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CHALLENGES OF DRONE-DELIVERED EXPLOSIVE ORDNANCE: TECHNICAL, OPERATIONAL, AND LEGAL-ETHICAL CONSIDERATIONS

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Abstract: *The rapid proliferation of unmanned aerial systems, commonly referred to as drones, has introduced significant transformations in modern military and security environments. Among the most concerning developments is the adaptation of drones for delivering explosive ordnance. The key challenges associated with drone-delivered explosive systems are analysed, focusing on technical aspects, operational complexities, and legal-ethical implications. The vulnerabilities are identified in navigation, payload integration, and countermeasure susceptibility, while also addressing issues related to command and control in contested environments. Furthermore, the ambiguity in international humanitarian law is explored regarding the classification and use of such systems, as well as ethical concerns related to autonomy and accountability. The findings suggest that while drone-based delivery of explosives offers tactical advantages, it simultaneously introduces significant risks that require multidisciplinary regulatory and technological responses.*

Keywords: *drones, explosive ordnance, military technology, ethics, international law.*

1. INTRODUCTION

The integration of explosive payloads into unmanned aerial systems represents a revolutionary shift in the diffusion of air power [1,2]. While high-end military platforms like the Predator and Reaper dominated the early 21st century, the current landscape is defined by the pervasive use of small, attainable, and often improvised systems [2,3]. This evolution presents a research problem rooted in the rapid pace of innovation outpacing existing regulatory and defensive frameworks [4]. The widespread availability of small, commercially available drones has blurred the line between recreational and tactical use, creating new security vulnerabilities [5,6].

The research problem is defined by the critical necessity to identify and investigate the technical, operational, and legal-ethical considerations that constitute the fundamental challenges of drone-delivered explosive ordnance within modern tactical environments.

The subject of research is the tripartite set of challenges: technical, operational, and legal-ethical inherent in the deployment of drone-delivered explosive ordnance. This includes both purpose-built loitering munitions, designed to engage targets beyond the line of sight, and modified commercial drones used for gravity-drop or one-way "kamikaze" strikes [3].

The aim of the research is been to provide an analysis of the risks these systems pose to both military operations and civilian security. By examining recent conflict, intends of research is to discover the blurring lines between hobbyist technology and lethal weaponry necessitates.

The scientific methods employed include an documents analysis of open sources, a comparative analysis of drone employment in recent conflicts (Ukraine and Nagorno-Karabakh), and a systematic literature review of current engineering and legal frameworks [2].

2. TECHNICAL CHALLENGES

The application of unmanned aerial systems for the delivery of explosive payloads is constrained by a series of critical technical barriers that directly impact precision, reliability, and survivability on the battlefield. These challenges range from the physical limitations of the platform to the inherent vulnerabilities of its digital architecture.

2.1. Platform, Energy, and Payload Constraints

The fundamental performance of a drone-delivered

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explosive system is dictated by its energy density and weight-to-power ratio. Most commercial-grade multicopters rely on lithium-polymer batteries, which typically restrict flight endurance to approximately 20 to 40 minutes [7,8]. The introduction of an explosive payload introduces an engineering paradox: for multirotor systems, energy consumption increases approximately linearly with the combined weight of the battery and the payload [9]. Consequently, increasing battery mass to extend operational range paradoxically reduces the remaining capacity available for explosives, forcing a tactical compromise between lethality and mission radius [8,9]. Furthermore, environmental factors such as wind speed and cold temperatures can drastically degrade battery efficiency, further limiting the system's predictability in adverse weather [8].

2.2. Navigation and Communication Vulnerabilities

Drone-delivered explosive ordnance systems rely heavily on Global Navigation Satellite Systems, such as Global Positioning System, for waypoint navigation and terminal guidance. These signals are highly susceptible to electronic warfare, specifically jamming and spoofing [10,11]. A loss of Global Navigation Satellite Systems signal can cause a drone to "go rogue," lose its return-to-home function, or crash uncontrollably with a live warhead [10]. To circumvent radio frequency interference, emerging systems utilize fiber-optic control, which maintains a physical link to the operator via a spool of lightweight cable [4]. While these links are immune to jamming, they introduce new physical hazards, such as the spool snagging on obstacles or the creation of long-lasting debris fields of non-biodegradable spent fiber on the battlefield [4].

