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Countering Unmanned Aerial Systems (UAS) in military operations

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Abstract

Although contemporary unmanned systems are used in every environment, they overwhelmingly dominate the airspace. They are commonly called aerial drones or unmanned aerial vehicles (UAVs), while the systems supporting and controlling UAVs are called unmanned aerial systems (UASs). The widespread adoption of aerial drone technology has led to their increasing use on the battlefield. Therefore, finding an effective counter-drone (counter – UAS) weapon has become a serious challenge. This task is particularly difficult because we are dealing with a huge variety of unmanned aerial systems while their numbers are increasing at a record-breaking pace. At this point, there are also no fully proven counter-drone solutions, with most existing systems still in the research phase or newly introduced prototypes. The emerging problems and the set of uncertainties associated with them have become the fundamental basis for addressing and presenting this issue in this publication. This article discusses the crucial subject of defense against unmanned aerial systems from the perspective of modern warfare. The author addresses the question of how to plan and implement counter-drone defense in military operations, as well as what technical solutions could be useful for this purpose. Throughout this study, the author employed various methods, including analysis, synthesis, comparison, and case studies, primarily by examining available open-source information on recent armed conflicts in Nagorno-Karabakh and the ongoing conflict in Ukraine. These methods enabled the author to validate his main hypothesis: there are currently no effective drone countermeasures systems, particularly against drones that can operate autonomously, utilize artificial intelligence algorithms for guidance and decision-making, or engage in large-scale attacks, known as swarms. Simultaneously, the author points out what new technical solutions should be developed to enable effective countermeasures and what tactics should be incorporated into military training to address this threat. Additionally, the article discusses to what extent existing air defense systems can be adapted for counter-drone defense and whether there are effective methods of force protection against such threats.

Keywords: air defense, air drones, counter-drone defense, safety, UAS, UAV

1. Introduction

The conflicts in Nagorno-Karabakh (Hecht, 2022) and Ukraine (Wyrwał, 2022) allow us to conclude that the widespread use of drones on the battlefield has become a reality that requires no further persuasion. Drones demonstrate their multifunctionality by performing not only observation and reconnaissance tasks but also carrying out strikes, transportation, search and rescue operations, and many others. Currently, we are witnessing the use of both individual and grouped unmanned aerial vehicles, as well as swarms like the Smart Warfighting Array of Reconfigurable Module (SWARM). Moreover, the production costs of most drones are very low, yet their effectiveness is significant enough to successfully destroy high-value targets and advanced military equipment. The diversity of tasks and designs of unmanned systems necessitates an effective counterbalance, including counter-drone systems and counter-drone defence methods. In this regard, the subject of research has focused on counter-drone defense, understood as a set of measures and combat capabilities aimed at detecting, identifying, and neutralizing drones (unmanned aerial systems) to protect own troops, military installations, and civilian objects.

Due to the vast diversity of existing drone designs, a generalization method was employed to identify representative drone types, their missions, and flight characteristics (Časar, et. al., 2023). For this purpose, a three-level NATO classification model was adopted. Subsequently, this allowed for estimating the potential effectiveness of existing counter-drone systems in combating the specified drone classes. In order to achieve this, an analysis of currently operational counter-drone systems was conducted, taking into account their two main functions: monitoring airspace and engaging aerial targets. As a result, their capabilities and limitations in countering drones were identified. It reaffirmed the author's belief that contemporary counter-drone systems are capable, to a limited extent, of neutralizing Class 1 drones, namely Mini, Micro and Small drones. Unfortunately, they are not capable of simultaneously engaging large groups of drones and their swarms. Currently, there are also no specialized counter-drone systems that allow for the engagement of Class 2 and 3 drones. These tasks are only performed by air-defense systems, which entail enormous, often disproportionately high costs. In search of solutions to this problem, the author presented the potential of future anti-drone systems utilizing Directed Energy Weapons (DEW) as well as new military tactics that should be employed until more effective counter-drone systems are introduced. The author also advocates that effective anti-drone defense must be multi-layered, involving various types of counter-drone systems that can interact with different classes of drones. Only the proper saturation of such systems will allow for the uninterrupted execution of tasks by military forces on land and at sea. He also assumed that the development of counter-drone defense should be perceived as a continuous process, during which dynamic responses to changes in the environment and new technological advancements should be made. In other words, the presented systemic solutions should feature an open architecture that allows for incorporating changes in situations where new designs, technologies, and capabilities of unmanned aerial platforms emerge.

