The role of High Energy Laser as a U.S. Army Counter-small Unmanned Aircraft System (UAS) Weapon

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Abstract

This qualitative study explores the potential of solid-state High Energy Laser (HEL) Directed Energy (DE) technology as an effective Counter-small Unmanned Aircraft System (C-sUAS) capability in the U.S. Army. The progression of laser technology from 1960s gas lasers to 2000s solid-state fiber laser is outlined. Solid-state fiber lasers show promise for defensive weaponization due to excellent beam quality, high efficiency, compact size, and robust thermal management. An analysis of current U.S. military HEL weapon system development across the Air Force, Army, and Navy revealed significant investments but limited operational fielding to date. HEL weapon systems offer advantages in speed, cost-effectiveness, precision, and graduated response compared to traditional kinetic weapons for countering small drone threats. However, limitations remain including line-of-sight constraints, atmospheric impacts on beam propagation, and integration challenges. Specific benefits and challenges of using HEL as a C-sUAS solution in the U.S. Army were examined. The Joint Counter-small Unmanned Aircraft Systems Office (JCO), led by the U.S. Army, plays a key role in aligning service efforts into a unified capability architecture. Ongoing research and development aim to address size, weight, and power demands, enhance testing realism, and fulfill industrial base manufacturing needs to transition HEL weapon systems from prototypes to operational weapon systems. Overall, solid-state fiber laser HEL technology shows strong potential, but integration and fielding challenges remain. The U.S. Army should continue advanced development while refining tactics, leveraging unified governance, and shaping policy to enable effective operational capability.

Introduction

In recent years, small unmanned aircraft systems (sUAS), also referred to as drones, have become increasingly prevalent on the modern battlefield. Their small size, low cost, and versatility make them attractive options for persistent intelligence, surveillance, and reconnaissance (ISR), and even attacking targets. However, the proliferation of drones presents increasing capability and cost challenges for ground forces and air defense units to detect and engage these agile threats. Directed Energy (DE) weapon systems, particularly High Energy Lasers (HELs), may be a promising counter-drone technology for the U.S. Army (Wilson, 2020). This paper examines the role of DE weapon systems, specifically solid-state lasers, as an effective method to counter sUAS (C-sUAS) capabilities in the U.S. Army.

Background

The 2022 Russian invasion of Ukraine, commencing with Russian tanks breaching Ukraine's borders, soon took on a modern dimension as the conflict evolved into World War I-style trench warfare and heavy Soviet-made artillery shelling across the Ukrainian landscape. There was a paradigm shift replacing physical proximity with the digital reach of drones and satellite-linked intelligence. This evolution from one-sided drone reconnaissance to a fully integrated, multi-layered drone ecosystem marked a watershed moment in military history. Both sides utilized extensive drone fleets, sophisticated air defense systems, and electronic warfare/attack capabilities, transforming the traditional battlefield into a dynamic digital tapestry woven with observations and engagements conducted across vast distances. The centrality of drones in this conflict highlighted their pivotal role in modern warfare, enabling combatants to observe and engage one another without immediate physical contact (Khurshudyan et al., 2022).

The Ukrainian battlefield hums with an astonishing variety of drones, from miniature Black Hornets with a 12 centimeters wingspan to colossal behemoths stretching over 15 meters. While commercially produced quadcopters like Da-Jiang Innovations (DJI) reign supreme for reconnaissance, smaller systems play a crucial role in targeting and close-range operations. Meanwhile, armed drones like Turkey's Bayraktar TB2 and Russia's Orion are highly effective launching missiles at ground troops. The rise of kamikaze drones, like single-use loitering munitions that explode on targets, adds another deadly layer, adopted heavily by Russia and, more recently, employed by Ukraine in the Moscow attacks (Franke, 2023).

Modern warfare has undergone a seismic shift with the widespread adoption of commercially available drones. The battlefield now buzzes with the whirring rotors of quadcopters and miniature marvels like the Black Hornet, originally birthed in the world of hobbyists and consumer tech. Remarkably, a significant portion, perhaps even the majority, of drones deployed by Ukrainian forces fall into this category, repurposed for a deadly new mission. This ubiquitous presence of modified civilian drones marks a fundamental change in the landscape of modern conflict (Khurshudyan et al., 2022). Once primarily the domain of expensive unmanned aircraft systems like the General Atomics Predator drone, rapid advances in technology have enabled even non-state actors to employ low cost drones. Their commercial availability, low cost, ease of development, small radar cross section, low altitude flight profiles, and increasing autonomy make neutralizing drones problematic with conventional kinetic weapon systems like surface-to-air missiles or aerial weapon systems. Additionally, firing expensive missiles against cheap drones provides a poor economic exchange. Thus, the emergence of drone swarming tactics by near-peer adversaries presents a critical threat to U.S. Army ground operations (Franke, 2023).

The 2018 National Defense Strategy introduced new technologies and weapons in the first section: "New technologies include advanced computing, 'big data' analytics, artificial intelligence, autonomy, robotics, directed energy, hypersonics, and biotechnology—the very technologies that ensure we will be able to fight and win the wars of the future." (DoD, 2018, p. 3). DE weapon systems, including solid-state HELs, have undergone significant development in the 21st century. Prototypes have demonstrated the ability to track and shoot down drones with pinpoint precision and agility at the speed of light. Most recently in 2023, the U.S. Army used Raytheon's 50kW-class laser to intercept and destroy drone targets during live-fire trials at the Yuma Proving Ground, Arizona (Manuel, 2023). As opposed to costly missile intercepts, lasers offer nearly unlimited magazines with minimal cost per shot and collateral damage (Wilson, 2020).

