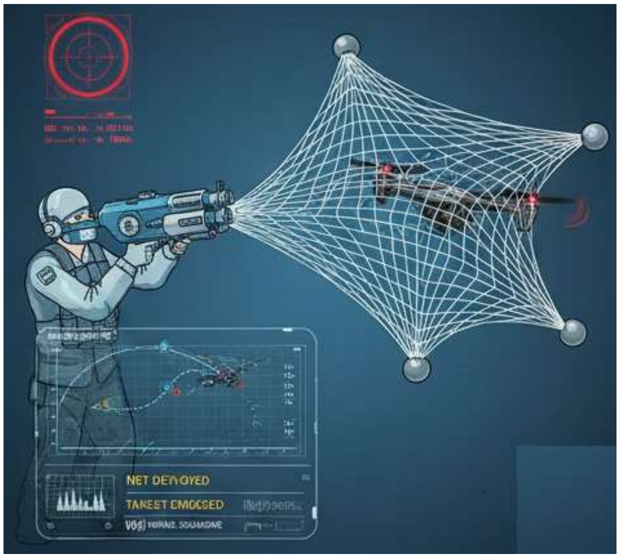

Figure 4. Physical Entrapment Method

The fundamental principle relies on the integration of mechanical and aerodynamic forces to neutralize threats in a controlled manner. Upon a target entering the effective engagement envelope, a net is kinetically deployed to entangle the propulsion system (propellers/rotors) or the airframe. This disruption of the flight mechanics results in a controlled descent or immediate immobilization of the target.

This method is highly regarded for its non-destructive neutralization capability. Upon contact, the entanglement of the rotors induces an instantaneous loss of aerodynamic lift.

Table 3. Comparison Based on UAV Recovery Capability

Method	Intact UAV Recovery	Value for Investigation & Training
Surveillance & Detection	No	None
Electronic Jamming / Control Takeover	Possible	Limited
High-Energy Neutralization	No	None
Physical Defense (Net Capture)	Yes	Very high

Unlike kinetic energy interceptors, this process is characterized by low collateral impact, minimizing the generation of fragmentation or secondary hazards to the surrounding environment. Consequently, it represents an optimal equilibrium between engagement efficacy and risk mitigation.

Table 4. Comparison Based on Cost and Technical Requirements

Method	Initial Investment Cost	Operation & Maintenance Cost	Infrastructure Requirements
Surveillance & Detection	High	High	Complex
Electronic Jamming / Control Takeover	Medium	Medium	Moderate
High-Energy Neutralization	Very high	Very high	Very complex
Physical Defense (Net Capture)	Low	Low	Simple

A primary technical advantage of net-firing systems is their inherent safety regarding personnel and infrastructure; the mechanism operates without the need for thermal energy, pyrotechnics, or high-power electromagnetic radiation. Furthermore, this approach facilitates post-engagement recovery with high structural integrity, enabling forensic investigation, technical exploitation, or intelligence gathering—a critical distinction from high-energy weapon systems (HEL) that typically result in total target destruction.

From an economical and logistical perspective, net-based systems feature simplified architectures with low capital expenditure (CAPEX) and operational/maintenance costs (OPEX). Their modularity allows for rapid deployment across diverse operational units. The most significant attribute is system reusability; following a successful engagement, the net canisters and primary components can be recovered and refurbished for subsequent mission cycles. This trait significantly enhances cost-effectiveness and is particularly advantageous for high-frequency training and simulation.

Conclusion In summary, physical entrapment via net deployment is an optimal solution for scenarios prioritizing safety, forensic preservation, and economic sustainability. Due to its ergonomic design and operational flexibility, this method is suitable for both military and civil-sector applications, ranging from large-scale public event security to specialized tactical training. Investing in the research and development of reusable net-firing systems is a strategic pathway toward establishing a sustainable, domestic low-altitude aerial defense infrastructure.

Table 5. Comparison Based on Applicability and Training Suitability

Method	Suitability for Training & Education	Legal & Social Acceptability	Operational Deployability
Surveillance & Detection	Limited	High	Limited
Electronic Jamming / Control Takeover	Limited	Moderate	Moderate
High-Energy Neutralization	Not suitable	Low	Very limited
Physical Defense (Net Capture)	Highly suitable	Very high	High

VI. CONCLUSIONS

This paper has presented a comprehensive evaluation of countermeasures for small, low-altitude UAVs. Through comparative analysis, physical defense methods—particularly net-based UAV capture—have been identified as the most suitable solution when safety, cost efficiency, UAV recoverability, and training applicability are prioritized. Although physical capture methods are inherently limited in engagement range, their effectiveness can be enhanced through integration with early detection and warning systems within a multi-layered defense framework.

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