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Classification and Performance Evaluation of Counter-FPV Unmanned Aerial Vehicle Defense Technologies

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Abstract:

First Person View (FPV) drones have introduced a low-cost, highly maneuverable threat that conventional air defense was not designed to counter, making it primarily a tactical counter-UAS and force-protection problem. States have responded with countermeasures spanning electronic warfare, kinetic interception, directed energy, and passive defense, while fiber-optic-controlled drones have rendered radio-frequency jamming ineffective. This study classifies and evaluates counter-FPV systems through a structured review of peer-reviewed publications, official statements, and verified procurement contracts (2018-2026), assessing each category against defined operational metrics. The analysis shows that no single category counters all threat dimensions and that a layered architecture combining electronic, kinetic, directed energy, and passive measures is the approach most consistently supported by the reviewed sources.

Keywords:

FPV drone, counter-UAS, electronic warfare, directed energy, kinetic interception, fiber-optic drone, high-power microwave, laser weapon system, layered defense

1 Introduction

First Person View (FPV) drones have constituted a new threat category on the battlefield since 2022. These systems, which can be manufactured at low cost from commercial components, possess high maneuverability, and can be guided instantaneously by the operator, present a profile that is incompatible with the design philosophy of conventional air defense systems. Conventional air defense architectures have been shaped against targets operating at high altitude, possessing prominent radar signatures, and following predictable flight profiles. FPV drones operate outside these design assumptions, at low altitude, in small form factors, and with irregular maneuver

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patterns. It should be emphasized, however, that the FPV threat does not render integrated air and missile defense obsolete; rather, it falls predominantly within the domain of tactical counter-unmanned aircraft systems (C-UAS) and force protection at the immediate front line. The relevant shortfall is therefore not a deficiency of strategic air defense as such, but the mismatch that arises when its design assumptions are applied to a low-altitude, short-range, close-proximity threat class for which it was never intended. The present review is framed accordingly, as an analysis of tactical C-UAS and force-protection countermeasures rather than of conventional air and missile defense.

One of the fundamental factors that underlies the significance of the FPV drone threat is cost asymmetry. An FPV drone that can be manufactured for approximately 2 000 to 5 000 USD possesses the capacity to destroy military platforms valued at millions of dollars [1, 2]. Tab. 1 presents the approximate unit costs of principal military platforms that can be targeted by FPV drones.

Tab. 1 Approximate unit costs of military platforms targetable by FPV drones

Platform Type	**Approx. Unit Cost (USD)**	**Cost Ratio (vs. FPV)**
Main Battle Tank (M1A2 SEPv3)	8 500 000–12 000 000	~1 700×–6 000×
Infantry Fighting Vehicle (M2 Bradley)	3 000 000–6 000 000	~600×–3 000×
Self-Propelled Howitzer (PzH 2000)	7 000 000–20 000 000	~1 400×–10 000×
Multiple Launch Rocket System (BM-21)	~2 500 000	~500×–1 250×
FPV Drone (field average)	2 000–5 000	-

Platform cost data compiled from official procurement contracts and budget documents: M1A2 SEPv3 [3]; M2 Bradley [3]; PzH 2 000 (BAAINBw procurement contract, reported by Breaking Defense, March 2023); BM-21 (manufacturer data). FPV drone unit cost represents a field-practice average reported in [1].

As Tab. 1 illustrates, the cost ratio between an FPV drone and the platform it destroys reaches magnitudes of hundreds to thousands of times. From a defense economics perspective, this disparity translates into a resource consumption advantage for the attacking party. This asymmetry has compelled states and defense industries to develop cost-effective, rapidly deployable, and layered defense solutions against the FPV drone threat [4].

