DOI: 10.32703/2415-7422-2024-14-2-487-512

UDC 621.373.826:623.4:681.7.069.24:903.22

Artemii Bernatskyi*
E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine
11, Kazymyra Malevycha Street, Kyiv, Ukraine, 03150
E-mail: bernatskyi@paton.kiev.ua
https://orcid.org/0000-0002-8050-5580

Volodymyr Lukashenko
E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine
11, Kazymyra Malevycha Street, Kyiv, Ukraine, 03150
E-mail: z_lyk@ukr.net
https://orcid.org/0000-0002-9685-4654

Oleksandr Siora
E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine
11, Kazymyra Malevycha Street, Kyiv, Ukraine, 03150
E-mail: siora@paton.kiev.ua
https://orcid.org/0009-0005-8542-1633

Mykola Sokolovskyi
E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine
11, Kazymyra Malevycha Street, Kyiv, Ukraine, 03150
E-mail: m_sokolovskyi@paton.kiev.ua
https://orcid.org/0000-0003-3243-5060

*(corresponding author)

Analysis of the application of lasers for counter-UAV purposes

Abstract. *From the dawn of human history, mankind has always made efforts to create more effective tools for combating other creatures, including fellow people. Thus, the utilisation of different species of animals, the creation of new weapons and other means of human progress have always led to new developments, aimed at* *emulating, replacing or combating these innovations. The development of unmanned aerial vehicles has prompted the need to develop alternative and innovative countermeasures. These methods may range from the usage of interceptor drones to the application of concentrated energy beams. This paper examines the progress and known uses of laser technology in the context of combating unmanned aerial vehicles. In order to deepen and systematize knowledge about the development of laser applications in the military field, a systematic bibliographic analysis of scientific papers and popular publications on the development of both laser technologies and unmanned aerial vehicles over the past century was conducted. The study focused on developments that were built (at least as a prototype) and tested against various unmanned aerial vehicles. The results were then compared with a number of articles that separately focused on the history, prospects, and current issues in the development of laser weapons and unmanned aerial vehicles. At the same time, due to the fact that laser technology is one of the most rapidly and comprehensively developing areas of scientific progress, it was decided to use a periodic classification model, the main criterion of which was the focus of laser technology development on countering unmanned aerial systems. The issue of determining the cause-and-effect relationship that links the development of unmanned aerial vehicle technologies and designs with the shift in the focus of laser weapons development to counteract them was considered. It is noted that, due to the high requirements for human and financial capital, the direction and pace of development of laser weapons depend not only on technological limitations, but also on the vision of military strategy and possible threats at a given time. As a conclusion, a variant of periodization of the history of the development of laser weapons as a means of combating unmanned aerial vehicles was proposed.*

Keywords: *laser; laser emission; technological development; laser weaponry; unmanned aerial vehicle; Counter Unmanned Aircraft Systems (C-UAS)*

Introduction.

From the ancient Greeks' wars with the Persian Achaemenid Empire to modern armed conflicts, armed conflict has been an integral part of human history. These conflicts have left their mark on humanity in many ways. One of the dimensions of this impact has been represented by weapons development. Since the first battle between tribes of primitive people, humanity has been striving to create more effective tools to fight other creatures, including other people. In different historical periods, the creation of new, more advanced weapons, as well as the development of methods for their production, gave one party of the conflict a significant advantage on the battlefield and contributed to their victory (Hacker, 1997). The emergence of such innovations on the part of one of the belligerents gave it an indisputable advantage over their opponent. However, the creation and use of innovative weapons has always triggered the emergence of new developments in both weapons and techniques designed to combat these weapons in a qualitative and cost-effective manner. This phenomenon is sometimes called an “arms race”. There are many developments of weapons that are considered to be milestones: from bronze swords and Macedonian sarissas to tanks, combat aircraft and nuclear weapons. However, the scientific and historical community has paid less attention to the methods of countering these weapons that have been developed throughout history. There are several explanations for this, ranging from the fact that countermeasures were often as much of a development milestone as their predecessor; and the fact that these developments were often defeated through the use of tactics, strategy and cunning. For example, during the Battle of Isandlwana (1879), Zulu forces, armed mainly with spears and leather shields, defeated the British army, armed with breech-loading rifles, machine guns and artillery, through trickery and skilful strategy (Beckett, 2023). However, in general, history shows that technological superiority provides a dramatic advantage. An extreme example of such an advantage occured during the next battle of the Anglo-Zulu War – the defence of the hospital in Rorke's Drift, where only 140 British soldiers stopped and repelled the attack of 4000 Zulus, armed not only with traditional spears but also with captured British weapons. The first use of tanks during the World War I did not change the course of the war immediately; however, it did manage to cause a certain amount of panic in the ranks of the Reichswehr command, which in turn launched programmes to both build their own tanks and create weapons specifically designed to combat tanks. These weapons became known as anti-tank rifles. In general, the development of tanks and combat aircraft are good modern examples of such an arms race and methods of countering them, since with the advancement of these types of weapons to a new level, the development of methods of countering these updated weapons would commence immediately (Salminen, 1992). Thus, the first tanks of the World War I, named so because of their visual resemblance to cisterns (which was used by British counterintelligence to create a legend that the project itself was not intended to create armoured vehicles, but to create a mechanised tank for the needs of the Entente armies (Fuller, 1920), turned into medium and heavy tanks of the World War II, and then into the main battle tanks of the Cold War. At the same time, anti-tank rifles have evolved into anti-tank guns, and subsequently into anti-tank missile systems (ATGM’s).

Over the last 30 years, we can observe a transition to a new round of such an "arms race" (Salminen, 1992; Hacker, 1997). The development of the latest stealth technologies, the development and use of the first hypersonic weapons; the increasing use of the Internet and space satellites for tracking of enemy actions as well as coordination of own units (GPS, Starlink, etc.), along with other innovations, provide a new set of challenges for weapons designers.

One of these weapon developments are unmanned aerial vehicles. With the overall development of various technologies, due to a variety of factors, a new ‘round’ of UAV development has taken place (Fuhrmann & Horowitz, 2017; Babak et al., 2021; Ajakwe, Kim, & Lee, 2023) These factors include:

a. Advances in materials science, including the development of new durable carbon fibre composites, as well as non-metallic composite materials, both of which have significantly reduced aircraft weight and increased payload.

b. Development of computer technology (miniaturisation of processors and other controller boards as well as an increase in their computing power) through the development of the semiconductor industry and IT technologies.

c. The development of design and theoretical calculation tools is directly related to the growth of the computer industry. The widespread adoption of computer software (CAD programs and mathematical modelling packages) makes it possible to quickly create structures of more complex shapes and more efficiently calculate any number of models required to confirm their effectiveness.

d. The development of the battery industry, namely the development of small-sized, high-capacity Li-ion batteries, has reduced their weight and dimensions by a factor of several times.

At the same time, the number of areas and types of work that can be performed with UAVs is growing rapidly every day. However, these also pose security risks, especially when used for espionage, smuggling, or military purposes. As a result, advanced anti-drone technologies have been developed to counter UAV threats. Military UAVs pose significant threats to various objects and infrastructure (Kim, Choi, & Kwon, 2024), as their capabilities expand from surveillance to direct attack roles (Liu, Zhang, L., Wang, Meng, & Zhang, B., 2024). Here are some key targets military UAVs can threaten and countermeasures to mitigate their impact:

1. Critical Infrastructure. UAVs can attack power plants (Mohsan, Khan, Noor, Ullah, & Alsharif, 2022), oil refineries (Chamola, Pavan, Aayush, Naren, Navneet, & Mohsen, 2021), water treatment facilities, and communication hubs. A successful attack could cause widespread outages, disrupt essential services, or create environmental hazards.