Problem Statement

An infusion of drones employed by strategic rivals, regional powers, and non-state actors continues to endanger vital U.S. interests across many fronts. In February 2022, the Under Secretary of Defense for Research and Engineering, Honorable Heidi Shyu, presented a list of critical and emerging technologies. Directed energy was on the list (Barnett, 2022). DE weapon systems, particularly solid-state HELs, need to be evaluated as an effective layered defense against drone threats.

Statement of Purpose

The purpose of this qualitative study is to explore the solid-state HEL DE Technology and its application as C-sUAS weapon systems in the U.S. Army.

Research Questions

1. What is solid-state HEL DE technology?

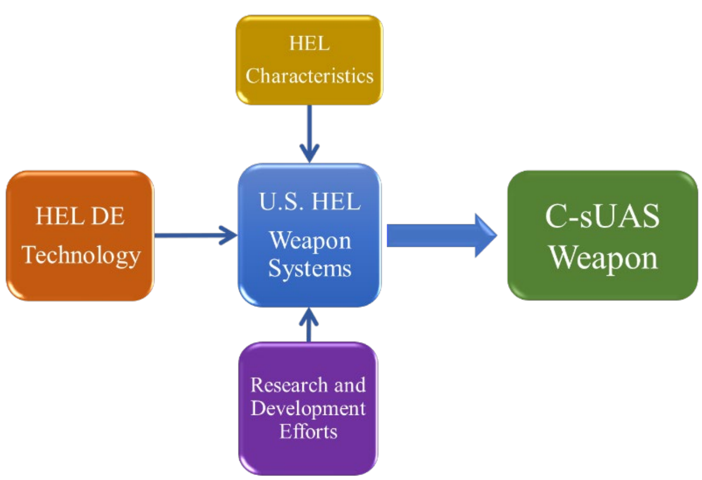
2. What is the state of HEL weapon systems development in the U.S. military?
3. What characteristics are associated with implementing HEL weapon systems?
4. What are the advantages and challenges of using HEL specifically as C-sUAS weapon systems in the U.S. Army?
5. What challenges are current research and development efforts aiming to address for HEL weapon systems?

Conceptual Framework

The conceptual framework, as shown in Figure 1, will start with providing an understanding of the solid-state HEL DE technology. The research will describe the state of HEL weapon systems development in the U.S. military and dive into the characteristics associated with implementing HEL weapon systems. Finally, the research will share the advantages and disadvantages of using HEL specifically as C-sUAS weapon systems in the U.S. Army and relay challenges being addressed in ongoing HEL weapon systems research and development efforts.

Figure 1

Research Conceptual Framework



Significance of This Research

Recognizing the increasingly complex threats to U.S. national security, the 2022 National Defense Strategy prioritizes measures to deter both high-powered missile programs and the disruptive potential of lower-tier threats like drones (DoD, 2022).

In the current Russia-Ukraine war, drones are not just tools; these are game-changers. Both sides have drastically adjusted their tactics to account for these versatile platforms. Retrofitted with explosives, drones bring death and disarray to unexpected corners of the battlefield, far from the front lines. Moreover, their ISR capabilities offer unparalleled battlefield awareness, while widespread sharing of drone footage on social media sites like YouTube, TikTok, Facebook and Instagram fuel a new kind of psychological warfare, eroding security and amplifying chaos (Edmonds & Bendett, 2023). The scale of drone usage in a military conflict is unprecedented. According to estimates from the Royal United Services Institute, Ukraine is experiencing a loss of approximately 10,000 drones each month, highlighting the extensive deployment of these unmanned systems. With aerial defense systems significantly countering manned aviation, the significance of unmanned systems has become particularly pronounced (Franke, 2023).

The rapid growth in usage of drone technology creates new risks. The rapid growth of legitimate drone applications provides cover/deniability for drone use outside of traditional combat contexts by criminals, non-state actors, and state actors. Drones can also pose hazards to DoD operations when controlled by negligent or reckless operators (DoD, 2021). General McConville equated drones as modern day improvised explosive devices. “Drones and other unmanned systems are going to pose significant challenges for us, again, part of why we’re looking at modernizing our air and missile defense system," quoted Secretary of the U.S. Army Christine Wormuth (Ferran et al., 2023, para. 15).

Overview of the Research Methodology

This research relied heavily on analyzing publications found in the U.S. Government Accounting Office (GAO), Defense Acquisition University Virtual Research Library, Congressional Research Service (CRS) database, Defense Technical Information Center (DTIC), Lawrence Technical Library, and Google Scholar. This research employed a qualitative approach, with a carefully crafted purpose statement and research question providing the roadmap for understanding the study's logic (Creswell & Guetterman, 2021). Open-ended questions helped guide qualitative research, providing richness to the data and some new perspectives (Bryman, 2008). A thematic analysis synthesized the collected data to answer the research questions and integrated the information across multiple sources to arrive at findings and relevant conclusions.

Limitations of the Study

This research is limited to the published literature posted in the public domain. Security classification concerns restrict the identification of performance limitations of HEL and C-sUAS capabilities across the DoD. Furthermore, the research excludes surveys, emails, phone calls, and interviews with HEL and C-sUAS subject matter experts. Limits of time and expertise prevent a thorough examination of all published literature. The dynamic nature of DE technologies might necessitate the reevaluation of the assumptions and conclusions presented herein, due to potential technological advancements in the foreseeable future. Lastly, this research maintains a limited scope for DE technologies to Solid-State HEL and air defense weapon systems to C-sUAS in the U.S. Army.