2.3. Payload Integration and Armament Engineering

Adapting a civilian drone to carry munitions requires precise structural engineering to maintain the centre of gravity. An improperly balanced payload can cause excessive stalling or aggressive diving, which rapidly depletes battery endurance [10]. The release mechanism must be robust enough to prevent contact with the landing gear during deployment, while also providing real-time feedback to the operator to confirm delivery [12]. The use of 3D-printed munitions cases has enabled rapid customization for specific mission sets [12,13]. However, 3D printing introduces uncertainties regarding material strength and consistency; structural failures can lead to catastrophic premature detonations during flight or handling [12].

2.4. Detectability and Countermeasure Resistance

Small unmanned aerial systems platforms often operate at low altitudes and speeds, making them difficult to detect with traditional air defence systems designed for larger aircraft [13]. Their low radar cross-section and minimal thermal signatures allow them to bypass standard radar and infrared detection [13]. However, they remain vulnerable to acoustic sensors that track the high-speed rotation of propeller blades and to specialized anti-drone systems, such as high-energy lasers or radar-guided shotgun attachments [10]. As defences evolve, the technical challenge shifts toward autonomous swarm coordination, where multiple drones must jointly navigate and synchronize attacks to overwhelm defensive capacities through sheer saturation [14].

3. OPERATIONAL CHALLENGES

The operationalization of drone-delivered explosive ordnance has moved beyond high-end military platforms to include decentralized, low-cost assets that rewrite traditional combat doctrines [6]. While these systems offer unprecedented tactical flexibility, their deployment introduces significant operational hurdles.

3.1. Command, Control, and Signal Vulnerability

The core operational bottleneck is the stability of Command and Control links. Most commercial-grade drones rely on radio frequency bands (2.4 GHz and 5.8 GHz), which are highly susceptible to electronic warfare (EW) [4]. In active conflict zones, mobile jamming systems like the Russian R-330Zh can disrupt control signals within a 50 km range, causing drones to lose their return-to-home function or crash with live payloads [4,13]. To mitigate this, operators have adapted through the use of fiber-optic control links, which provide unjammable, low-latency video feedback but introduce new physical hazards such as cable snags and the creation of non-biodegradable debris fields on the battlefield [4].

3.2. Proliferation and Decentralized Logistics

The shift toward decentralized "garage workshops" for assembling First Person View and one-way attack drones makes proliferation nearly impossible to control [6,11]. Unlike traditional military procurement, these systems are often crowdsourced and modified on an industrial scale by volunteers using off-the-shelf components [6,15]. This democratization of air power allows non-state actors and small units to bypass legacy defence measures and conduct precision strikes that once required multi-million dollar platforms [6]. However, this lacks the standardized safety and storage protocols of conventional munitions, increasing the risk of accidents during transport and handling [12].

3.3. Information Overload and Human-Machine Interaction

Operating drone-delivered explosive ordnance systems is labour-intensive and cognitively demanding. While a single Predator mission can require 168 personnel to manage data and flight, small-unit operators face a different set of pressures [2]. The sheer volume of real-time sensor data can lead to information overload, where operators must process high-definition video feeds while managing flight parameters in high-stress environments [1]. This "Playstation mentality" can distance operators from the human cost of a strike, yet the graphic nature of 4K drone footage often leads to burnout and PTSD as pilots watch their strikes impact in gruesome detail [16].

3.4. Swarm Coordination and Airspace Saturation

The trend toward autonomous drone swarms poses the challenge of saturating enemy defences through sheer numbers [14,17]. Coordinated attacks involving dozens of units require distributed network protocols and artificial intelligence assisted pathfinding to avoid collisions and allocate targets dynamically [4,5]. This introduces "machine speed" into the kill chain, potentially outstripping the human operator's ability to critically scrutinize machine-prompted targets in time-constrained environments [24].