2. Military Bases and Personnel (Kratky, Minařík, Šustr, & Ivan, 2020). UAVs can be used for reconnaissance or launching missile strikes against troops, equipment, and military installations. They can carry bombs, missiles, or act as kamikaze drones, directly targeting high-value military assets.

3. Government Buildings. UAVs can be deployed for espionage, capturing sensitive information, or even direct attacks on key government sites such as command centers, embassies, or defense ministries.

4. Transportation Infrastructure. UAVs pose threats to airports, ports, bridges, and highways. Attacks on these facilities can paralyze logistics, hinder troop movements, and disrupt supply chains.

5. Nuclear Facilities. UAVs can be used to attack nuclear power plants or weapons facilities, risking catastrophic consequences like radiation leaks or the destruction of nuclear materials.

6. Civilian Population and Public Events. UAVs can target densely populated areas or major public events, resulting in mass casualties and creating widespread panic, especially in cases of terror attacks.

7. Industrial and Economic Targets (Lykou, Moustakas, & Gritzalis, 2020). UAVs can disrupt factories, financial centers, or major corporations, causing economic instability by damaging production lines, data centers, or financial infrastructure.

8. Naval and Maritime Assets. Drones can threaten ships, ports, or offshore oil rigs, using surveillance to monitor naval movements or deploying explosives to cause physical damage.

As UAV technology advances, so too must the tactics and technologies designed to combat them. However, to understand them, we first must understand their development cycle throughout history.

The first real-world application of this type of weapon is generally considered to be German developments from the World War II, namely the V-1 projectile aircraft (Palik & Nagy, 2019), as well as the US Operation "Aphrodite" plane-bombs (Boyne, 2010). Afterwards, UAVs became an integral part of the arsenal of countries around the globe, performing reconnaissance and auxiliary tasks (such as target aircraft), and since the early 2000s, strike missions. At the same time, the rather large size of this generation of unmanned aerial vehicles made them vulnerable to traditional air defence methods, and therefore did not require the development of special countermeasures. Nevertheless, the events of the last decade have shown a rapid paradigm shift in this regard. Smaller combat drones are becoming an increasingly integral part of the modern battlefield. At the same time, the skilful use of Bayraktar TB-2 UAVs during the Azerbaijani-Armenian conflict in 2020 and at the beginning of the Russian-Ukrainian war in 2022 showed that classical methods of using air defence systems were ineffective against these vehicles. However, due to their rather massive size, traditional air defence equipment was still able to fight this class of drones, so over time, methods of fighting these UAVs were developed, and due to the high rate of losses, Bayraktars were transferred to the Black Sea maritime patrol duties.However, the main technological breakthrough in the field of combat UAVs was the use of smaller UAVs such as the Sha'ed, Orlan, and later - even more miniaturised drones such as the DJI Mavic as well as various FPV drones. Here, it is worth noting that there are currently several classifications of UAVs used for military purposes. Two classifications are mainly used: the NATO classification (STANAG 4670), shown in Table 1, and the Pentagon classification (DOD-USRM-2013), shown in Table 2.

Their size made the use of existing air defence systems virtually impossible, forcing both sides of the conflict to adapt and develop methods to counter drones of this size. The Israeli-Palestinian conflict of 2024 deserves special attention, during which Israeli air defence systems were able to overcome waves of Iranian attack drones by using multi-echelon air defence systems such as the Patriot and Iron Dome. However, while the cost of one Iranian attack drone is 50 thousand dollars, the cost of a Petriot interceptor missile is 4 million dollars. It is interesting to note that this issue has been on the agenda of the Israeli military for some time, as the first documented and proven use of laser weapons as an interceptor of flying objects (UAVs and missiles) was recorded during the same conflict.

Table 1. UAV classification according to NATO standards (NATO, 2019).

Class	Category	Normal employment	Normal operating altitude	Normal mission radius	Primary supported commander
Class III (> 600 kg)	Strike/ Combat	Strategic/ National	Up to 20000 m	Unlimited (BLOS)	Theater
	HALE	Strategic/ National	Up to 20000 m	Unlimited (BLOS)	Theater
	MALE	Operational/ Theatre	Up to 14000 m	Unlimited (BLOS)	Joint Task Force
Class II (150—600 kg)	Tactical	Tactical Formation	Up to 5500 m	200 km (LOS)	Brigade
Class I (<150 kg)	Small (>15 kg)	Tactical Unit	Up to 1500 m	Up to 50 km (LOS)	Batallion, regiment
	Mini (<15 kg)	Tactical Subunit (manual or hand launch)	Up to 900 m	Up to 25 km (LOS)	Company, platoon, squad
	Micro (<66 J)	Tactical Subunit (manual or hand launch)	Up to 60 m	Up to 5 km (LOS)	Platoon, squad

Table 2. US DOD classification of UAVs (Department of Defense, 2013).

Class	Size	Maximum gross takeoff weight	Normal Operating altitude	Airspeed
1	Small	under 9 kg	<300 m	<190 kph
2	Medium	9.5 – 25 kg	<1000 m	<460 kph
3	Large	up to 600 kg	<6000 m	<460 kph
4	Larger	over 600 kg	<6000 m	Any airspeed
5	Largest	over 600 kg	>6000 м	Any airspeed

Modern countermeasures to mitigate UAV threats are extremely varied and can be divided into several categories (Ajakwe, Kim, & Lee, 2023; Shaohui et. al., 2023; Liu, Zhang, L., Wang, Meng, & Zhang, B., 2024):

1. Electronic warfare. Electronic warfare systems operate by disrupting or blocking communication between the operator and the UAV or interfering with GPS navigation. The main methods of electronic warfare include:

1.a. Jamming. Systems that emit signals that jam or interrupt the drone's control, disabling it. This is one of the most common methods for neutralizing commercial and military UAVs.

1.b. Spoofing. A technology that transmits fake GPS or radio signals to a drone, fooling its navigation systems and forcing it to change course or land.

1.c. Communication jamming. Used to cut off communication between a UAV and its operator, making the drone uncontrollable and often leading to a crash.

2. Kinetic destruction systems. These systems involve physical damage or destruction of UAVs using conventional or specialized weapons:

2.a. Surface-to-Air Missile systems. Used to destroy drones at long distances. For example, Patriot or S-400 systems can intercept drones at high altitude or range.

2.b. Anti-aircraft guns: specialized artillery systems, such as CIWS or ZSU-23-4 Shilka systems, that can effectively destroy low-flying drones with rapid-fire cannons.

2.c. Combat interceptor drones: specially equipped drones that can shoot down or intercept other UAVs in the air by striking or physically engaging them.

By combining these defensive measures, nations and organizations can effectively counter the threats posed by military UAVs, ensuring the protection of both critical infrastructure and civilian populations.