Several recent studies have addressed the counter-drone domain from different perspectives. Chauhan et al. [4] provide a comprehensive review of anti-drone systems and strategies with particular emphasis on civilian and military frameworks. The COURAGEOUS project team [5] proposes a standardized evaluation methodology for counter-drone systems. Chaari [1] analyzes drone capabilities and anti-drone limitations observed in recent large-scale conflicts, while Tytarenko [2] offers tactical insights from recent operational experience in countering FPV drones. The present study differs from and builds upon these works by focusing specifically on the counter-FPV defense domain, incorporating the most recent developments including fiber-

optic drone countermeasures and directed energy demonstrations from late 2025 and early 2026, and by providing a structured comparative evaluation of all four countermeasure categories against defined operational parameters.

2 Methodology

This study employs a structured review methodology to classify and evaluate counter-FPV drone defense technologies. The source selection process was guided by three criteria: (1) peer-reviewed academic publications indexed in Scopus, Web of Science, or IEEE Xplore addressing drone detection, radar cross-section characterization, or counter-UAS systems; (2) official institutional statements and policy documents from international defense organizations and national defense ministries; and (3) verified procurement contracts and manufacturer press releases confirmed through at least two independent reporting sources.

The temporal scope covers publications and events from 2018 to April 2026, with particular emphasis on developments from 2024 onward reflecting the rapid evolution of the FPV drone threat and associated countermeasures. Sources were identified through systematic searches in the aforementioned databases using keyword combinations including "counter-UAS", "FPV drone", "electronic warfare drone", "directed energy counter-drone", and "fiber-optic drone".

Countermeasure systems were classified into four categories based on their fundamental operating principle: electronic warfare measures, kinetic interception solutions, directed energy systems, and passive defense measures. Each category was evaluated against seven operational parameters: effectiveness against RF-controlled drones, effectiveness against fiber-optic drones, capacity against drone swarms, cost per engagement, impact on friendly systems, position disclosure risk, and weather dependency. These parameters were derived from the operational requirements identified in the NATO Innovation Challenge [6] and a military lessons-learned report [7].

3 Technical Characteristics of the FPV Drone Threat

FPV drones are difficult to detect and neutralize on the battlefield. In terms of radar cross-section (RCS), academic measurement studies have demonstrated that small multirotor and fixed-wing drones typically exhibit values ranging from 0.01 m^2 to 0.1 m^2 [8, 9]. Manufactured from materials with low reflectivity such as plastic and carbon fiber, these drones remain well below the design parameters of conventional air defense radars. The similarity of small drone RCS values to those of birds introduces an additional complication by increasing false alarm rates in detection systems [10].

In addition to low RCS values, the flight profile of FPV drones further complicates engagement. Operating at low altitude, high speed, and with irregular maneuver patterns, these drones exceed the predictive capacity of target tracking algorithms employed by conventional air defense systems. The operator's ability to provide instantaneous guidance through a real-time visual feed prevents the formation of a predictable flight path pattern. Cost and ease of production also amplify the scale of the threat; Chaari [1] reports that over 1.5 million FPV drones were procured in 2024, with a production target of 4.5 million units established for 2025. This production scale constitutes a parameter that directly affects the per-unit cost and capacity calculations of countermeasure systems.

A major transformation in the FPV drone threat occurred with the introduction of fiber-optic-controlled variants to the battlefield. In these drones, which began appearing in combat from the spring of 2024, control signals and video data are transmitted as light pulses through a thin fiber-optic cable rather than via radio frequency (Fig. 1). Fiber-optic control eliminates the detection and jamming capacity of conventional electronic warfare systems, as the drone emits no RF radiation. NATO Allied Command Transformation, in the official request document published for the 16th Innovation Challenge (RFIP-ACT-SACT-25-48), explicitly stated that EW counter-UAS systems are ineffective against such drones and that the combination of high maneuverability, jamming immunity, and low visual and radar signature poses a serious threat to frontline units [6]. A military lessons-learned institution also emphasized in its published report that fiber-optic drones are extremely difficult to detect within the electromagnetic spectrum and that a significant portion of existing counter-UAS systems are inadequate against this threat [7]. Operational reports indicate that fiber-optic FPV drones with ranges of up to 50 km have been deployed, extending the threat well beyond the immediate contact line to logistics routes, artillery positions, and rear-area command posts [11].