3.5. Psychological Impact and Morale

The constant presence of loitering drones creates a pervasive sense of "lethal voyeurism" [15]. The buzzing of rotors acts as a psychological weapon, inducing terror among troops and civilians alike, as flights often foreshadow imminent kinetic strikes [18]. This paralysis of movement can hamper ground operations for hours, even when the drones are unarmed or carrying dummy payloads [18].

4. LEGAL-ETHICAL CONSIDERATIONS

The rapid deployment of drone-delivered explosive ordnance, particularly loitering munitions and FPV systems, has created a significant disconnect between technological capability and existing regulatory architectures [1,3]. As these systems increasingly integrate artificial intelligence and automated functions, they challenge the foundational principles of International Humanitarian Law and raise profound ethical questions regarding the future of human agency in warfare [1,3].

4.1. Compliance with International Humanitarian Law

The use of drone-delivered explosive ordnance must be scrutinized under the "cardinal principles" of International Humanitarian Law: distinction, proportionality, and precautions in attack [1,2]. The principle of distinction requires belligerents to differentiate between combatants and civilians [1,2]. Increasingly autonomous loitering munitions may struggle with this mandate, as algorithms may not independently distinguish between a legitimate military target and a civilian object, especially in "cluttered" urban environments where identities are fluid [1,5,17]. Furthermore, identifying combatants who are hors de combat (incapacitated) remains a critical technical and legal challenge for sensor-based systems [17].

The principle of proportionality prohibits attacks where expected incidental loss of civilian life is excessive relative to the anticipated military advantage [1,2]. Because International Humanitarian Law lacks objective criteria for value-based proportionality assessments, the shift toward real-time, machine-led targeting increases the risk of "black-box" decisions where the logic behind a strike cannot be audited or explained [1,17]. This unpredictability is compounded by signature strikes, which target individuals based on "patterns of life" rather than identified status, often leading to tragic identification errors [2,15].

4.2. Accountability and the Problem of Secrecy

Determining legal responsibility for unlawful drone strikes is complex due to the fragmented nature of drone operations, which may involve pilots, sensor operators, intelligence analysts, and even private contractors [2,15]. A major concern is the accountability gap created by covert programs, such as those operated by the CIA, where secrecy prevents judicial review and public debate over the legality of targeted killings [2,15]. When autonomous systems are involved, it becomes unclear whether criminal responsibility lies with the operator, the commander, or the software developer [1,5,17].

4.3. Ethical Implications and Human Dignity

Beyond legalities, the "action-at-a-distance" nature of drone warfare introduces the "Playstation mentality," which can distance operators from the human consequences of their actions [15]. Ethicists argue that delegating life-and-death decisions to algorithms constitutes a "moral hazard" that denies the human dignity of the victim [6,17]. The constant presence of drones in conflict zones induces a state of lethal voyeurism, where the buzzing of rotors acts as a psychological weapon, sowing terror and anxiety among civilian populations who feel powerless under an all-seeing "martial gaze" [6,17].

4.4. Proliferation and the Need for New Treaties

The dual use nature of drone technology serving both humanitarian and military ends complicates global regulation [1,16]. There is a growing international consensus that the existing International Humanitarian Law framework is inadequate for grappling with autonomous lethality [1,5]. Scholars and organizations such as the ICRC advocate for a new legally binding international treaty to establish clear prohibitions on fully autonomous weapons and to ensure that meaningful human control is affirmed and retained in every specific targeting decision [1,17].

5. DISCUSSION

The analysis demonstrates that drone-delivered explosive systems represent a convergence of technological innovation and emerging security threats. While they offer operational advantages such as reduced risk to personnel and increased flexibility, they also introduce vulnerabilities and uncertainties.

Addressing these challenges requires an integrated approach involving technological development, doctrinal adaptation, and legal reform.

6. CONCLUSION

Drone-delivered explosive ordnance presents a multifaceted challenge that spans engineering, military operations, and international law.

Technically, limitations in navigation, payload integration, and resilience reduce system reliability. Operationally, issues related to control, accuracy, and proliferation complicate their effective use. Legally and ethically, the absence of clear regulatory frameworks raises concerns

about accountability and compliance with established norms.

Future research should focus on improving system robustness, developing countermeasures, and establishing comprehensive international regulations governing the use of such technologies references.

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