Recently, the interest in the use of laser systems to combat UAVs has grown significantly, as evidenced by a large amount of information from various sources, such as news, official statements, expert comments, as well as scientific research and technical reports. The use of the latest technologies to combat these threats, namely small-sized drones and, in the future, drone swarms, is one of the most pressing issues in modern armaments development. The main developments focus on technologies such as the use of electromagnetic weapons of directed action, as well as the use of laser radiation. The use of laser radiation as a weapon has been one of the fundamental issues for weapons scientists since the 1970s (Hecht, 2010), but due to the development of laser technologies, the creation of lasers capable of fighting aircraft at distances comparable to the destruction distances of traditional (artillery and missile) anti-aircraft systems has only become close to being a reality in recent years. The main advantages of laser weapons are the high speed of the laser beam (travelling at the speed of light, since the laser is a directed stream of light), the low cost per shot, measured in units of dollars per shot, and the fact that laser radiation can completely destroy its target, not just disable its electronics, as is the case with electromagnetic weapons (Cheng, 2006; Lykou, Moustakas, & Gritzalis, 2020).

The development of science and technology has profoundly transformed modern society, driving progress in nearly every aspect of life. Innovations in fields such as manufacturing (Zavdoveev et al., 2022; Halchuk et al., 2023; Shevchenko et al., 2024; Stoyan, et al., 2024), processing of materials (Voinarovych et al., 2017; Balitskii, et al., 2022; Demchenko et al., 2022; Pliuhin, Tsegelnyk, Plankovskyy, Aksonov, & Kombarov, 2023) have significantly improved the quality of life and expanded human capabilities. One such groundbreaking advancement is the development of laser technology, which has had a wide array of applications, ranging from medicine and telecommunications to industrial manufacturing and scientific research. Lasers have revolutionized numerous industries due to their precision and versatility. In medicine, lasers are used for delicate surgeries, vision correction, and even cancer treatments. In communication, fiber optic networks powered by laser technology have enabled high-speed internet and global connectivity. Industrial applications include cutting, welding, additive manufacturing (3D printing), and others, which have enhanced production efficiency and accuracy (Goncharuk, Zhuk, Kaglyak, Dzhemelinskyi, & Lesyk, 2018; Shelyagin et al., 2018; Bernatskyi, Sydorets, Berdnikova, Krivtsun, & Chinakhov, 2020; Berdnikova et al., 2021). Lasers also play a vital role in scientific research, enabling high-resolution imaging and experiments at the quantum level.

While science and technology have brought immense benefits, their development also introduces significant challenges and ethical dilemmas. One of the most concerning issues is the use of advanced technologies, including lasers, for military purposes. High-energy laser systems are increasingly being developed as weapons capable of targeting drones, missiles, and even satellites with unparalleled precision. This raises the risk of escalating arms races and the proliferation of destructive capabilities, potentially destabilizing global security.

The development of science and technology, particularly laser and related innovations, exemplifies humanity's potential to solve complex problems and improve lives (Bernatskyi & Khaskin, 2021; Lyubomir, Edmunds, & Risham Singh, 2021; Tsybulenko, 2022). However, it also highlights the need for careful consideration of the ethical, social, and environmental implications of these advancements, ensuring that progress serves as a force for good rather than harm.

The relevance of this paper is argued by the need to consider the historical stages of creation, implementation, first applications, review of the reasons for the rapid development and prospects for the use of lasers to combat UAVs.

The purpose of this study is to identify the patterns of interaction between scientific progress and its integration into military affairs through a multifaceted analysis of the processes of development, testing and adoption of laser technologies by countries around the world as a countermeasure to the development and spread of the use of unmanned aerial vehicles. This analysis focuses on the development of laser technologies in the context of countering unmanned aerial vehicles. With this in mind, the article will focus on the use of lasers as a countermeasure to UAVs, as well as on the development of UAVs and laser weapons in armaments in chronological order.

Research Methods.

In order to study the history and the current state of development of laser technologies for countering UAVs, a bibliometric and literature review of scientific papers published over the past 10 years was conducted. The dynamics of the scientific community's interest in this topic was also analysed by analysing the scientometric databases Google Scolar and Scopus, as well as Google and Microsoft search engines. Bing!' for queries related to the terms "C-UAS laser", "anti-drone laser", etc. The total number of references for each query in different databases over the past 10 years was compared; the dynamics of changes in the number of scientific papers by year; and the countries of authors of articles with dynamics by year.

Research in this area can be divided into several main areas:

a. announcements and popular science articles in the press (Abott, 2023; Rtx.Com, 2023) – – in general, such articles simply confirm the fact of one of the stages of development or testing of weapons systems (Abott, 2023; O'Rourke, 2024), but they often contain a small amount of technical information that does not appear in other sources;
b. various publicly available reports of parliaments, ministries of defence and other government agencies of different countries are broadly analytical in nature with sufficient references to scientific review and scientific and practical articles (O'Rourke, 2024);
c. scientific review articles (Chamola, Pavan, Aayush, Naren, Navneet, & Mohsen, 2021), as well as scientific (Kim, Choi, & Kwon, 2024; Mohsan, Khan, Noor, Ullah, & Alsharif, 2022) (theoretical, experimental and combined, containing both theoretical and experimental components) articles devoted to the development of individual components of such complexes (Lyu & Zhan, 2022).

The Research and its Results.

To determine the extent to which this topic has been studied in the modern scientific community, a bibliometric analysis of scientometric databases over the past 10 years was conducted.

Table 3. Papers on C-UAS, published in scientometric bases over the last 10 years.

Keywords	Scopus	Google Scholar
Laser Counter Drone	21	17500
Laser C-UAS	6	802
Laser Anti-drone	8	990
Laser anti UAV	44	16500

It is necessary to emphasise the small number of articles on this topic in rigorously peer-reviewed scientometric databases. This can be explained by the closed nature of data in many countries, in which a large number of works on the development of laser anti-drone weapons are being carried out (as evidenced by practical results in the form of prototypes of laser systems), as well as the overwhelming majority of works, presented by the Chinese scientific community. This alone demonstrates the relevance of this topic and the importance of its proper study in different contexts.

Despite the numerous advantages of laser systems for UAV countermeasures, such as high accuracy and speed of response, they also have important limitations.

The main advantages of laser anti-UAV systems include:

1. Speed of action. Lasers operate at the speed of light, which makes them an almost instantaneous means of defeating targets. As soon as a drone is detected and brought into view, the system can immediately activate the laser beam to neutralize it. This is especially important when dealing with high-speed or maneuverable UAVs.

2. High accuracy. The lasers of an anti-UAV system are usually equipped with target detection and tracking systems that can accurately target critical drone components such as the engine, electronics, or cameras. This makes it possible to quickly disable the drone without causing its complete physical destruction. Accuracy is also important to avoid collateral damage in areas with civilian infrastructure or on a battlefield with close proximity to your own units.

3. Unlimited number of shots. Laser weapons do not require physical ammunition such as missiles or bullets. This means that it can be used continuously as long as there is power supply. This autonomy makes laser systems cost-effective in prolonged conflicts or in situations with a large number of attacking drones.

4. Minimization of collateral damage. Laser engagement systems are highly accurate and can operate at certain distances without risking surrounding infrastructure or people. This makes them ideal for use in densely populated areas or when protecting critical facilities such as airports, power plants, or military bases.

5. Mobile platforms. Many laser systems can be installed on mobile platforms such as cars, ships, or even airplanes. This allows for rapid deployment of the laser system in different environments and provides high maneuverability. For example, military lasers are already being integrated into vehicles to protect against drone attacks on the battlefield.

Laser-based anti-UAV systems are gaining popularity as an innovative means of neutralizing drones in various military and civilian situations. Due to their high accuracy, rapid response time, and lack of ammunition requirements, lasers have the potential to become a key component of air defense systems in the near future. Technological developments in this area continue to improve these systems, expanding their capabilities for use in real-world combat situations.