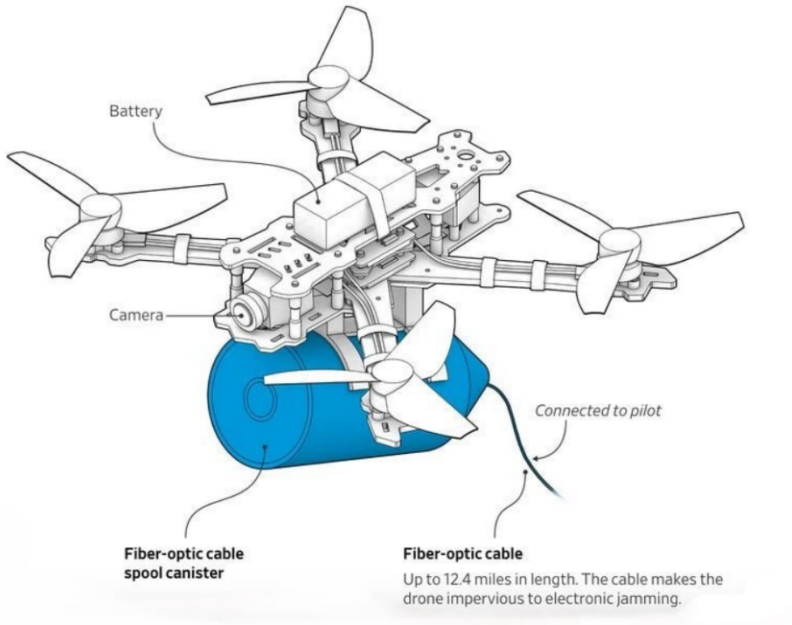


Fig. 1 Fiber-optic drone system [12]

4 Classification of Countermeasure Systems

Defense solutions developed against the FPV drone threat can be categorized into four fundamental groups based on their operating principles: electronic warfare measures, kinetic interception solutions, directed energy systems, and passive defense measures. Each category offers advantages against specific threat scenarios while carrying inherent limitations. The categories can also be distinguished along the soft-kill versus hard-kill axis: electronic warfare is a soft-kill approach that defeats the control or

guidance link without physically destroying the platform, whereas kinetic interception and directed energy are hard-kill approaches that physically damage or destroy the drone; passive measures act largely by denial and obstruction rather than engagement. This distinction, together with the underlying detection-to-engagement (kill-chain) requirement common to all active categories, is used in the comparative evaluation of Section 5.

4.1 Electronic Warfare Measures

Electronic warfare (EW) systems constitute the first defense layer developed against FPV drones and are among the most widely deployed. The fundamental operating principle involves severing the radio frequency link between the drone and its operator, causing loss of control. A standard FPV drone whose control signal is severed either crashes to the ground or remains suspended in the air until its battery is depleted.

Among the EW systems reported in field applications, the Volnorez (Russia) is a portable jamming system operating between 900 MHz and 3 000 MHz. The 13 kg device can be mounted on armored vehicles via magnetic attachment and creates a 360-degree protective dome (Fig. 2). The frequency bands of the system were verified from captured units analyzed in 2024 [2]. Following the identification of vulnerabilities in Volnorez's field performance, a different EW system designated Saniya (Russia) was introduced, offering a detection range of 1.5 km and a jamming range of 1 km [2]. The Multik system, produced by the Gradient Research Institute (Russia), was developed to protect helicopters from FPV drone attacks, operating between 700 MHz and 6 000 MHz with three simultaneous jamming channels providing 360° azimuth coverage [2].