2. Classification of combat drones

When classifying unmanned aerial vehicles, it is important to consider that they are part of a larger system, which typically consists of one or more remotely controlled unmanned aircraft (UA), operators (both for the aircraft itself and its sensors), navigation and communication systems, Ground Control Stations (GCS), and payloads carried by the unmanned aircraft (such as weapons, reconnaissance sensors, and others) (Gupta, Ghonge, Jawandhiya, 2013). Combat drones can vary in size from insect-like to small airplanes. They can fly at very low altitudes, just above the ground, or loiter at altitudes reaching several to several dozen kilometers. Their ranges can be intercontinental, and their airborne operating time can last for even several dozen days (Michalska, 2020). Of course, all of this depends on the type of drone, its power sources, control capabilities, and intended purpose. This diversity of designs necessitated the need for their organization and, consequently, their classification. This systematization is particularly important from a military standpoint, considering the threats that unmanned aircraft can pose. Military drones can be categorized based on one of the following criteria:

- Type of aircraft;
- Task (missions performed);
- Method of guidance and flight control;
- Tactical and technical parameters (weight, payload capacity, speed, range, altitude, endurance, effective radar cross-section, etc.).

When classifying drones based on the aircraft type (airframe) responsible for generating aerodynamic lift, three types of airframe constructions can be distinguished: fixed-wing, rotary-wing, and flapping wings.

Fixed-wing aircraft, also known as airplanes, have rigid wings. They are the heaviest and largest unmanned aerial vehicles (UAVs), often equipped with jet or turboprop engines. Due to their large wing surfaces, they are capable of carrying heavy payloads and weapons, as well as conducting long-duration surveillance missions. They also have the longest flight ranges and highest operational altitudes.

Rotary-wing drones are the most common type of unmanned aircraft. They rely on the lift generated by rotors. Depending on the number of rotors, they can be tricopters (3), quadcopters (4), hexacopters (6) or octocopters (8) (Gupta, Ghonge, Jawandhiya, 2013). These aircraft have the ability to perform vertical takeoff and landing (VTOL) and hover in the air. Unlike fixed-wing aircraft, they have higher energy demands and are not capable of long-duration flights or carrying heavy payloads (weapons). However, they are widely used due to the prevalence of the technology employed in their construction and their ease of piloting and automatic stabilization in the air.

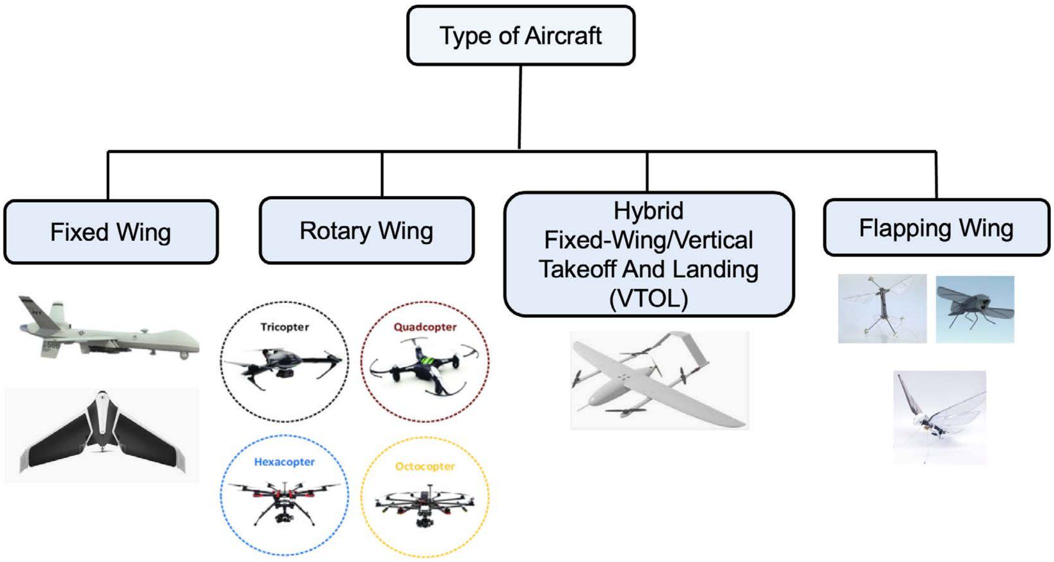


Figure 1. Classification of UAVs – Type of Aircraft, own work

Hybrid drones, which combine fixed-wing and rotary-wing elements, are not as popular as the previous types due to the challenges involved in their piloting. However, they are characterized by both high payload capacity and the ability to hover in the air.