Laser anti-UAV systems have significant advantages, such as high accuracy, instant response, and no need for ammunition. However, like any other technology, they have a number of disadvantages that affect their effectiveness and application in real-world conditions.

The main disadvantages of laser anti-UAV systems:

1. High power requirements. Laser systems require a significant amount of energy to operate efficiently. The laser power must be sufficient to quickly heat up and damage the materials from which the UAVs are made. This means that laser systems require a reliable power supply, which can be challenging for mobile platforms or for extended operations in remote areas.

2. Limited range. Although lasers can operate over long distances, their effectiveness decreases with distance due to beam energy dissipation. The further away the target is, the more energy is lost due to atmospheric factors. In real combat conditions, especially at long distances, this can significantly reduce the effectiveness of lasers.

3. Vulnerability to weather conditions. Laser radiation is very sensitive to weather conditions. Rain, fog, snow, dust, or even extreme heat can scatter or absorb some of the laser beam energy, making the system less efficient. This is a serious limitation for using lasers in difficult weather conditions or in certain climatic zones.

4. Reflection and absorption of materials. The materials from which UAVs are made can have reflective or absorptive properties, which reduces the efficiency of the laser. For example, metal surfaces or special coatings can partially reflect laser radiation, making it difficult to destroy the drone. In addition, heat-resistant materials may require more power or longer laser exposure times to damage them.

5. Cooling of the laser system. High-power laser operation generates a large amount of heat, so the system needs a reliable cooling system to maintain optimal temperature. This adds complexity to the design and can limit the amount of continuous laser operation. Inadequate cooling can lead to overheating and reduced system efficiency or even damage.

6. High cost of development and implementation. Laser systems are an emerging technology that requires significant investment in research, development, and manufacturing. Although they can reduce ammunition costs in the long run, the initial costs of developing laser systems are high. This may limit the widespread adoption of such systems, especially for countries with limited defense budgets.

7. Ability to counter lasers. Over time, methods of countering laser systems are evolving. For example, the use of drones with reflective surfaces or special coatings can make it more difficult to destroy them with lasers. In addition, there is a growing likelihood that UAVs will be made of materials resistant to high temperatures or with low thermal conductivity, which will make them more difficult to damage with a laser.

8. Limitations in multi-target operations. Although lasers have a fast response and can destroy targets almost instantly, there are certain limitations to the simultaneous destruction of multiple objects. A laser beam can only focus on one target at a given time, which creates a problem with simultaneous attacks by a large number of drones (flock attacks), when several UAVs attack an object at the same time.

High energy requirements, dependence on weather conditions, vulnerability to special materials and coatings, and high implementation costs are key drawbacks that require further improvement and research. However, the development of technology and engineering solutions can gradually reduce these shortcomings and make lasers more effective in real-world combat.

In this context, research on the development of a methodology for determining the impact of laser radiation parameters on the destruction of materials from which UAV parts are made is becoming increasingly relevant.

Lasers can be used for interdiction of UAVs in many ways: from using laser radiation as an alternative to radio waves to detect drones at long distances (utilizing the LIDAR principle), using a laser beam to guide a more traditional kinetic or explosive munition, to direct laser interaction with the drones themselves. In terms of direct engagement, laser radiation can interact with its target in many ways. The simplest is to blind the sensors, as it does not require great amounts of laser radiation energy to disable cameras and infrared targeting heads. However, there is still a chance that the enemy drone will reach its target with the help of redundant secondary control systems.

When directly engaging a drone, there are a large number of variables and problems associated with the principles of laser propagation in the atmosphere: from atmospheric aberration to thermal blooming and airborne defocus effects. Weather conditions also play a significant role in determining the required laser power.

It should also be noted that the type of material used to make a UAV plays a major role in its ability to be affected by laser emission. For example, a plastic UAV requires several times less energy to destroy than a UAV, made out of metal. At the same time, there are various options for the results of the interaction between laser radiation and individual parts of unmanned aerial vehicles.

The development of laser weapons has a number of problems and challenges that are directly related to the conditions associated with the design and the environment in which they operate (Garcia & Herz, 2016; Zabunov & Mardirossian, 2020; Tsybulenko, 2022; Yang, Wang, Chen, & Yan, 2024). It is evident that the design and characteristics of the laser directly determine its effectiveness against certain materials at certain distances; the calculation of optimal parameters for combating different UAV types at different distances is one of the most pressing tasks in the development of laser weapons. At the same time, much depends on the design conditions of the laser system: mobile, and even more so, portable systems have significantly more restrictions on their characteristics, as well as a radically different approach to use. At the same time, the environment, in which a particular laser system is used, dictates its own conditions, which is why, for example, for marine applications of lasers, there is a complex problem of the specifics of using laser weapons in marine conditions, since for proper operation it is necessary not only to meet the conditions present in any atmosphere (mass concentration, humidity and wind speed), but also marine issues in the form of a different composition of sea water and their vapours; problems of splashing and oscillations generated by waves; the problem of operation in the environment At the same time, for land-based laser applications, there are similar complex problems associated with the greater prevalence of dust, soil, diverse flora and fauna, as well as weather factors that cannot be reproduced in marine conditions.

The development of powerful lasers emitting invisible infrared rays led to a number of impressive technological demonstrations, especially in the United States and the former Soviet Union in the 1970s (Hecht, 2010). For example, the first case of UAVs being shot down by laser radiation is considered to be the MIRACL (Mid-

Infrared Advanced Chemical Laser), which was tested in 1978 as part of the US Navy's Joint Program, successfully intercepting and destroying a BQM-34 Vandal unmanned aerial vehicle in flight (Appell, 1997). Since then, the United States and the Soviet Union have conducted various efforts to destroy missiles or supersonic reconnaissance drones in flight. The PRC joined this 'race' to develop laser weapons in the mid-1980s, although due to limited access to Chinese documentation, it is currently impossible to determine the exact date (Qiwan, Zhixiang, & Chuanfu, 1998; Cheng, 2006; Bernatskyi & Sokolovskyi, 2022). Similar developments took place in the United Kingdom, which not only developed a laser shipboard system for blinding aircraft pilots under the 'Raker' and 'Shingle' codenames, but also deployed a ship with a prototype of this system in the flotilla that participated in the Falklands conflict in 1982 (Garcia & Herz, 2016; Zohuri, 2016, p. 45; Lyubomir, Edmunds, & Risham Singh, 2021). However, it is worth noting that there is no verified data on the use of this weapon during the hostilities against Argentinian forces.

At the same time, technological advances have led to the deepening and development of unmanned aerial vehicles in various directions – from the USSR's turbojet reconnaissance drones (such as the Tu-141) to barraging drones such as the american RQ-1\2, which used a small turboprop engine (Figure 1).

Figure 1. Tu-141 – a typical unmanned aerial vehicle from the end of the Cold War (Rogoway, 2022).

However, the completion of the first working laser designs coincided with the beginning of dramatic changes in the vision of the armed conflicts' future. With the end of the Cold War and the collapse of the USSR, laser weapons development began to be re-profiled, and in some ways has continued in these countries and their successors to this day.