Summary

The expanding threat posed by the increasing use of drones by a wide range of actors requires solutions (Khurshudyan et al., 2022). In this research, solid-state HEL will be evaluated as a potential DE solution to counter the growing danger of drone swarms on the modern battlefield. The next section is a literature review of the HEL DE technology, state of HEL weapon systems development, implementation benefits and limitations and use as C-sUAS weapon systems.

Literature Review

Introduction

This section examines several categories of literature to help explore the solid-state High Energy Laser (HEL) Directed Energy (DE) technology prevalent in HEL weapon systems and the state of HEL weapon systems development in the U.S. military. The literature review also examined the benefits and limitations of implementing HEL weapon systems and use as C-sUAS weapon systems. Finally, the literature review shares immediate and long-term challenges for HEL weapon systems being addressed by research and development efforts.

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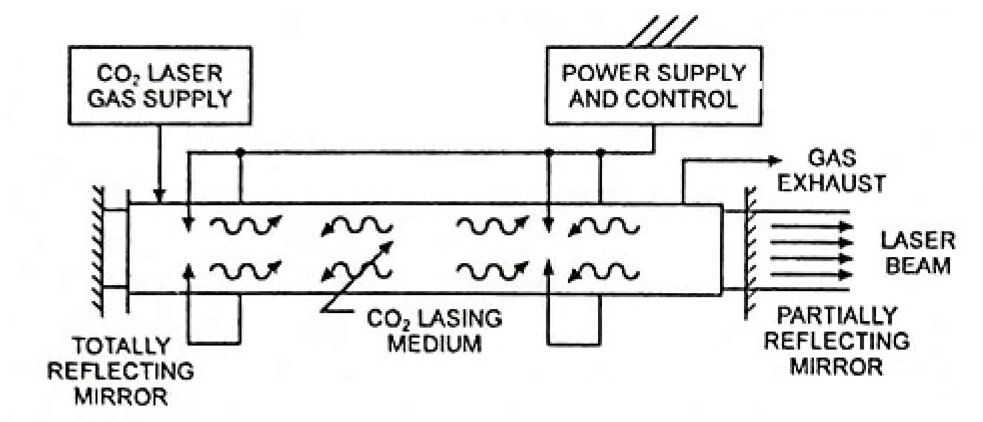
Solid-State HEL DE Technology

LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. Most physics courses that discuss the nature of light as a particle and a wave introduce the concept of Laser. The heart of a laser lies in the stimulated emission process, where the lasing medium, energized by intense optical pumping or electrical discharge, generates an inverted population of excited atoms. This population inversion provides the necessary gain for stimulated emission, wherein excited atoms, falling back to the ground state, release photons coherent in phase and direction. These photons, guided and amplified by mirrors, coalesce into a concentrated, high-energy laser beam. Figure 2 shows a generic block diagram of a gas-based laser system (Eeeguide, 2023).

Figure 2

Basic CO2 (Gas) Laser system



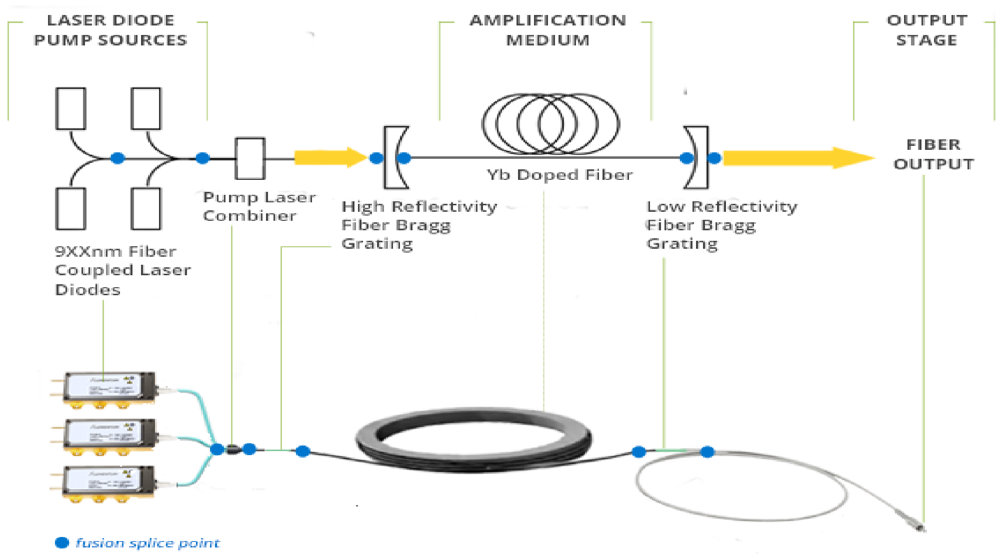
Note. Mirrors help guide the photons into a laser beam in one direction. Image sourced from "Laser beam welding - definition, block diagram and workings." EEEGUIDE.COM. (https://www.eeeguide.com/ laser-beam-welding).