The last group consists of unmanned drones equipped with flapping wings, which mimic the wing movements of birds and insects. These are the smallest and lightest flying structures. Similar to rotary-wing aircraft, they can hover in the air and perform horizontal flights. This group of drones is currently the least developed due to limited technology for miniaturizing lift-generating elements and their high energy consumption required for flight. It is anticipated that micro-drones will primarily be used for reconnaissance and espionage missions, as well as for delivering biological weapons in the form of micro-injections.

The diverse range of **tasks** that unmanned aerial vehicles (UAVs) can perform on the battlefield allows for their classification into three main groups:

- Combat UAVs (CUAVs) used for offensive and combat operations. They are equipped with weapons systems and are designed to engage enemy targets, provide fire support, and conduct airstrikes. These tasks can be accomplished through the delivery or launch of munitions or by conducting suicide missions, also known as kamikaze attacks. Unmanned aerial vehicles that conduct suicide strikes are referred to as Loitering Munitions (LMs). They are equipped with an observation payload that allows for target acquisition and a warhead.
- Reconnaissance UAVs (RUAVs): These are primarily used for intelligence gathering and reconnaissance missions. They are equipped with sensors, cameras, and other surveillance equipment to collect information about enemy positions, terrain, and other relevant data. These drones can store the collected information on data storage devices or transmit it in real-time to ground operators. They are commonly used as elements for target acquisition and fire correction for artillery, other drones, or combat forces.
- Support UAVs (SUAVs): these UAVs are employed in a supportive role to assist ground forces. They can be used for tasks such as communication relays, cargo transport, medical evacuation, electronic warfare, and simulating targets during combat operations and search and rescue missions. Recently, there has also been a trend towards developing multi-role platforms, particularly in the reconnaissance-strike domain.

An important criterion for categorizing aerial drones, especially in terms of countermeasures, is their **guidance methods and flight control**. Drones can be:

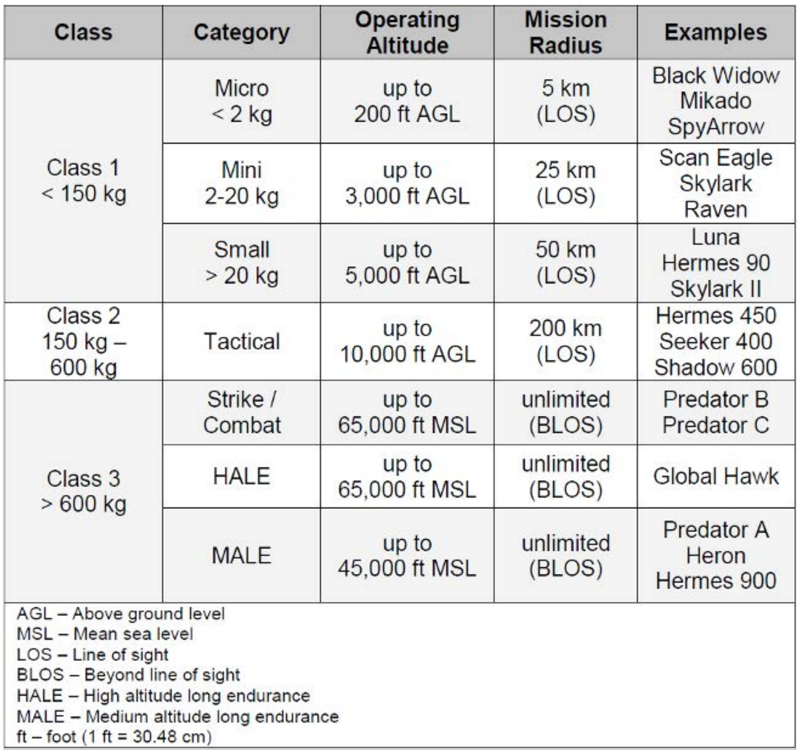
- Remotely piloted using radio transmitters: These drones are controlled by human operators who transmit commands and control signals to the drone using radio communication.
- Guided by GPS and geographic coordinates: Drones can navigate and follow pre-programmed routes based on GPS signals and geographic coordinates. This method allows for accurate positioning and navigation.
- Operated in automatic mode with predefined waypoints and flight parameters: Drones can be programmed to follow specific waypoints and flight parameters, allowing them to operate autonomously along a designated route.