In the modern sense, ‘anti-drone’ laser weapons began to develop in the early 2010s, after the introduction of small UAVs (DJI Enterprise, n. d.), shown in Fig. 2, by armies and illegal armed groups as reconnaissance vehicles. Moreover, there is evidence that most developed countries are interested in this topic for various reasons, from airport security to military operations. Thus, tracking the years of the first publicly known developments of laser weapons allows us to conclude that the development of a laser system requires years and expertise in optics and physics of interaction of concentrated energy flows. The first laser to be developed and tested against modern unmanned aerial vehicles is the United States' Navy AN/SEQ-3 LaWS, which began development in 2010 and was first installed on a naval installation in 2014 (Zabunov & Mardirossian, 2020). This system is currently being upgraded to the AN/SEQ-4 ODIN (O'Rourke, 2024), which will specialise in protecting ships from unmanned aerial systems.

Figure 2. A typical modern UAV, also known as a ‘drone’ (pictured – DJI Mavic 3 Enterprise) (DJI Enterprise, n. d.).

Two other systems have been developed at approximately the same time: the Chinese “Silent Hunter” with a power of 10 and later 30 kW (Lyu & Zhan, 2022; Gruszczak & Kaempf, 2023), and the French High Energy Laser for Multiple Applications (HELMA-P) with a power of 5 kW see Fig. 3 (Michau & Védrenne, 2024): both were presented in 2017 and are currently among the available offers on the market. It should be noted that they are fundamentally similar, as these lasers are among the first examples of modern fibre lasers being used to combat UAVs.

The next generation of anti-UAV laser systems, designed to counter UAV threats, is a family of Raytheon HELWS laser systems (Sanyal, Bevington, & Brigham, 2017; Lyu & Zhan, 2020, 2022; Rtx.Com, 2023). This family of lasers, designed to be used as a mobile installation and protect against short-range aerial threats for both the US Air Force in the form of the 10-kilowatt Raytheon H4 (Fig. 4), as well as a 15-kilowatt laser system on a British Wolfhound, developed in 2021 duringed Ministry of Defence's Land Demonstrator programme (Rtx.Com, 2023).

Figure 3. The HELMA-P laser system (Michau & Védrenne, 2024).

Figure 4. American anti-UAV laser system Raytheon H4 (Rtx.Com, n. d.).

It could be considered that Raytheon UK is a continuation of the success of previous U.S. investment, since a total of eight high-energy laser weapons have been delivered to the U.S. military (Grigoraş & Muşat, 2024). Over the years of testing and usage, these systems are claimed to have defeated more than 400 targets over 25,000 operational hours (Lyu & Zhan, 2020; Rtx.Com, n. d.).

One of the most developed systems at the moment is the American DE M-SHORAD, which currently exists in a number of designs. All variants of this system use solid-state fibre lasers with a power of 25 to 50 kW and are planned to be used by the US Army on the basis of the Stryker armoured personnel carrier in the coming years. During tests in 2022, a variant of this system from Raytheon (Fig. 5) successfully shot down a Class 3 UAV (Rtx.Com, n. d.).

Figure 5. Raytheon DE M-SHORAD air-defense system on trials (Rtx.Com, n. d.).

At the same time, the system from Leonardo (Figure 6) has proven itself as a combined air defence system that uses a 25 kW fiber laser to destroy UAVs at a distance of more than 2 km.

Figure 6. Leonardo DE C-UAS air-defense system on trials (Leonardo US Inc., 2024).

One of the most closely monitored laser systems is the Israeli Iron Beam (Ross, 2023; Gruszczak & Kaempf, 2023; Neice & Wostenberg, 2024), which began development in 2010 and is due to be commissioned in October 2025. It is considered the culmination of 15 years of work on this system. Unconfirmed reports indicate that this system has already been used during the current Israeli-Palestinian conflict, which would make it the only "battle-proven" system (Neice & Wostenberg, 2024).

These and other indicators make it possible to understand that the creation of a laser system for destruction of UAVs requires a large expenditure of human resources and finances. For example, the production of the AN/SEQ-3 prototype cost the US $40 million, and the programme to upgrade it to the AN/SEQ-4 level costs the US Navy $1.1 billion in the first year alone. At the same time, the US Army's multi-year programme to develop a combined ground laser system based on existing equipment that would be capable of engaging a variety of targets, including UAVs, is estimated to cost about $1.3 billion (O'Rourke, 2024).

Discussion.

From the analysis of papers that study the history and prospects of laser weapons, it can be noted that most articles positively consider the prospects of using laser weapons to combat unmanned aerial vehicles. For example, Steinwal (2021) notes in his work that *“Unmanned aerial vehicles (UAV:s) have become an increasing threat in both civilian and military arenas. ...The criminal world has quickly realized how UAV:s can be used to smuggle weapons or drugs, for example. Militarily, UAV:s are established for reconnaissance, fire control and electronic warfare operations etc. Laser-guided weapons from a UAV, is an example of a widely used system for precision operations during later conflicts… The laser can be used as a support sensor to others like radar or IR to detect end recognise and track the UAV and it can dazzle and destroy its optical sensors. A laser may also be used to sense the atmospheric attenuation and turbulence in slant paths, which are critical to the performance of a high power laser weapon aimed to destroy the UAV.”* It is difficult to disagree with this point of view, as the statistics provided by Lykou, Moustakas, & Gritzalis (2020) and Kudzai (2021) indicate a large increase in the usage of UAVs in no-fly zones, while the experience of modern conflicts suggests that the issue of combating UAVs is becoming critical for the international community.

However, when considering the sources that examined the development of laser technologies from a more historical perspective (Hecht, 2010;), it can be concluded that in the past, most authors considered laser weapons as ‘promising weapons of the next generations’. However, more recent articles (Ahmed, Mohsin, Ali, 2021; Ajakwe, Kim, & Lee, 2023; Gruszczak & Kaempf, 2023) indicate that the use of lasers to counter UAVs in a military environment may occur in the next 5–10 years. This point of view is confirmed by the large number of laser anti-UAV systems that have been developed in the last decade and are already undergoing military trials (such as Iron Beam and DE M-SHORAD) (Bernatskyi & Sokolovskyi, 2022; Hengyu, Xingwen, Xinyi, & Yu, 2024; He et al., 2024). This difference in perspective is attributed to the authors' view of slower development of laser technologies, especially fibre and diode lasers, which can provide high-quality (single-mode) laser radiation of sufficient power with relatively small installation sizes.

At the same time, it should be noted that the development of laser weapons with the primary function of countering unmanned aerial vehicles is directly related to the development of UAVs (Sanyal, Bevington, & Brigham, 2017; Lyubomir, Edmunds, & Risham Singh, 2021; Ross, 2023; Yang, Wang, Chen, & Yan, 2024) and their proliferation (Fuhrmann & Horowitz, 2017)). In his work, Fuhrmann & Horowitz (2017) notes that due to technological advances, UAVs are expected to become one of the most influential and rapidly developing weapon types. In the current context, it is hard to disagree with this point of view. In modern conflicts, individual companies use dozens of drones per day, whilst kamikaze strike drones are often used instead of bombers and bombs. Therefore, it is important to understand how the development of laser weapons and unmanned aerial vehicles has affected the trajectory of their development.