The development of high energy lasers can be traced back to the 1950s, when scientists began experimenting with different methods of generating concentrated beams of light. In 1960, the first working laser was invented by Theodore Maiman, at Hughes Research Laboratories, by flashing a high-power lamp at a ruby crystal (Hecht, 2010). This first laser produced pulses of coherent red light. Later that decade, researchers began developing more powerful gas lasers that could operate continuously rather than in pulses. These early gas lasers used helium-neon or carbon dioxide and produced beams in the infrared range (Bridges, 1964). Through the 1960s, laser power increased rapidly with the invention of new lasing mediums like argon, krypton, and excimer lasers. In the 1970s, high energy laser development was driven in part by military interests. Significant progress was made in chemical laser systems which involve a chemical reaction in the lasing medium. The United States and Soviet Union both worked on hydrogen fluoride and deuterium fluoride lasers designed to be used as directed energy weapon systems. The 1980s and 1990s saw the invention of new laser designs like slab lasers and thin-disk lasers that improved beam quality and average power output. Important civilian applications also emerged like laser cutting, welding, and eye surgery (Ready, 1997).

More recently, solid-state fiber laser systems have been scaled to high powers by combining multiple fiber gain modules. Fiber lasers now reach multi-kilowatt power levels (Richardson et al., 2010). Optical fibers doped with rare earth elements are used in fiber lasers as the lasing medium (Figure 3).

Figure 3

Fiber Laser Block Diagram



Note. Image sourced from “Learn the Basics of Fiber Laser Design and the Key Components used to Build a Fiber Laser. Fiber Laser Basics and Design Principles (with VIDEOS)” by

Gwinner, S. (https://www.laserlabsource.com/Solid-State-Lasers/Solid-State-Lasers/fiber-laser-basics-and-design-principles).

Active dopant, typically ytterbium, erbium, neodymium, or thulium are contained in the core of the fiber. When pumped with diode lasers, the doped core amplifies light through the process of stimulated emission as the light propagates down the fiber. Fiber lasers provide excellent beam quality, high efficiency, compact size, and robust thermal management. These advantages have enabled high power level scaling in fiber lasers. By combining multiple fiber gain modules using spectral beam combining, fiber lasers have achieved kW-class output powers providing potential for a weapon system capable of cost-effective interdiction of sUAS (Dawson et al., 2008).

Ongoing research on fiber laser technology includes improving power scaling limits, pulsed operation, and wavelength coverage. Materials processing, directed energy weapon systems, and optical communications are some of the applications of high-power fiber lasers (Richardson et al., 2010). Challenges for higher power fiber lasers include optical damage, nonlinear effects, and gain saturation but fiber architectures continue to enable innovations in high energy laser systems (Jeong et al., 2004). High energy laser research continues to advance with applications in manufacturing, defense, medicine, and science.

State of U.S. military HEL weapon systems development

This section details the development of HEL weapon systems in the Air Force, Army, and Navy. HEL weapon systems utilize a highly focused narrow beam of light, usually in the infrared to visible region, to deliver thermal damage to targets at the speed of light. A typical HEL weapon system consists of five main subsystems (Figure 4) –

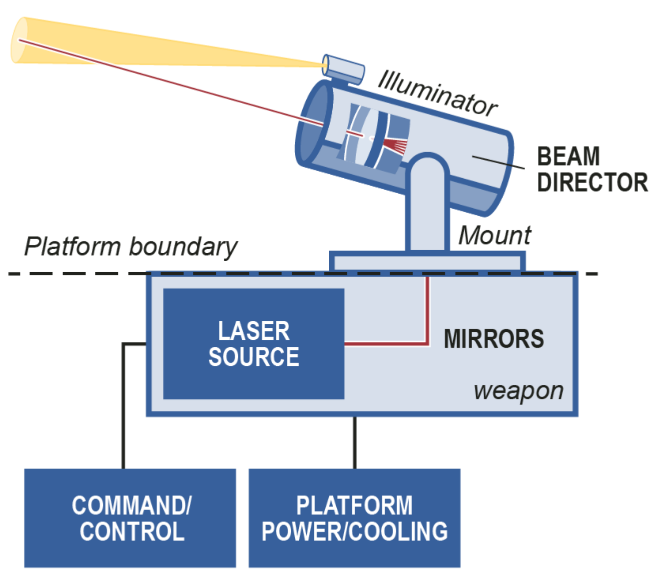
- Laser source that generates high-power laser beam

- Beam Director including optical components to shape, focus and steer the laser beam precisely onto targets sometimes tens of kilometers away.
- Platform for providing electricity to power the laser, which can be a battery, generator, or external power source.
- Platform for advanced thermal management systems to cool the system while in use.
- Command and control to receive cues from a sophisticated sensor and operate the weapon system.

With an annual budget of $1 billion, the U.S. military is pushing forward with developing directed-energy weapons to combat aerial threats like drones and missiles. Fiscal year 2023 alone sees approximately $669 million allocated for research and development and approximately $345 million earmarked for procurement (Sayler et al., 2023).

Figure 4

Illustration of a HEL weapon system



Note. Image sourced from "DIRECTED ENERGY WEAPONS. DOD Should Focus on Transition Planning." Government Accountability Office Publication No. 23-105868, p. 4.

Air Force HEL weapon systems development

High-Energy Laser Weapon System (HELWS). The HELWS is a 10kW-class to 15 kW-class HEL that provides air base defense capability as a mobile C-sUAS weapon system. The base of the HEL weapon system is a Polaris MRZR all-terrain vehicle (Figure 5). Raytheon, the prime contractor, delivered three prototypes to the Air Force starting in 2019. These systems were deployed overseas for field assessments. The Air Force also awarded Raytheon an upgraded version of HELWS in 2021 to be delivered on pallets (Strout, 2022b).