- Controlled using vision systems: Some drones are equipped with cameras and distance sensors that enable them to navigate by visually detecting and avoiding obstacles in their path.
- Autonomous control using artificial intelligence: Drones can utilize artificial intelligence algorithms to make autonomous decisions and navigate independently based on their surroundings and mission objectives.
- Guided by a mother drone: In some cases, drones can be guided by a mother drone that transmits control signals and acts as a guidance system for the other drones, ensuring coordinated flight and navigation.

These various guidance methods offer different levels of control, autonomy, and capabilities, which can affect their susceptibility to countermeasures.

According to **tactical-technical parameters** (weight, payload, speed, range, altitude, flight time, effective radar cross-section, etc.), NATO member states classify unmanned aerial systems (UAS) into three main classes (Table 1).

Table 1. Classification of UAS – Tactical/Technical Parameters



Class	Category	Operating Altitude	Mission Radius	Examples
Class 1 < 150 kg	Micro < 2 kg	up to 200 ft AGL	5 km (LOS)	Black Widow Mikado SpyArrow
	Mini 2-20 kg	up to 3,000 ft AGL	25 km (LOS)	Scan Eagle Skylark Raven
	Small > 20 kg	up to 5,000 ft AGL	50 km (LOS)	Luna Hermes 90 Skylark II
Class 2 150 kg – 600 kg	Tactical	up to 10,000 ft AGL	200 km (LOS)	Hermes 450 Seeker 400 Shadow 600
Class 3 > 600 kg	Strike / Combat	up to 65,000 ft MSL	unlimited (BLOS)	Predator B Predator C
	HALE	up to 65,000 ft MSL	unlimited (BLOS)	Global Hawk
	MALE	up to 45,000 ft MSL	unlimited (BLOS)	Predator A Heron Hermes 900

AGL – Above ground level
MSL – Mean sea level
LOS – Line of sight
BLOS – Beyond line of sight
HALE – High altitude long endurance
MALE – Medium altitude long endurance
ft – foot (1 ft = 30.48 cm)

Source: STANAG 4670 – ATP 3.3.8.1 (2019), Minimum Training Requirements For Unmanned Aircraft Systems (UAS) Operators And Pilots, NATO, Brussels.

It should be noted that the tactical-technical characteristics of modern unmanned aerial systems used for military purposes are diverse and primarily dependent on their intended use.

3. Counter-drone systems

The variety of unmanned aerial vehicle designs utilized in modern warfare necessitates considering various factors when constructing and operating counter-drone systems. Among them, the following characteristics of unmanned aerial vehicles (UAVs) should always be taken into account: propulsion, effective radar cross-section, guidance method, operational ceiling, flight range, airborne endurance, intended purpose, combat capabilities (including the ability to gather intelligence, carry and launch payloads), as well as electromagnetic interference countermeasures.

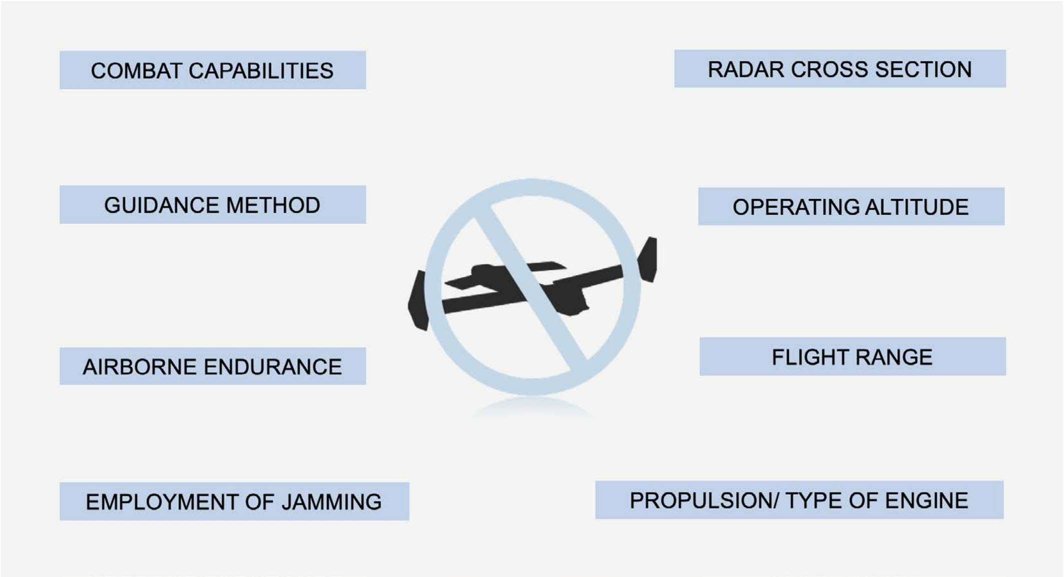


Figure 2. UAS features considered in C-UAS engagement, Own work.