Based on this, the following scheme for periodising the focus of laser technology development for combating UAVs is proposed:

1. Development of lasers, where the counter-UAS aspect was considered a secondary task, used to test lasers before testing installations in accordance with their primary task of engaging cruise (and ballistic) missiles sharing the same altitude and/or speed range. This period was characteristic of the Cold War and ended with the curtailment of these laser weapons development programmes in the mid-1990s and early 2000s.
2. The development of universal laser systems - this process was associated with a change in the vision of warfare and current threats of the time, which focused on the fight against irregular forces (threats of terrorism, piracy, etc.). UAVs of the time were also developing in this direction, and therefore, despite the decrease in speed, size, and visibility, classical air defence measures have proven to be quite effective in countering such drones. For this reason, a mainly anti-drone approach to the development of laser weapons was not adopted. This period begins in the late 1990s and ends in the early to mid-2010s.
3. A sharp change in focus of the laser weapon development has occured in the mid-2010s, which can be contributed on both the widespread use of drones and UAVs, which began to rapidly shrink in size due to the use of more modern materials in their construction (carbon, aramid honeycomb, various composites, etc.), on top of the reduction in weight and size of their batteries. At the same time, the market for fibre lasers in that period has developed rapidly, with several manufacturing facilities being established in all around the world. This, among other factors, led to reduction in the cost of manufacturing fibre lasers by a magnitude of several times, allowing for their widespread usage during development of laser systems to counter UAVs. The use of

miniaturised UAVs by ISIS, as well as their large-scale use in conflicts starting from 2016–2018, has forced the scientific community to quickly look for methods of specialised counteraction to small UAVs. In this regard, laser radiation is poised to be one of the most promising areas for the possible development of methods to counter such vehicles due to the multiple possibilities of direct interaction with the UAV itself (including its possible destruction), as well as the low cost of a shot.

Conclusions.

As a result of the analysis of the available information on the development of laser weapons in the context of counteracting the widespread use of unmanned aerial vehicles and the development of their designs, the following periodization principle for concentrating efforts aimed at developing laser weapons to combat UAVs was proposed: the period when laser weapons were used against UAVs on an experimental basis; the period when the fight against UAVs was considered one of the secondary tasks, which was established by the general focus on the fight against the irregular enemy; and a period of focus on countering UAVs due to their proliferation and miniaturization. It was observed that the change in the main focus of laser weapons development was driven not only by technological advances in laser technology, but also by general technological developments in many fields, from materials science to IT, as well as by the military-geopolitical situation and military planning “vision of the upcoming war.”

Funding.

This research was funded by the National Research Foundation of Ukraine under the project No. 2023.04/0166 “Study of the effect of a laser beam on the materials of UAV parts and substantiation of the technical parameters of the laser equipment of the mobile complex to combat them” (grant support No. 155/0166 dated August 01, 2024).

Conflicts of interest.

The authors declare no conflict of interest.

References

Abott, R. (2023, February 15). Navy cautious on lasers because first program of record could cost $1 billion, ONR official says. *Defense Daily*. Retrieved from https://www.defensedaily.com/navy-cautious-on-lasers-because-first-program-of-record-could-cost-1-billion-onr-official-says/navy-usmc/

Ahmed, S. A., Mohsin, M., & Ali, S. M. Z. (2021). Survey and technological analysis of laser and its defense applications. *Defence Technology*, *17*(2), 583–592. https://doi.org/10.1016/j.dt.2020.02.012.

Ajakwe, S., Kim, D. S., & Lee, J. M. (2023). Radicalization of airspace security: prospects and botheration of drone defense system technology. *The Journal of Intelligence, Conflict, and Warfare*, *6*(1), 23–48. https://doi.org/10.21810/jicw.v6i1.5274

Appell, D. (1997, November 1). Military may test powerful laser in space. *Laser Focus World*. Retrieved from https://www.laserfocusworld.com/test-measurement/research/article/16550391/military-may-test-powerful-laser-in-space

Babak, V. P., Babak, S. V., Eremenko, V. S., Kuts, Y. V., Myslovych, M. V., Scherbak, L. M., ... & Zaporozhets, A. O. (2021). Monitoring the air pollution with UAVs. In *Models and Measures in Measurements and Monitoring. Studies in Systems, Decision and Control*, *360* (pp. 191–225). Cham: Springer. https://doi.org/10.1007/978-3-030-70783-5_7

Balitskii, A. I., Dmytryk, V. V., Ivaskevich, L. M., Balitskii, O. A., Glushko, A. V., Medovar, L. B., ... & Krolikowski, M. A. (2022). Improvement of the mechanical characteristics, hydrogen crack resistance and durability of turbine rotor steels welded joints. *Energies*, *15*(16), 6006. https://doi.org/10.3390/en15166006

Beckett, I. F. W. (2023). Indigenous resistance in the Anglo-Zulu War. *Historical Encounters*, *10*(2), 12–21. https://doi.org/10.52289/hej10.202

Berdnikova, O., Kushnarova, O., Bernatskyi, A., Polovetskyi, Y., Kostin, V., & Khokhlov, M. (2021). Structure features of surface layers in structural steel after laser-plasma alloying with 48(WC–W_2C)+ 48Cr+ 4Al powder. In *2021 IEEE 11th International Conference Nanomaterials: Applications & Properties (NAP), 05–11 September 2021, Odessa, Ukraine*, (pp. 1–4). Odessa: IEEE. https://doi.org/10.1109/NAP51885.2021.9568516

Bernatskyi, A., & Khaskin, V. (2021). The history of the creation of lasers and analysis of the impact of their application in the material processing on the development of certain industries. *History of Science and Technology*, *11*(1), 125–149. https://doi.org/10.32703/2415-7422-2021-11-1-125-149

Bernatskyi, A., & Sokolovskyi, M. (2022). History of military laser technology development in military applications. *History of Science and Technology*, *12*(1), 88–113. https://doi.org/10.32703/2415-7422-2022-12-1-88-113

Bernatskyi, A., Sydorets, V., Berdnikova, O., Krivtsun, I., & Chinakhov, D. (2020). Pore formation during laser welding in different spatial positions. *Solid State Phenomena*, *303*, 47–58. https://doi.org/10.4028/www.scientific.net/SSP.303.47

Boyne, W. J. (2010). The remote control bombers. *Air Force Magazine*, (November), 86–88. Retrieved from https://www.airandspaceforces.com/PDF/MagazineArchive/Documents/2010/November%202010/1110bombers.pdf

Chamola, V., Pavan, K., Aayush, A., Naren, N., Navneet, G., & Mohsen, G. (2021). A comprehensive review of unmanned aerial vehicle attacks and neutralization techniques. *Ad hoc networks*, *111*, 102324. https://doi.org/10.1016/j.adhoc.2020.102324

Cheng, T. C. (2006). The evolution of China's Strategic Nuclear Weapons. *Defense & Security Analysis*, *22*(3), 241–260. https://doi.org/10.1080/14751790600933863

Demchenko, V., Rybalchenko, N., Zahorodnia, S., Naumenko, K., Riabov, S., Kobylinskyi, S., ... & Kowalczuk, M. (2022). Preparation, characterization, and antimicrobial and antiviral properties of silver-containing nanocomposites based on polylactic acid–chitosan. *ACS Applied Bio Materials*, *5*(6), 2576–2585. https://doi.org/10.1021/acsabm.2c00034

Department of Defense. (2013). *DOD-USRM-2013. Unmanned Systems Integrated Roadmap FY2013-2038.* Retrieved from https://dod.defense.gov/Portals/1/Documents/pubs/DOD-USRM-2013.pdf

DJI Enterprise. (n. d.). *DJI Mavic 3 Enterprise.* https://enterprise.dji.com/mavic-3-m?site=enterprise&from=nav

Fuhrmann, M., & Horowitz, M. C. (2017). Droning on: Explaining the proliferation of unmanned aerial vehicles. *International Organization*, *71*(2), 397–418. http://www.jstor.org/stable/44651946

Fuller, J. F. C. (1920). *Tanks in the Great War, 1914–1918*. New York: E. P. Dutton and Company. Retrieved from https://ia601209.us.archive.org/27/items/cu31924027835168/cu31924027835168.pdf