Figure 5

HELWS prototype

Note. Image sourced from "Raytheon awarded $15.5 million to upgrade laser weapon" by Strout, N. C4ISRNet. (https://www.c4isrnet.com/unmanned/2021/04/07/raytheon-awarded-155-to-upgrade-laser-weapon/)

Self-Protect High-Energy Laser Demonstrator (SHiELD). The SHiELD is being developed by Northrop Grumman, Lockheed Martin, Boeing, and the Air Force Research Laboratory (AFRL) (Figure 6). The demonstrator is intended to target incoming surface-to-air and air-to-air missiles while mounted as an external pod on an aircraft. The first flight demonstration is planned in fiscal year 2024 (Strout, 2022a).

Figure 6

SHiELD Prototype Rendering

Note. Image sourced from "Department of Defense Directed Energy Weapons: Background and Issues for Congress" by Sayler, K. M., Feickert, A., Hoehn, J. R., & O'Rourke, R. Congressional Research Service Report No. R46925, p. 9. (https://crsreports.congress.gov/product /pdf/R/ R46925).

Army HEL weapon systems development

Directed Energy Maneuver-Short Range Air Defense (DE M-SHORAD). The DE M-SHORAD is a 50kW-class HEL mounted on a Stryker. The system is a maneuver solution designed to neutralize various aerial threats. Kord Technologies, prime contractor, helped deliver four prototype weapon systems to the 4th Battalion, 60th Air Defense Artillery Regiment (4-60th ADAR) currently located at Fort Sill, Oklahoma (Figure 7) in fiscal year 2023. 4-60th ADAR crew conducted live fire training prior to receipt and plans to conduct further training in conjunction with its kinetic variant (Manuel, 2023).

Figure 7

Soldiers of 4-60th ADAR alongside four DE M-SHORAD prototype systems

Note. Image sourced from “US Army receives high-energy laser weapon prototypes” by Manuel, R. The Defense Post. (https://www.thedefensepost.com/2023/09/25/us-shorad-laser-weapon-prototypes/)

Indirect Fire Protection Capability-High Energy Laser (IFPC-HEL). The IFPC-HEL is being developed as a 300kW-class HEL mounted on a truck (Figure 8). The U.S. Army recently selected Lockheed Martin, prime contractor, to deliver IFPC-HEL prototypes by mid-October 2025. The IFPC-HEL is intended to provide defense capability for fixed and semi-fixed sites from rockets, artillery, and mortars, cruise missiles, rotary and fixed-wing threats, and drones (Roque, 2023a).

Figure 8

IFPC-HEL prototype rendering

Note. Image sourced from "Lockheed secures $221M army deal for high-powered air defense laser prototype" by Roque, A. Breaking Defense. (https://breakingdefense.com/2023/07/lockheed-secures-221m-army-deal-for-high-powered-air-defense-laser-prototype/)

Army Multi-Purpose High Energy Laser (AMP-HEL). The AMP-HEL is a 20kW-class HEL mounted on an infantry squad vehicle (Figure 9). The U.S. Army recently selected Blue Halo, prime contractor, to deliver AMP-HEL prototypes by fiscal year 2024. The AMP-HEL is intended to provide defense capability for division and brigade combat teams from the growing drone threats (Watkins, 2023).

Figure 9

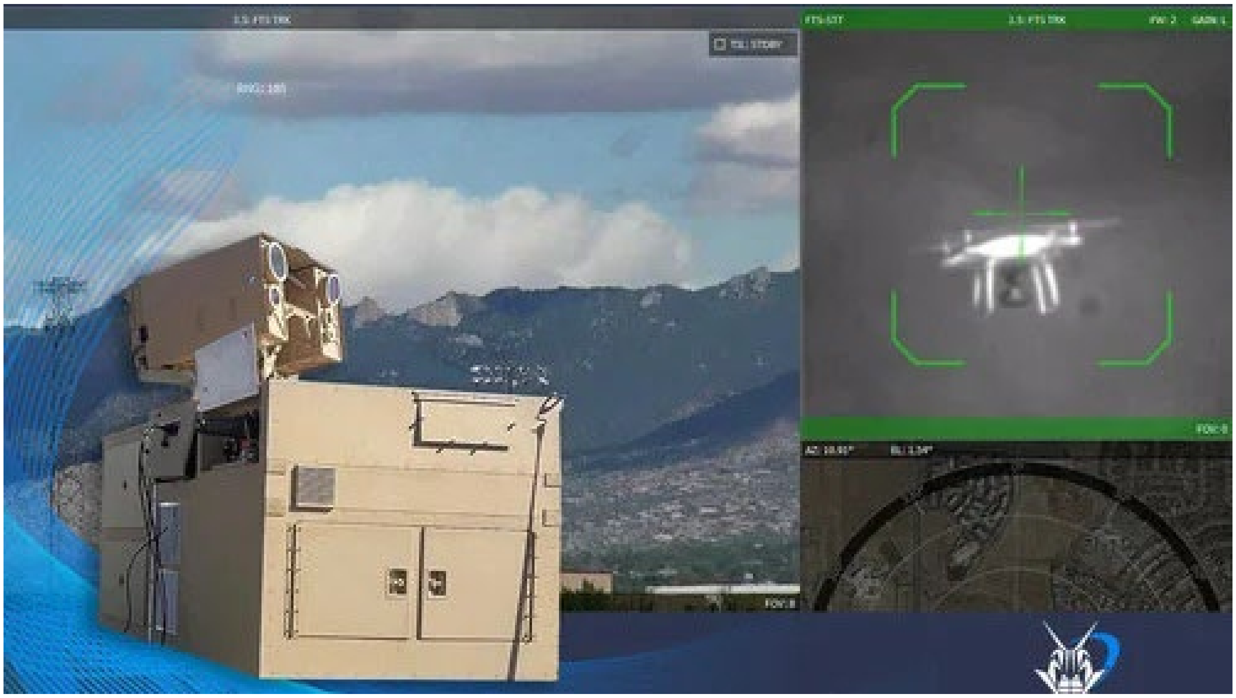
AMP-HEL prototype rendering

Note. Image sourced from “US Army to mount high-energy laser on Infantry Squad vehicles to destroy drones” by Watkins, R. The Defense Post. (https://www.thedefensepost.com/2023/04/12/us-army-laser-weapon-squad-vehicles/)