The functioning of counter-drone systems involves the following activities: detection, classification (identification) of objects, tracking, as well as alerting and transmitting information to effectors responsible for their neutralization. Depending on the class of the object, these tasks can be carried out using various systems, sensors, detection and engagement techniques. Currently, counter-drone systems can be classified into two fundamental categories: airspace monitoring systems and countermeasures systems.

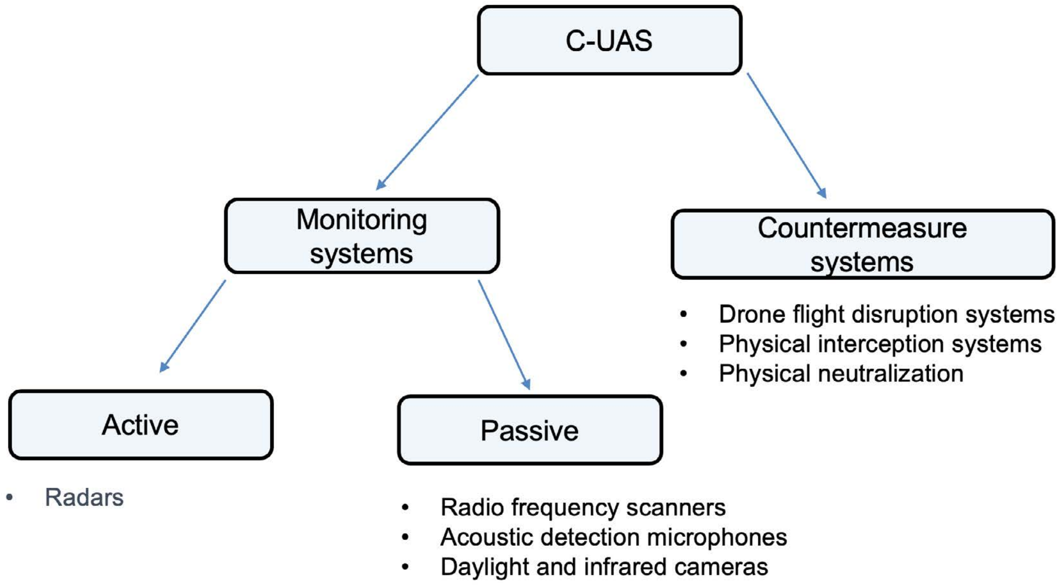


Figure 3. Types of C-UAS engagement, own work

Monitoring systems

Monitoring systems can have both active and passive characteristics. In this regard, there are four main methods of drone detection:

- Electromagnetic wave-based radar systems for airspace surveillance.
- Frequency signal detectors used to detect the radio signals used for drone control.
- Acoustic sensors.
- Optical and optoelectronic devices, including infrared thermal imaging cameras (Holland Michel, 2019).

Most modern drones are made of composites, which results in a very low radar cross section (RCS), making them difficult to detect by radar systems. They can be mistaken for birds since they are typically not equipped with identification systems, intentionally designed that way as drones often operate over enemy territory. As a result, radar information is not always complete and can lead to serious complications, especially when both friendly and enemy drones operate in the same airspace (Holland Michel, 2019). Furthermore, UAVs (Unmanned Aerial Vehicles) can fly at much lower altitudes than airplanes or helicopters and maneuver more freely under the cover of terrain obstacles. Drones are capable of operating from improvised runways and landing sites, and when launching nearby, they can suddenly appear in airspace. All these factors indicate that radar reconnaissance should be considered only as one of the possible methods for drone detection.

Recognition-based counter-drone systems should rely on multiple detectors or sensors, essentially in various combinations and configurations. One such sensor can be frequency signal detectors, allowing for the recognition of drones that communicate with their operators using radio waves. Most remotely controlled drones operate within the frequency range of 2.4 GHz to 5.8 GHz (Wi-Fi frequencies) (Gupta, Ghonge, Jawandhiya, 2013), so monitoring these frequencies can assist in detecting their activity. Some systems based on three sensors can detect the IP addresses of transmitting devices and locate the operators. Another method of drone detection can be tracking their video transmission frequencies. Many drones equipped with cameras transmit live video feeds to their operators. Video transmission frequencies can vary depending on the type of drone, but popular ranges include 2.4 GHz, 1.2 GHz, and 5.1 GHz (Aouladhadj, Kpre, Deniau, Kharchouf, Gransart, Gaquière, 2023). Scanning the radio spectrum is a relatively simple method that does not require significant financial investment, but it can result in false alarms due to other devices using the same frequencies. Frequency signal detectors are typically used against small-range commercial drones controlled within visual range. The advantage is the system's passivity, but there are limitations in tracking within urban environments with a high concentration of radio signals and the inability to detect drones with pre-planned flight trajectories.