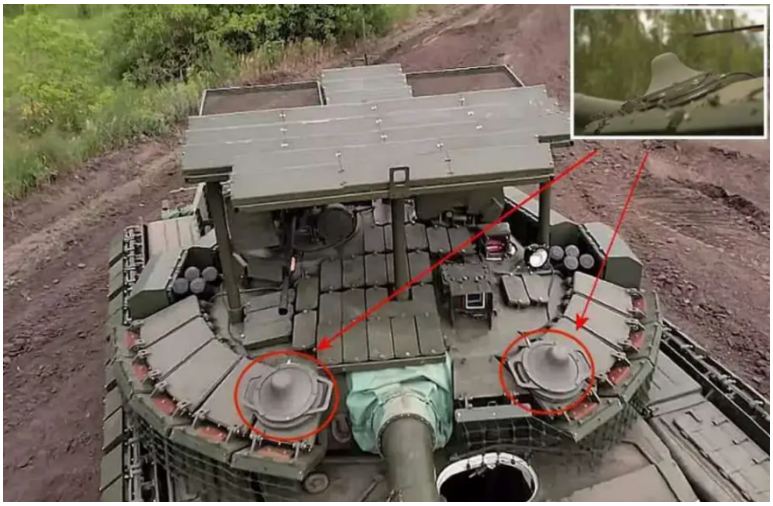


Fig. 2 Volnorez electronic warfare system

Updated counter-UAS doctrines mandating that every battalion and platoon carry at least one electronic countermeasure have extended EW measures down to the individual soldier level [2]. Portable jamming domes such as Volnorez and Rubezh (Russia) have been distributed to forward-deployed infantry units, and drone suppression tasks have been integrated into joint tactical planning. At a larger scale,

networked EW defense projects such as the Atlas system have emerged, aiming to provide continuous counter-UAS coverage through interconnected jamming nodes spanning hundreds of kilometers [2]. Dedicated organizational structures for unmanned systems operations have also been established, tasked with coordinating reconnaissance, strike, and counter-drone operations [2].

A tactical challenge in the EW domain is the rapid adaptation cycle of FPV drone operators. As jamming systems target specific frequency bands, operators respond by shifting to alternative frequencies, employing frequency-hopping spread spectrum techniques, or increasing transmission power. The resulting adaptation dynamic means that EW systems require regular software updates to remain effective, and a system optimized against one frequency profile may be ineffective against a modified drone operating on a different band [1]. RF jamming systems also carry structural limitations beyond frequency adaptation. Jamming signals can adversely affect friendly force communication and navigation systems while neutralizing adversary drones. Jamming devices can be detected by radio direction finders due to their RF emissions, enabling position identification and targeting. The principal constraint is the ineffectiveness of these systems against fiber-optic-controlled FPV drones, as control signals transmitted through fiber-optic cable produce no airborne RF emission to be jammed [6, 7].

4.2 Kinetic Interception Solutions

Kinetic interception solutions aim to physically destroy the drone body rather than sever its control link, thereby offering effectiveness against all drone types regardless of guidance method.

Among specialized ammunition solutions, 5.56 mm caliber anti-drone cartridges represent an emerging capability that leverages existing infantry weapons without modification. The 5.56 mm L-variant Drone Round, developed by Drone Round Defense (USA), fragments into five projectiles after leaving the barrel, creating a shotgun-like dispersion pattern that increases the probability of hitting fast and agile drones at ranges up to approximately 100 meters (Fig. 3). In April 2026, infantry soldiers conducted live-fire familiarization training with this ammunition at a military training facility, successfully engaging FPV drone targets [13]. Comparable multi-projectile cartridges in other calibers have also been developed independently by multiple manufacturers [14].



Fig. 3 Anti-drone 5.56 mm *ammunition*

In the interceptor drone domain, the Yolka (Elka) system (Ukraine) is among the most frequently reported systems in field conditions. The 1.3 kg device is launched from a pistol-type launcher (Fig. 4) and autonomously homes on its target using an AI-powered visual tracking system. Reaching speeds of 230 km/h, Yolka carries no explosive warhead and destroys the target through kinetic impact via a reinforced nose section. As it uses no control channel, the system is unaffected by EW systems. As of April 2026, its active use in both infantry protection and infrastructure defense has been verified through documented field deployments. Official operating manuals indicate that the system operates in daytime and dry weather conditions, requires a clear sky background for target lock, and its materials require careful handling [2].