Garcia, D., & Herz, M. (2016). Preventive action in World Politics. *Global Policy*, *7*(3), 370–379. https://doi.org/10.1111/1758-5899.12323

Goncharuk, O., Zhuk, R., Kaglyak, O., Dzhemelinskyi, V., & Lesyk, D. (2018). Laser sintering of abrasive layers with inclusions of cubic boron nitride grains. *Lasers in Manufacturing and Materials Processing*, *5*, 298–316. https://doi.org/10.1007/s40516-018-0068-0

Grigoraş, C. & Muşat, O.Ş. (2024). Countering unmanned aircraft systems – A multi-domain effort. In *International Conference Knowledge-Based Organization* (vol. 30, no. 1, pp. 1–7). Warsaw, Poland: Sciendo. https://doi.org/10.2478/kbo-2024-0011

Gruszczak, A., & Kaempf, S. (Eds.). (2023). *Routledge Handbook of the Future of Warfare.* Abingdon, Oxon; New York, NY: Routledge. http://dx.doi.org/10.4324/9781003299011

Hacker, B. C. (1997). Military technology and World History: A Reconnaissance. *The History Teacher*, *30*(4), 461–487. https://doi.org/10.2307/494141

Halchuk, T. N., Povstyanoy, O. Y., Bembenek, M., Redko, R. G., Chetverzhuk, T. I., & Polinkevych, R. M. (2023). Impact of technological system's characteristics on the machining accuracy of bearing rings. *Journal of Engineering Sciences*, *10*(1), A22–A30. https://doi.org/10.21272/jes.2023.10(1).a4

He, W., Gao, Y., Tang, L., Liu, X., Wang, Z., Zhang, X., ... & Liu, J. (2024). A study on the present situation and development trend of the short-range air defense weapon system of the US Six Armies. In *International Conference on Man-Machine-Environment System Engineering* (pp. 487–492). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-7139-4_67

Hecht, J. (2010). Short history of laser development. *Optical Engineering*, *49*(9), 091002. https://doi.org/10.1117/1.3483597

Hengyu, Y. I., Xingwen, S. U. O., Xinyi, Y. I., & Yu, Q. I. (2024). Development analysis of American directed energy maneuver short-range air defense program. *Journal of Applied Optics*, *45*(3), 485–494. https://dx.doi.org/10.5768/JAO202445.0310001

Kim, J., Choi, J., & Kwon, H. (2024). A study on the development directions of a smart counter-drone defense system based on the future technological environment. *KSII Transactions on Internet & Information Systems*, *18*(7), 1929–1952. http://doi.org/10.3837/tiis.2024.07.011

Kratky, M., Minařík, V., Šustr, V., & Ivan, J. (2020). Electronic warfare methods combatting UAVs. *Advances in Science, Technology and Engineering Systems Journal*, *5*(6), 447–454. http://dx.doi.org/10.25046/aj050653

Kudzai, N. (2021). *The Effectiveness of Counter UAS Solutions in the UK and USA* (Dissertation of MSc in Physics). Imperial College London, London. https://doi.org/10.13140/RG.2.2.23050.54728

Leonardo US Inc. (2024, October 14). Leonardo DRS and BlueHalo successfully demonstrate new Counter-UAS Directed Energy Stryker, shooting down drones in live-fire engagement. *Leonardo US Inc*. Retrieved from https://usa.leonardo.com/en/press-release-detail/-/detail/c-uas-de-stryker-successfully-demonstrated

Liu, W., Zhang, L., Wang, D., Meng, X., & Zhang, B. (2024). Application and key technologies of laser weapons in anti-UAV swarm operations. *Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica*, *45*(12), 329457. https://doi.org/10.7527/S1000-6893.2023.29457

Lykou, G., Moustakas, D., & Gritzalis, D. (2020). Defending airports from UAS: A survey on cyber-attacks and counter-drone sensing technologies. *Sensors*, *20*(12), 3537. https://doi.org/10.3390/s20123537

Lyu, C. Y., & Zhan, R. J. (2020). Research on the cutting-edge application of high energy laser C-UAS technology. In *International Conference on Optoelectronic and Microelectronic Technology and Application*, *11617*, 291–304. https://doi.org/10.1117/12.2585023

Lyu, C., & Zhan, R. (2022). Global analysis of active defense technologies for unmanned aerial vehicle. *IEEE Aerospace and Electronic Systems Magazine*, *37*(1), 6–31. https://doi.org/10.1109/MAES.2021.3115205

Lyubomir, L., Edmunds, T., & Risham Singh, G. (2021). Applications of laser technology in the army. *Journal of Defense Management*, *11*, 210. Retrieved from https://www.longdom.org/open-access/applications-of-laser-technology-in-the-army-79830.html

Michau, V., & Védrenne, N. (2024). Les lasers et l'optique adaptative. *Photoniques*, (126), 46–50. https://doi.org/10.1051/photon/202412646 [in French]

Mohsan, S. A. H., Khan, M. A., Noor, F., Ullah, I., & Alsharif, M. H. (2022). Towards the unmanned aerial vehicles (UAVs): A comprehensive review. *Drones, 6*(6), 147. https://doi.org/10.3390/drones6060147

NATO. (2019). *NATO standard. STANAG 4670. Minimum training requirements for unmanned aircraft systems (UAS) operators and pilots. Atp-3.3.8.1.* Brussels: NATO. Retrieved from https://www.scribd.com/document/731963739/ATP-3-3-8-1-EDB-V1-E-STANAG-4670

Neice, M., & Wostenberg, R. (2024). Securing directed energy weapon supply chains. *National Defense, 108*(843), 12. Retrieved from https://link.gale.com/apps/doc/A783578278/AONE?u=anon~14e12b88&sid=googleScholar&xid=bea55a03

O'Rourke, R. (2024, August 6,). Navy shipboard lasers: background and issues for Congress. CRS Report No.R44175. *CRS Report*. Retrieved from https://crsreports.congress.gov/product/pdf/R/R44175/111

Palik, M., & Nagy, M. (2019). Brief history of UAV development. *Repüléstudományi Közlemények, 31*(1), 155–166. https://doi.org/10.32560/rk.2019.1.13

Pliuhin, V., Tsegelnyk, Ye., Plankovskyy, S., Aksonov, O., & Kombarov, V. (2023). Implementation of induction motor speed and torque control system with reduced order model in ANSYS Twin Builder. In D. D. Cioboată (Ed.), *International Conference on Reliable Systems Engineering (ICoRSE) – 2023. ICoRSE 2023. Lecture Notes in Networks and Systems, 762* (pp. 514–531). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-40628-7_42

Qiwan, F., Zhixiang, Y., & Chuanfu, J. (1998). Menace of anti-ship missiles and shipborne laser weapons. *Jiguang Jishu (Laser Technology), 19*(6), 365–370.