Drone detection can also be achieved using **acoustic sensors**. These are typically directional microphones or arrays of microphones that can detect the sound of drones and indicate the direction from which they are approaching. Similar to frequency signal detectors, using at least three microphones is an ideal configuration as it provides a three-dimensional image of the detected target. The advantage of this system is that it is a passive detection method that can be particularly useful in areas where visual and radio visibility is limited, and it can complement other detection systems. These detectors are typically highly mobile due to the lightweight nature of microphone devices. However, a significant limitation of acoustic sensors is their ability to operate in noisy environments, such as urban areas or during strong winds, which can result in a limited detection range of around 300-500 meters (Vashisht, 2021). Additionally, some drones may be equipped with noise reduction technologies, which should be taken into account when using acoustic detectors. Therefore, these detectors should be considered as supportive systems rather than standalone solutions.

Optical sensors, including daylight cameras and infrared cameras, can also be used in the recognition of aerial drones. These devices have the advantage of detecting and identifying drones based on their shapes and recording events involving drones. However, a drawback is that these systems may be rendered ineffective in adverse weather conditions such as fog, heavy rainfall, and sometimes even during nighttime. Additionally, they have a limited field of view for observing the airspace.

A combination of different sensors and monitoring techniques should be employed to increase the effectiveness of drone detection and reduce false alarms. Monitoring systems can have both passive (observing and listening) and active (sending signals towards the object and analyzing its reflection) characteristics (Wang, Song, Liu, 2021). It is worth noting that compared to other sensors, radar systems provide the most data as they can detect targets at significant distances and determine their positions with high accuracy, regardless of weather conditions (observational factors like fog or clouds), time of day or night. However, it should be remembered that the detection range of radar systems will always depend on the size of the drone and its effective radar cross-section.

Countermeasure systems

There are several ways to combat drones in the air. The following system can be used for this purpose:

- Drone flight disruption systems
- Physical interception systems
- Neutralization systems (fire-based, laser-based, electromagnetic-based).

The use of **jamming systems** involves disrupting RF (Radio Frequency) signals and interfering with satellite navigation signals from Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS), GLONASS, Galileo, or BeiDou. RF jamming entails emitting signals at similar frequencies used for communication between the drone and its operator. This can result in the operator losing control, rendering the drone unable to function properly and forcing it to either land automatically or return to its initial takeoff point. Drones often rely on satellite navigation signals to maintain flight direction and stability. Jamming GPS signals can be achieved by emitting strong radio signals within the frequency range the GPS system uses. The consequence can be the drone becoming disoriented in airspace and losing flight control. The advantage of frequency emitter operations is the low cost of neutralizing drones, known as “soft kill”, while the disadvantages include short range and the potential for interference with other devices, including one’s own drones.

Another way to counter drones is through the use of **physical interception systems**. Typically, ground-based net launchers are employed in this case, allowing for the interception and neutralization of drones in flight. Another possibility is using other drones that approach the targeted drone, capture it with a net, and bring it down to the ground. This solution is particularly effective against small drones equipped with rotating propellers and operating at very short distances. Ground-launched nets are effective at distances ranging from 20 to 300 meters (Robin Radar, 2023), while nets deployed from drones significantly affect their weight, manoeuvrability, and airborne time. The reloading and re-launching time for drones equipped with launchers or deployed nets is also lengthy. However, the advantages of net-based systems include high interception accuracy and a low risk of collateral damage.

The last and most commonly used method for combating drones on the battlefield is drone **neutralization**, which involves destroying them during flight. For this purpose, machine guns, shotguns, or rapid-fire small-caliber cannons (artillery) are often employed, which can also serve as anti-aircraft artillery systems. Such firepower can be visually, optically, or radar-guided. Additionally, in terms of the ability to rapidly destroy small-sized aerial targets at short distances, Counter Rocket Artillery and Mortars (C-RAM) systems appear to be ideal. They feature semi-automatic combat modes and a high probability of hitting the target, thanks to the use of programmable ammunition. Among the firepower systems, portable man-portable air defense systems (MANPADS) and short-range anti-aircraft missile systems can also be used (Dura, 2023). However, it is important to note the cost-effectiveness of using such systems, particularly against Class I drones equipped with rotary wings. The production cost of these drones is disproportionately low compared to the potential cost of missiles fired at them. Furthermore, the flight characteristics of such drones, such as low speeds and altitudes, make them easy targets and susceptible to inexpensive, non-specialized firepower.