Fig. 4 Yolka interceptor drone [15]

Beyond Yolka, a broader ecosystem of interceptor drones has emerged. Several models have been developed specifically to counter loitering munitions, including jet-powered variants (130–309 km/h), 3D-printed FPV-guided interceptors, and mass-produced models manufactured through international partnerships at rates exceeding 2 000 units per month [14]. While these interceptors are primarily designed against larger loitering munitions rather than FPV-class targets, the same AI-assisted visual tracking and autonomous terminal engagement technology is also used against FPV-class targets.

Net guns also represent a kinetic solution employed against fiber-optic FPV drones in the field. Devices that launch nets opening to 3.5 m to 4 m in width have been in use since late 2025, though their single-shot nature and long reload time constitute a significant operational disadvantage [2]. Smart optics solutions such as the SMASH 2000L (Smart Shooter, Israel) rifle-mounted fire control system provide another approach, using computerized target tracking to calculate a firing solution against small UAS targets and enabling standard rifles to engage drones with conventional ammunition at improved hit probabilities [14].

Beyond man-portable small arms, a broader spectrum of gun-based kinetic effectors is being adapted to the counter-FPV role, scaling up in both caliber and fire-

control sophistication. General-purpose 7.62 mm and heavy 12.7 mm machine guns extend projectile energy and reach relative to 5.56 mm cartridges, but their single-shot hit probability against small, agile targets remains low unless paired with the computerized fire-control optics described above. At the upper end of the caliber range, automatic cannons in the 20–35 mm class fire programmable air-burst munitions, which detonate a dispersing cloud of sub-projectiles at a computed point near the target and thereby compensate for the low single-shot hit probability inherent to small-UAS engagement. Such cannons form the core of dedicated short-range air defense (SHORAD) gun systems and of remotely operated weapon stations (RWS) mounted on armored vehicles (for example, 35 mm air-burst gun systems of the German Skynex class), which combine radar or electro-optical cueing, automatic tracking, and stabilized fire to engage drones out to effective ranges on the order of 2–4 km. These crew-served and vehicle-mounted effectors extend engagement ranges beyond the roughly 100 m limit of individual-weapon countermeasures.

The majority of solutions presented within NATO's 16th Innovation Challenge were also physical destruction-oriented. AI-powered autonomous turrets featured wide elevation and azimuth ranges, thermal optics, and automatic tracking capabilities. The first-place winner was the modular radar solution by KMB Telematics, the second-place winner was Sentradel's autonomous turret system integrating sensor fusion and AI-driven fire control, and third place went to a stabilized Remote Weapon Station developed by the DONS team [6]. The main limitation of kinetic solutions lies in the risk of saturation in dense drone swarm scenarios due to per-unit engagement requirements. These approaches, which require a separate munition, interceptor, or engagement cycle for each target, face scalability challenges against large numbers of simultaneous threats. Directed energy systems capable of neutralizing multiple targets in a single engagement are examined in the next section.

4.3 Directed Energy Systems

Directed energy weapons aim to address the scalability limitations of kinetic solutions by offering low cost per engagement and unlimited magazine capacity in counter-drone defense. These systems can be examined in two subcategories: high-power microwave (HPM) and laser-based systems.

Among HPM systems, the Leonidas system developed by Epirus (USA) is one of the most frequently reported examples in the field (Fig. 5). Employing gallium nitride (GaN) semiconductor transistors instead of conventional magnetron vacuum tubes, the system can optimize waveform for increased range and perform friend-or-foe discrimination through its software-defined architecture. Unlike conventional jamming, which targets the drone's RF communication link, HPM delivers a physics-layer kill by inducing irreversible damage to onboard semiconductor components, including MOSFET gate oxide breakdown and CMOS latchup, regardless of whether the drone uses RF, fiber-optic, or autonomous guidance [11]. A reported result of Leonidas was the successful neutralization of a fiber-optic-controlled FPV drone during a live-fire demonstration in December 2025 at a government testing site. Targeting the electronic components within the drone body rather than its RF link, the system was described by Epirus as the first counter-UAS technology to defeat fiber-optic drones through weaponized electromagnetic interference [11]. In a separate demonstration on August 26, 2025, at a testing facility (results announced on September 10, 2025), the system neutralized an entire formation of 49 drones in a single engagement across five opera-