Palletized-High Energy Laser (P-HEL). The P-HEL is a 10kW-class HEL mounted on a pallet (Figure 10). Blue Halo, prime contractor, helped deliver the first P-HEL prototype in fiscal year 2022 which was deployed overseas for field assessment. The program was supported by the JCO. P-HEL is designed to combat the threat of sUAS (Chakraborty, 2022).

Figure 10

P-HEL prototype



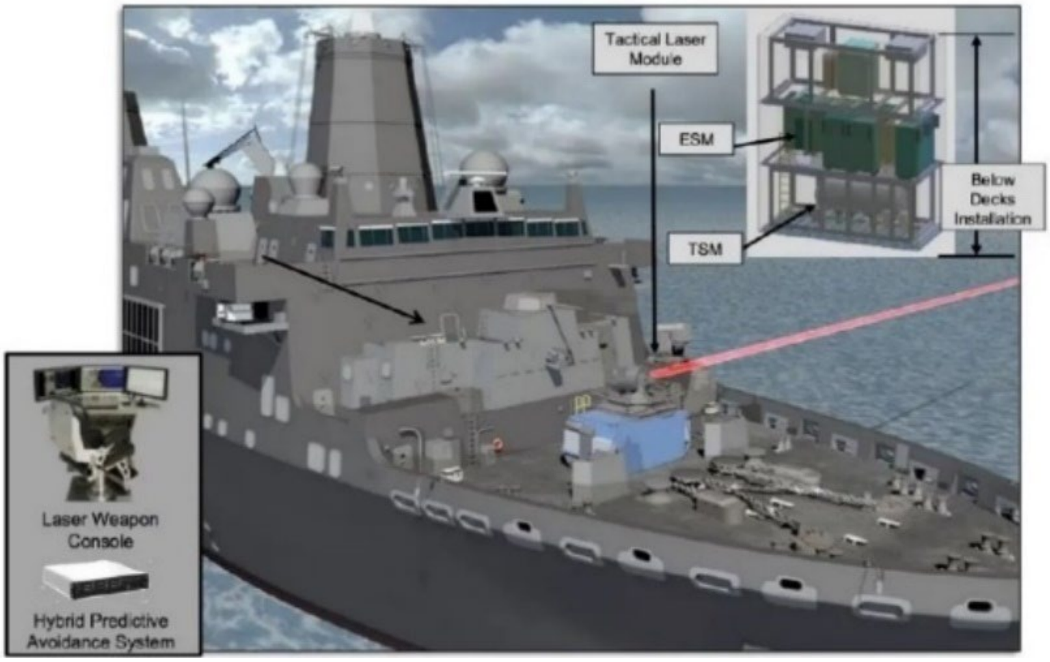
Note. Image sourced from Chakraborty, A. (2022, April 21). “BlueHalo delivers locust system for P-Hel Program. Army Technology” by Chakraborty, A. (https://www.army-technology.com/news/ bluehalo-locust-p-hel/)

Navy HEL weapon systems development

Solid-State Laser Technology Maturation (SSL-TM). The SSL-TM is a 150kW-class HEL mounted on amphibious ship USS Portland (Figure 11). The Navy selected Northrop Grumman, prime contractor, to deliver the prototype. The SSL-TM is intended to address asymmetric threat – unmanned aircraft systems, small boats and ISR sensors (Rogoway, 2019).

Figure 11

Navy graphics of SSL-TM installed on USS Portland



Note. Image sourced from "Mysterious object Northrop is barging from Redondo Beach is a high-power naval laser" by Rogoway, T. The Drive. (https://www.thedrive.com/the-war-zone/30500/that-big-mystery-object-northrop-is-barging-from-redondo-beach-is-a-high-power-laser)

High Energy Laser with Integrated Optical dazzler and Surveillance (HELIOS). HELIOS or Surface Navy Laser Weapon System (SNLWS) Increment 1 is a 60kW-class HEL and dazzler installed onboard the destroyer Preble (DDG 88). The Navy selected Lockheed Martin, prime contractor, to deliver the prototype (Figure 12). HELIOS is scalable to 120kW-class HEL and is intended to counter drones, ISR sensors, small boats, and damage assessment (O'Rourke, 2023).

Figure 12

Artist rendering of HELIOS installed on destroyer Preble

Note. Image sourced from "Destroyer Preble to get Lockheed high-energy laser in 2022" by Katz, J. Breaking Defense. (https://breakingdefense.com/2022/01/destroyer-preble-to-get-lockheed-high-energy-laser-in-2022/)

High Energy Laser Counter Anti-ship cruise missiles Program (HELCAP). HELCAP is a 300kW-class HEL currently under development for completion in fiscal year 2024. The Office of the Secretary of Defense (OSD) laser scaling initiative will provide one of the solutions as the laser source. HELCAP is intended to defend against targets like Anti-Ship Cruise Missiles (ASCM) (O'Rourke, 2023).