Rogoway, T. (2022, March 11). Tu-141 'Strizh' missile-like drone from the war in Ukraine looks to have crashed in Croatia (Updated). *The War Zone Wire*. Retrieved from https://www.twz.com/44697/ukrainian-tu-141-strizh-missile-like-drone-appears-to-have-crashed-in-croatia

Ross, P. E. (2023). Economics drives a ray-gun resurgence: Lasers, cheaper by the shot, should work well against drones and cruise missiles. *IEEE Spectrum, 60*(1), 40–41. https://doi.org/10.1109/MSPEC.2023.10006667

Rtx.Com. (2023, September 13). Raytheon UK set to receive and integrate UK's first laser weapon system in October. *Rtx.Com*. Retrieved from https://www.rtx.com/news/news-center/2023/09/13/raytheon-uk-set-to-receive-and-integrate-uks-first-laser-weapon-system-in-octobe

Rtx.Com. (n. d.). High-Energy Lasers. *Rtx.Com*. Retrieved from https://www.rtx.com/raytheon/what-we-do/integrated-air-and-missile-defense/lasers

Salminen, P. (1992). *The impact of Arms Technology on military doctrines: Documentation*. Helsinki, Finland: War College (Finnish Defence Studies). ISBN 951-25-0622-X

Sanyal, S., Bevington, C. J., & Brigham, A. (2017). Navy efforts in directed energy weapons: importance of metrology and calibration. *Naval Engineers Journal, 129*(3), 53–68. Retrieved from https://www.ingentaconnect.com/contentone/asne/nej/2017/00000129/00000003/art00020#trendmd-suggestions

Shaohui, X., Ji, F., Baohua, W., Fengge, W., Yong, H., Jiajia, M., & Ye, W. (2023). Development of a shooting strategy to neutralize UAV swarms based on multi-shot cooperation. *Journal of Physics: Conference Series, 2460*(1), 012035. https://doi.org/10.1088/1742-6596/2460/1/012035

Shelyagin, V., Zaitsev, I., Bernatskyi, A., Sydorets, V., Dubko, A., & Bondarenko, O. (2018). Contactless monitoring of welding processes with computer processing of acoustic emission signals. In *Proceeding's 14th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering, TCSET 2018* (pp. 706–710). Lviv: IEEE. https://doi.org/10.1109/TCSET.2018.8336298

Shevchenko, V., Korzhyk, V., Gao, S., Khaskin, V., Cai, D., Luo, Z., Illiashenko, Y., Kvasnytskyi, V., & Perepichay, A. (2024). Formation of stainless steel welded joints produced with the application of laser and plasma energy sources. *Metals, 14*(6), 706. https://doi.org/10.3390/met14060706

Steinvall, O. (2021). The potential role of laser in combating UAVs: Part 2; laser as a countermeasure and weapon. In *Technologies for Optical Countermeasures XVIII and High-Power Lasers: Technology and Systems, Platforms, Effects V* (Vol. 11867, pp. 14–30). https://doi.org/10.1117/12.2601755

Stoyan, Y., Pankratov, O., Lemishka, I., Duriagina, Z., Bennell, J., Romanova, T., & Stetsyuk, P. (2024). Simulation of 3D volume filling with non-spherical and spherical titanium alloy powder particles for additive manufacturing. *Cybernetics and Systems Analysis, 60*, 422–432. https://doi.org/10.1007/s10559-024-00683-6

Tsybulenko, E. (2022). Blinding laser weapons. In S. Sayapin, R. Atadjanov, U. Kadam, G. Kemp, N. Zambrana-Tévar, N. Quénivet (Eds.), *International Conflict and Security Law* (pp. 367–378). Berlin: T.M.C. Asser Press, The Hague. https://doi.org/10.1007/978-94-6265-515-7_16

Voinarovych, S., Kyslytsia, O., Kuzmych-Ianchuk, I., Masiuchok, O., Kaliuzhnyi, S., Teodossiev, D., ... & Dyakova, V. (2017). Innovative coatings for implants and parts for osteosynthesis. *Series on Biomechanics, 31*(4), 27–33. Retrieved from http://jsb.imbm.bas.bg/page/en/details.php?article_id=254&tab=en

Yang, R., Wang, H., Chen, C., & Yan, D. (2024). Distributed collaborative allocation of multi-laser weapons for countering unmanned aerial vehicles. In *2024 43rd Chinese Control Conference (CCC)* (pp. 1879–1884). Kunming, China: IEEE. https://doi.org/10.23919/CCC63176.2024.10661197

Zabunov, S., & Mardirossian, G. (2020). Malicious drones interception and neutralization – latest technologies overview. In *Proceedings of SES 2020 Sixteenth International Scientific Conference Space, Ecology, Safety* (pp. 120–123). Sofia: Space Research and Technology Institute. Retrieved from http://space.bas.bg/SES/archive/SES%202020_DOKLADI/2_Aerospace%20Technologies/5_Zabunov.pdf

Zavdoveev, A., Pozniakov, V., Baudin, T., Kim, H. S., Klochkov, I., Motrunich, S., ... & Skoryk, M. (2022). Optimization of the pulsed arc welding parameters for wire arc additive manufacturing in austenitic steel applications. *The International Journal of Advanced Manufacturing Technology, 119*(7–8), 5175–5193. https://doi.org/10.1007/s00170-022-08704-4

Zohuri, B. (2016). Laser Safety. In *Directed Energy Weapons* (pp. 35–46). Cham: Springer. https://doi.org/10.1007/978-3-319-31289-7_3

Артемій Бернацький
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Володимир Лукашенко
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Олександр Сіора
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Микола Соколовський
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Аналіз застосування лазерів для боротьби з БПЛА

Анотація. *З самого початку людської історії, людство завжди прикладало зусилля до створення більш ефективних інструментів боротьби з іншими істотами, включаючи й інших людей. Таким чином, створення і використання нових видів тварин, створення нового озброєння та інші методи прогресу людства завжди спонукало до нових розробок, спрямованих на емуляцію, заміну або для боротьби з даними новинками. Розвиток безпілотних літальних апаратів створив необхідність у розробці альтернативних та новітніх методів протидії. Ці методи можуть бути різними, від використання дронів-перехоплювачів, до використання концентрованих потоків енергії. Дана робота присвячена вивченню прогресу та відомих використань лазерних технологій у* *контексті боротьби з безпілотними літальними апаратами. Для поглиблення та систематизації знань про розвиток застосувань лазерів у військовій галузі, було проведено систематизований бібліографічний аналіз наукових робіт та науково-популярних публікацій, щодо напрямку розвитку як лазерних технологій, так і безпілотних літальних апаратів на протязі останнього сторіччя. Дослідження фокусувалось на розробках, котрі були фактично реалізовані та випробовувались проти різноманітних безпілотних літальних апаратів. Після цього, його результати було порівняно з рядом статей, котрі окремо фокусувались на історії, перспективах та нагальних питаннях розвитку лазерного озброєння та безпілотних літальних апаратів. При цьому, завдяки тому, що лазерні технології є одним з найбільш стрімко та всебічно розвиваючихся напрямків наукового прогресу, було вирішено використати періодичну модель класифікації, головним критерієм якої був фокус розробок лазерних технологій на протидію безпілотних літальних апаратам. Було розглянуто питання визначення причинно-наслідкового зв'язку, котрий пов'язує розвиток технологій та конструкцій безпілотників з зміщенням фокусу розробки лазерного озброєння на протидію ним. Відзначено, що через високі потреби в людському та фінансовому капіталі, напрямок та темпи розвитку лазерного озброєння залежать не тільки від технологічних обмежень, але й від бачення військової стратегії та можливих загроз в той чи інший момент часу. В результаті було запропоновано варіант періодизації історії розвитку лазерного озброєння як засобу боротьби з безпілотними літальними апаратами.*

Ключові слова: *лазер; лазерне випромінювання; розвиток техніки та технологій; лазерна зброя; безпілотний літальний апарат; протидія безпілотним авіаційним системам*

Received 02.10.2024
Received in revised form 15.11.2024
Accepted 21.11.2024