tionally relevant flight scenarios, achieving a 100 % success rate against 61 total drones [16]. A $66.1 million IFPC-HPM contract was awarded in January 2023, with four prototypes delivered by March 2024. In July 2025, an additional $43.5 million contract was awarded by a defense rapid capabilities office for two second-generation Leonidas systems, which are expected to more than double operational range and lethality [16].



Fig. 5 Epirus Leonidas HPM (High Power Microwave Anti Drone System) [17]

Laser weapon systems constitute the other component of the directed energy category. The 60 kW HELIOS (High Energy Laser with Integrated Optical-dazzler and Surveillance) system developed by Lockheed Martin (USA) was integrated onto a naval destroyer and successfully neutralized four drone targets during a naval counter-UAS demonstration at sea, as disclosed by Lockheed Martin CEO James Taiclet during the company's Q4 2025 earnings call in January 2026 [18]. The system operates in conjunction with the ship's radar and fire control infrastructure through direct integration with the Aegis Combat System. The DragonFire laser system (United Kingdom), developed by the MBDA, QinetiQ, and Leonardo consortium, destroyed drones flying at speeds of up to 650 km/h during trials in 2025 (Fig. 6), and the procuring ministry of defense stated that the system demonstrated engagement accuracy sufficient to strike targets the size of a £1 coin at one kilometer range. With a £316 million production contract awarded in November 2025, two DragonFire fits are planned for naval destroyers, with the first ship integration scheduled before the end of 2027. The energy cost per engagement is approximately £10, compared with approximately £1 million per conventional interceptor missile [19].

The principal advantages of directed energy systems include low cost per engagement, unlimited magazine capacity, and multi-target engagement capability in HPM systems. Laser systems offer engagement at the speed of light, though they can engage only a single target at a time, require sustained dwell time on each target to inflict sufficient thermal damage, and experience performance degradation in fog, rain, and dusty conditions due to atmospheric attenuation of the laser beam. HPM systems carry the risk of position detection due to their high-power RF emissions and are currently limited in effective range compared to laser systems.

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Fig. 6 DragonFire laser [20]

4.4 Passive and Physical Defense Measures

In addition to active defense systems, low-cost passive measures also constitute an additional defense layer against the FPV drone threat. The system known as the anti-drone curtain is constructed by adding vertical rope segments to a horizontally stretched line; the drone's propellers become entangled in the ropes, causing loss of control or a crash. These ropes are nearly invisible to the operator at the drone's flight speed and can be applied to wide areas at low cost [2]. Protective cage structures (commonly referred to as cope cages or slat armor) mounted on armored vehicles aim to detonate the drone's warhead before it reaches the vehicle's armor, thereby reducing damage effect. Originally designed to counter rocket-propelled grenades, cope cages have been adapted for the FPV drone threat and have become a standard feature on armored vehicles deployed in active conflict zones [1]. Shaped-charge warheads optimized for top-attack profiles can still penetrate the cage structure at favorable angles.

At the field fortification level, a range of passive countermeasures have been developed through field experience. Measures such as adding bends to trench entrances, preparing anti-drone niches where personnel can shelter during an attack, positioning irregularly shaped camouflage netting at a set distance from equipment, and creating decoy positions with false thermal and visual signatures all complicate target identification by drone operators [2]. The construction of anti-drone tunnels (extended overhead netting structures covering roads and supply routes) has been adopted as a passive defense measure. In early 2025, multi-kilometer tunnels of nets were reported to have been installed along contested supply routes to protect vehicle movement [14]. Multiple armed forces have adopted this technique to create protected corridors through areas of dense FPV drone activity (Fig. 7).