Implementation of HEL weapon systems

The characteristics associated with implementation of HEL weapon systems can be broken into distinct benefits and limitations.

Benefits –

Swift Engagement Times: HEL weapon systems utilize an efficient kill chain for engagement.

The kill chain includes detection, acquisition, pointing, tracking, and irradiation. During irradiation, laser beams reach their targets almost instantly since they travel at the speed of light. This eliminates the need for calculating intercept courses, as is required with interceptor missiles. Through concentrated, high-energy focus on a designated point, a laser inflicts debilitating damage on its target within a matter of seconds. The extent of this damage is contingent on the laser's power output. Moreover, the highly maneuverable nature of the beam allows for immediate retargeting, facilitating rapid-fire engagement sequences and efficient neutralization of multiple targets (Sayler et al., 2023).

Low Cost per Shot: HEL weapon systems offer a cost-effective solution for engagements. Despite the potential high upfront costs associated with the development of HEL weapon systems, their cost per engagement is considerably lower. DoD officials estimate a firing cost of just $1-$10, the cost of fuel needed to operate the power and cooling systems. This stands in stark contrast to the hefty millions per shot for defensive missiles, allowing for more frequent and flexible engagements (GAO, 2023).

Precision Engagements: HEL weapon systems are characterized by precision engagement capabilities. The laser beam's irradiation area, which can range from several millimeters to several inches in diameter, allows for precise targeting, affecting only the intended target without directly impacting nearby objects (Sayler et al., 2023).

Magazine Depth: Unlike traditional weapon systems that use ammunition and depend on significant logistics supply chain, HEL weapon systems are electrically recharged and need no mechanical reloading. Their firepower depends solely on available power and cooling, readily provided by the platform itself. As long as power keeps flowing and heat is under control, they can fire repeatedly (GAO, 2023).

Graduated Responses: HEL weapon systems offer a spectrum of functions beyond target destruction. They can detect, monitor, and produce non-lethal effects, such as reversible jamming or dazzling of target electro-optic (EO) sensors. HEL weapon systems enable graduated responses, ranging from delivering disabling damage to targets, causing limited damage as an escalated warning, or warning targets by temporarily jamming systems when necessary (Sayler et al., 2023).

Limitations –

Line of Sight: Laser light travels through the atmosphere in a straight path. As a result, HEL weapon systems are constrained by line-of-sight engagements, limiting their effectiveness against targets beyond the line of sight. Additionally, this results in limited engagement ranges for certain targets, particularly low-flying ones addressed by ground-based HEL weapon systems (Sayler et al., 2023).

Distance to Target: HEL weapon systems tend to be less effective towards targets that are at a farther distance. Focus and ability to maintain aim point by HEL weapon systems has significant impact on the amount of energy (kW/cm^2) imparted on the target. Focus is a function of the size of the optical lenses and mirrors and aim point lock depends on the sensitivity of the control feedback loop (GAO, 2023).

Atmospheric Absorption, Scattering, and Turbulence: Various atmospheric factors, including turbulence, salt particles, dust, smoke, sand, and water vapor can absorb and scatter laser light. This results in defocus of the laser beam which reduces effective range. Absorption by water vapor is particularly relevant in marine environments with high humidity. Designing lasers to emit light at wavelengths with reduced atmospheric absorption can maximize effectiveness. However, lasers are less suitable for longer-range operations since absorption generally increases with distance to the target. Adaptive optics can counteract atmospheric turbulence effects, but lasers may not function well in rain or fog, limiting their all-weather capabilities (GAO, 2023).

Thermal Blooming: Prolonged firing in the same direction can heat the air, causing thermal blooming, which results in a defocusing effect. Thermal blooming is more problematic when countering targets coming directly toward the laser ("down-the-throat" shots), especially as laser power increases. Tests often involve crossing targets rather than direct approaches (Sayler et al., 2023).

Delicate Components: HEL weapons rely on pristine optics for precise laser transmission. Even tiny impurities like dust or contaminants can disrupt the beam and damage the lenses, absorbing heat and causing cracks. Therefore, these sensitive components are maintained and repaired in dedicated clean rooms to ensure immaculate condition (GAO, 2023).

Saturation Attacks: The inherent sequential engagement capability of HEL weapon systems, coupled with their potential dwell time per target, presents a critical vulnerability in scenarios characterized by coordinated saturation attacks, where multiple hostile entities approach the platform concurrently or within rapid succession. Mitigation strategies involve the integration of additional laser modules, subject to constraints of platform space and available energy reserves (Sayler et al., 2023).

Hardened Targets and Countermeasures: For hardened targets equipped with shielding, high-reflectivity surfaces, or ablative materials, laser effectiveness diminishes significantly, particularly for kilowatt-range systems. Countermeasures such as smoke or other obscurants, while increasing target weight and cost, can offer effective mitigation against laser targeting and engagement (Sayler et al., 2023).

C-sUAS and HEL weapon systems

In 2008, the Joint Unmanned Aircraft Systems Center of Excellence (JUAS CoE), in collaboration with the U.S. Special Operations Command (USSOCOM) and the Services, created UAS categories for planned and existing DoD UAS. The vice-chairman of the Joints Chiefs of Staff approved these categories (U.S. Army, 2010).