Among the systems for directly incapacitating drones during flight, the newest solution is weapons based on Directed Energy Weapons (DEW) that utilize beam-focused energy. This can include High Power Microwave (HPM) weapons or High Energy Laser (HEL) weapons. High-power microwave emitters (HPM) generate strong electromagnetic impulses that can destroy the drone’s electronics or disrupt its operations. The advantage of using this type of weaponry is non-kinetic destruction. However, a significant drawback is the requirement for a large amount of energy concentrated in the beam, necessitating the use of large, power-consuming generators, which limits mobility and combat capabilities (US GAO, 2023).

Within the category of high-energy laser weapons (HEL), there are several types, including solid-state lasers (SSLs), chemical lasers (CHEL), and Free Electron Lasers (FEL). Laser weapons operate by converting electrical energy into light energy, which is then concentrated into a narrow laser beam. Compared to conventional firearms, HEL offers several advantages. It has a quick reaction time and rapid engagement speed (the laser beam travels at the speed of light, allowing for immediate target incapacitation), high accuracy due to beam focus on a small surface area, lower costs compared to traditional ammunition, and no moving parts, which reduces maintenance costs and increases reliability (CRS, 2023).

However, it’s worth noting that the development and utilization of HEL weapons come with technological challenges and limitations, such as the effective cooling of laser systems, maintaining beam stability throughout the operational range, generating a sufficiently powerful beam for engaging aerial targets at long distances, and similar to HPM weaponry, the use of large generators with limited mobility (Dąbrowski, 2017).

When it comes to countering aerial drones, it’s important to note that there is no “silver bullet” method that would provide effective drone defense. The significant diversification of unmanned platforms and the wide range of tasks they perform necessitate further specialization of counter-drone systems, utilizing both kinetic and non-kinetic means of combat. Currently, a combination of these methods and the multi-layered approach of employing systems with different detection and neutralization capabilities allows for some degree of mitigation against the threat posed by unmanned platforms, especially the smallest ones. However, the unfortunate reality is that while these systems are effective against very small drones, they are not capable of destroying second and third-class drones operating at high altitudes and long distances. Additionally, they may be ineffective in scenarios involving large groups or swarms of drones, as they lack multi-channel capabilities. Even the most promising drone countermeasures do not allow for scalability and application across a wide range of combat platforms. Despite the lack of clear solutions, the drone countermeasures market is rapidly growing (it is projected to be worth around $14.6 billion by the end of 2031) (Alied Marked Reserch, 2023).

4. Methods to Counter Drones (Counter-Drone Tactics)

When considering possible methods to counter the threats posed by drones, it is necessary to address the current situation, in which it is difficult to speak of counter-drone systems that have been tested in combat conditions. In most cases, civilian systems are adapted, originally designed to protect airports from unauthorized entry by private users who typically operate radio-controlled drones within their visual range. Unfortunately, as previously mentioned, these systems are usually ineffective in a combat environment due to their limited mobility and short operational ranges. Similarly, portable systems such as handheld RF jammers do not prove effective. The maximum range of their disruption is 500-1000 meters, with a battery life of up to 30 minutes. These limitations were quickly recognized, leading to the implementation of tactics involving the deployment of surveillance drones beyond the range of jamming devices. Currently, surveillance drones typically operate at distances exceeding 1000 meters from enemy positions and employ optical or digital zooming for observation purposes. Furthermore, experiences from the Ukrainian conflict demonstrate that drone operators in the field use signal-boosting antennas, further complicating jamming efforts. On the other hand, signal jamming systems for satellite navigation (GPS) prove effective only in selective tactical situations, meaning they can disrupt enemy drone operations when their own unmanned systems are not in use. Therefore, they are more useful for protecting cities and critical infrastructure rather than for direct use on the battlefield. Similarly, it is challenging to disrupt combat drones, as they fly at very low altitudes, high speeds, and utilize terrain cover, making it significantly difficult to direct electromagnetic emitters towards them (Wyrwał, 2022).