Fig. 7 Anti-drone net

Against fiber-optic FPV drones specifically, physical countermeasures targeting the cable itself have been tested in field conditions. Applications in which stretched barbed wire lines are vibrated by battery-driven motors to sever the fiber-optic cable or damage the propeller system represent a low-cost adaptation to this specific threat variant [2]. Electronic decoys that generate false thermal and RF signatures to divert drone operators from actual targets represent another passive approach, though their effectiveness depends on the operator's experience and the quality of the decoy presentation.

The main advantages of passive measures are their low cost, ease of application, and energy independence. These methods, which carry no risk of electronic or mechanical failure, can function as the last line of defense when active systems are disabled. Their main limitations are the ability to protect only fixed or semi-fixed positions, limited applicability for maneuvering forces, the labor investment required for installation and maintenance (as demonstrated by the multi-kilometer netting tunnels), and the inability to guarantee that the drone encounters a physical obstacle before reaching its target.

5 Comparative Evaluation

Each countermeasure category examined in the preceding sections offers advantages in specific threat scenarios while proving inadequate under different conditions. Tab. 2 presents a comparison of the four fundamental categories across principal parameters, incorporating quantitative cost data where available from verified sources.

The comparative ratings in Tab. 2 are assigned on a defined three-level ordinal scale rather than as free-form descriptors. For a given parameter, "High" denotes that the category satisfies the requirement across most representative conditions, "Moderate" (or "Limited") that it does so only under favorable conditions or with significant constraints, and "Low"/"Ineffective" that it largely fails to meet the requirement. To make the ratings comparable across categories with fundamentally different operating principles, each is anchored to indicative quantitative measures where data permit: effectiveness in terms of single-engagement neutralization capability, swarm capacity in terms of the number of targets addressable within one engagement window, cost in

US dollars per engagement, and effective range in kilometers. Two reference scenarios bound the assessment: (S1) protection of a dismounted or lightly mechanized frontline unit against single or small numbers of FPV drones in open terrain, and (S2) point defense of a fixed high-value asset against a coordinated multi-drone (swarm) attack. Where a category behaves differently across the two scenarios, the rating reflects its better-supported case and the divergence is noted in the discussion. Because several figures derive from manufacturer-reported or test-range data (Section 6), the ratings should be read as relative ordinal comparisons rather than as validated operational probabilities of kill.

Tab. 2 Comparison of counter-FPV defense approaches

Parameter	Electronic Warfare	Kinetic Interception	Directed Energy	Passive Defense
Effectiveness vs. RF Drones	High	High	High	Moderate
Effectiveness vs. Fiber-Optic Drones	Ineffective	High	High (HPM)	Limited
Capacity vs. Drone Swarms	High (area effect)	Low (1-to-1)	High (HPM: 49+ simultaneous)	Low
Est. Cost per Engagement	~$0 (energy only)	$50-$2 500 per unit	~$13 (laser); energy only (HPM)	$0 (no consumable)
Impact on Friendly Systems	Adverse (GPS/comms)	None	Limited (HPM side-lobes)	None
Position Disclosure Risk	High (RF emission)	Moderate (visual/acoustic)	High (HPM RF emission)	None
Weather Dependency	Low	Moderate (wind/visibility)	High (Laser: fog/rain)	Low
Effective Range (representative)	~1–1.5 km (point); networked area	~0.1 km (small arms) to 2–4 km (cannon/SHORAD)	HPM: short-range (asset); Laser: ~1+ km	N/A (fixed barrier)

Tab. 2 data compiled from sources referenced in Section 4. Cost estimates: laser per-engagement cost from DragonFire procurement statement (~£10 ≈ $13) [19]; kinetic per-unit cost range covers anti-drone cartridges (~$50) through interceptor drones (~$1 000-$2 500) [1, 13]; EW and HPM engagement costs reflect energy expenditure only, excluding system acquisition. HPM swarm capacity figure based on Leonidas 49-drone demonstration [16]. Qualitative ratings follow the three-level ordinal scale and the two reference scenarios (S1, S2) defined in the preceding paragraph;

effective-range figures are representative open-source values and should be treated as order-of-magnitude indicators rather than guaranteed performance.

Saniya was introduced following performance shortfalls identified in the Volnorez system, and the Atlas networked EW project was developed subsequently [2].

While the Yolka interceptor drone has demonstrated verified effectiveness under combat conditions, its operational capacity limited to daytime and dry weather conditions constrains operational flexibility [2]. The single-shot nature and long reload time of net guns, and the limited effective range of anti-drone cartridges (~100 m), are reported limitations of the same kind.

The neutralization of a 49-drone formation by Leonidas in a single engagement [16] and its reported defeat of a fiber-optic drone [11] are the principal reported results in this category; both demonstrations occurred under controlled test conditions rather than operational combat environments. The effective range of current HPM systems has not been publicly disclosed. The per-engagement costs reported in the HELIOS [19] and DragonFire [19] tests are given above.

Verified field data reveal that passive measures serve as a last line of defense within a layered defense architecture [2].

6 Discussion and Limitations

Several aspects of the counter-FPV defense domain are addressed below. First, this study primarily addresses countermeasures against operator-controlled FPV drones; the emerging trend of AI-powered autonomous guidance represents an additional threat vector. Machine vision systems that store a target's image and maintain lock through visual recognition algorithms are already deployed in limited numbers in active conflict zones [14]. Such systems require no external guidance signal in their terminal phase; RF jamming and fiber-optic-link countermeasures therefore have no control link to target in that phase.

Second, acoustic detection methods, which are used for detecting small drones through propeller noise signatures, are not examined in this study as a distinct countermeasure category due to the limited availability of peer-reviewed field data on their operational effectiveness against FPV-class targets. Acoustic sensors may complement radar and electro-optical detection systems, particularly in cluttered urban environments where RF and radar-based detection face challenges. Third, the legal and ethical dimensions of autonomous counter-drone systems, particularly regarding AI-powered turrets operating in or near populated areas, lie beyond the technical scope of this review.

The primary limitation of this study is the reliance on manufacturer-reported performance data for several systems, particularly the Epirus Leonidas demonstrations [11, 16] and the HELIOS sea trials [18]. While these claims are corroborated by institutional endorsements, independent third-party verification under contested operational conditions remains limited. A distinction should be drawn between test-range demonstrations against cooperative targets and operational performance against evasive, adversary-operated drones in electronically contested environments. The HELIOS four-drone engagement, for example, did not disclose whether the targets approached simultaneously or sequentially, a distinction relevant to performance against saturation attacks. The rapidly evolving nature of ongoing conflicts means that

field data may become outdated quickly, and access to classified operational assessments restricts the depth of analysis possible in an open-source study.

7 Conclusion

FPV drones, owing to their low cost, effectiveness, and continuously evolving technological infrastructure, constitute a threat element on the battlefield.

The introduction of fiber-optic-controlled FPV drones to the battlefield has shown that RF-based EW systems cannot be sufficient on their own. The reported neutralization of a fiber-optic drone by Epirus Leonidas using HPM in December 2025 [11] was described by the manufacturer as a first in the directed energy domain, though operational validation under combat conditions remains to be demonstrated. AI-powered autonomous guidance, which eliminates the need for an external control link, is already deployed in limited numbers [14].

Verified official test results demonstrate that an effective counter-FPV defense cannot rely on a single system or category. According to the reviewed sources, a layered defense architecture combining electronic, kinetic, directed energy, and passive measures covers the identified threat dimensions most completely. Future research should focus on the integration of AI-powered autonomous counter-drone systems, the development of standardized evaluation frameworks applicable to operational conditions [5], and the assessment of directed energy systems under realistic combat environments.

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