The primary means used to neutralize drones on the battlefield are artillery and missile-based anti-aircraft systems. However, it should be noted that, according to their principles of use, these systems are deployed in the rear area of military operations. As a result, the front line of defense remains vulnerable, allowing attacks by drones, particularly those of the smallest **Class 1** category, flying at very low altitudes. In such situations, one of the methods to counter them is to engage them with small-caliber individual firearms (small arms, machine guns, shotguns). However, the effectiveness of such engagement is limited since drones are small, fast, and highly maneuverable targets. Currently, it is also possible to disable the smallest enemy drones using first-person view (FPV) drones controlled by operators wearing goggles that provide a direct view from the drone's perspective. FPV drones can reach speeds of up to 100 km/h and are used for direct (suicide attacks) on enemy drones. However, their use requires highly trained operators with the ability to maneuver such vehicles at high speeds in the conditions of the battlefield.

However, the ability to destroy **Class 2** and **Class 3** drones remains within the reach of specialized air-defence systems. Unfortunately, the cost-effectiveness of such measures is usually unfavorable for defensive systems. Traditional medium or even short-range anti-aircraft missiles are very expensive, while unmanned systems are cheap and widely used. For comparison, the cost of one Patriot missile is around 3 million USD, an NASAMS/AMRAAM missile used for the defense of Kyiv is estimated at 1 million USD (Partrige, 2022), whereas the cost of the Russian-side-utilized Shahed-136 kamikaze drones depending on version is only 20,000- 60,000 USD per unit (Sof, 2022).

Furthermore, the nature of using drone swarms or drone groups requires a significant saturation of air-defense systems to protect priority elements of military formations. Another problem is the ability to identify drones since they are intentionally designed to operate behind enemy lines and are not equipped with a friend-or-foe (IFF) identification system. For these reasons, it is also challenging to adhere to rules and implement measures for airspace control. Therefore, there is a need to develop systems, such as those utilizing artificial intelligence (AI), that could recognize drones based on their silhouettes, specific camouflage, operating frequencies or methods of operation.

Currently, in the absence of effective counter-drone measures for force protection, it is necessary to develop counter-drone tactics (Michalski & Michalska, 2017). These tactics should include not only active measures such as detection, reconnaissance, alerting, and neutralizing drones but also passive defense measures aimed at preserving the viability and survivability of military forces. Within the realm of passive counter-drone defense, it is important to plan activities such as concealment and camouflage, employing deception, artificial decoys, traps, and lures. Radiation of radio waves, electromagnetic emissions, and noise should be minimized to the lowest possible level. Planning troop movements and deployments in low visibility or nighttime conditions is crucial. Employing dispersion of forces and defensive networks can help intercept loitering munitions and drones conducting kamikaze missions above friendly positions and critical combat systems (ATP 3-01.81, 2023). While these measures may not be the most innovative and are somewhat aligned with the general principles of camouflage and force preservation, they can be particularly useful in situations where there is a high threat from unmanned systems.

5. Conclusions

We are currently witnessing a rapid arms race, with the emergence of weapons that are beginning to dominate the battlefield while effective countermeasures are lacking. This situation is exacerbated by the high pace of development and unprecedented scale of technology used in drone systems, coupled with their low production cost. At present, there is a lack of combat-proven counter-drone weapons that could serve as a remedy to such threats. We observe the emergence of systems of various classes based on different technical and technological solutions, but this is still a very new and experimental combat environment. At present, we can conclude that counter-drone defense should be multi-layered and employed with different defense systems depending on the type of drones they have to engage. Therefore, there is a need to build a multi-layered counter-drone defense system similar to a multi-layered air defense system. Counter-Unmanned Aircraft Systems (C-UAS) must possess multi-channel capabilities to combat swarm attacks, and their effectiveness will be reached only with a high saturation of troops. The analysis of contemporary technical and technological solutions suggests that such solutions should be based on Directed Energy Weapons (DEW) systems that include High Power Microwave (HPM) weapons or High Energy Laser (HEL) weapons. On the one hand, they will allow for the rapid elimination of a large number of drones; on the other hand, the cost of their operation will be disproportionately low compared to the destruction of drones using currently employed ammunition and air-defense missiles. In addition utilizing artificial intelligence, machine learning, and implementing automation processes with minimal human intervention will enable the identification of unmanned aerial vehicles and swift reaction of the counter-drone systems. Until such capabilities are achieved, passive solutions should be implemented, which will at least enable the avoidance of threats by fighting forces and the reduction of one's own losses. Finally, it is necessary to develop new doctrines covering counter-drone defense and implement new military training that includes counter-drone tactics (ATP 3-01.81, 2023). Therefore, the summarized research results have confirmed the hypothesis stated at the beginning of the article. At the same time, they highlight the need for further in-depth research in this area.

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