Table 1 delineates the categories of UAS based on their speed, maximum weight, and operational altitude. As outlined in the table, Groups 1-3 encompass smaller-scale UAS characterized by shorter operational ranges. These UAS pose significant challenges in terms of detection and counter measures compared to their larger counterparts. Owing to their cost-effectiveness and widespread availability, non-state actors are more inclined to employ Groups 1-3 sUAS for tasks like reconnaissance, surveillance, precise payload delivery, and disruptive activities. On the other hand, Groups 4-5 UAS are notably larger in size, capable of covering substantial distances, and typically entail higher costs than Groups 1-3 sUAS. Due to their size and expense, these UAS categories are more commonly employed by state actors for various purposes (U.S. Army, 2010).

Table 1

DoD defined UAS categories

UAS Category	Max Gross Takeoff Weight	Normal Operating Altitude (Ft)	Airspeed
Group 1	< 20 pounds	< 1200 above ground level (AGL)	<100 Knots
Group 2	21-55 pounds	< 3500 AGL	<250 Knots
Group 3	< 1320 pounds	<18,000 mean sea level (MSL)	
Group 4	> 1320 pounds		Any Airspeed
Group 5		> 18,000 MSL	

Note. As an instance, if a UAS has two characteristics in Group 1 and one characteristic in Group 2, it is still considered a Group 2 UAS. Table sourced from "U.S. Army Unmanned Aircraft

Systems Roadmap 2010-2035: Eyes of the Army." U. S. Army Report ADA518437 p. 12. (https://apps.dtic.mil/sti/tr/pdf/ADA518437.pdf).

The establishment of the JCO in 2020, with the U.S. Army as its executive agent, represents a pivotal juncture in coordinating and directing C-sUAS activities. The JCO's core mission: lead, synchronize, and guide joint initiatives. This encompasses formulating and overseeing crucial facets like doctrine, requirements, equipment, training, and capabilities. The ultimate objective: establish a unified solution, built on a common architecture, to effectively counter and contain existing and future sUAS threats (DoD, 2021).

Through the JCO's efforts, the Department ensures a consistent approach, harmonized technology adoption, cohesive operational frameworks, and alignment of developmental goals for joint C-sUAS solutions. Furthermore, as part of the Department's ongoing drive to eliminate unnecessary duplication and enhance program efficiency and effectiveness, the JCO serves as a central hub for coordination across numerous organizations. This collaborative approach is geared towards preventing redundant efforts and maximizing the overall efficiency and effectiveness of program activities and developmental endeavors (DoD, 2021).

As depicted below, HEL weapon systems offer a number of advantages over traditional C-sUAS methods such as kinetic weapon systems and electronic warfare.

Advantages of HEL weapon systems specifically for C-sUAS (Angell, 2012) --

- **Precision**: HEL weapon systems can be focused on a very small area, making them ideal for engaging small UAS targets.
- **Speed**: HEL weapon systems tracking algorithm allows for fast slew rate and aim-point lock reduces irradiation time, making them ideal for engaging fast-moving small UAS targets.

- **Non-lethal effects**: HEL weapon systems can be used to disable small UAS targets without destroying them. This is important for situations where it is necessary to capture or recover the UAS.
- **Cost-effectiveness**: HEL weapon systems are relatively inexpensive to operate.

Challenges of using HEL weapon systems specifically for C-sUAS (Angell, 2012) --

- **Detection and Discrimination**: The optics and tracking algorithms used in HEL weapon systems require precision to detect and discriminate small UAS targets especially with background clutter. Additionally, the algorithms must deconflict with friendly air traffic and, due to the nature of the laser, extend all the way up to satellites in orbit.
- **Atmospheric attenuation**: HEL weapon systems are susceptible to atmospheric attenuation, which means that the beam of light can be weakened or scattered by clouds, rain, or other atmospheric conditions.
- **Maintenance**: The optics used in HEL weapon systems are specialized and currently have long lead times for production. The supply chain limits the quantity of spare parts for maintenance.

At the Space and Missile Defense Symposium held in August 2023, MG Sean Gainey, director of the JCO, acknowledged that progress is being made in terms of training and organization for HEL C-sUAS weapon systems, but the challenge lies in sustaining these systems for broader deployment. The U.S. Army has deployed 10kW-class HEL weapon systems for operational assessments to commands such as Indo-Pacific Command (INDOPACOM)), Central Command (CENTCOM), and Africa Command (AFRICOM). A 20kW-class HEL weapon system is also planned for CENTCOM. However, deployments have encountered challenges in maintaining these weapon systems, particularly in remote areas like AFRICOM, where acquiring spare parts and skilled technicians for repairs is a major challenge (Roque, 2023b).

HEL weapon system research and development efforts

Current research and development efforts are aiming to address several HEL weapon system challenges. These include issues related to space, weight, and power, testing limitations, defense industrial base, battle management, tactics, techniques, and procedures (TTPs), maintainability, and user safety concerns (GAO, 2023).

Space, Weight, and Power: Integrating HEL weapon systems into existing platforms, whether these are vehicles, ships, or aircraft, presents a significant challenge. This integration can range from straightforward connections to more complex modifications, such as reconfiguring sections of Navy ships. HEL weapon systems require power, which can either be self-contained within the weapon system or supplied directly by the platform. Effective thermal management of HEL weapon systems remains a critical challenge. The substantial heat generated by laser firing necessitates the implementation of robust cooling mechanisms, potentially consuming significant space aboard platforms with limited capacity. Furthermore, the current efficiency rate of HEL weapons, ranging from 25 to 40 percent, highlights the need for advanced energy management solutions to mitigate the generation of excess heat as waste. Addressing these multifaceted challenges necessitates meticulous planning and innovative engineering approaches (GAO, 2023).

Testing Limitations: Operational environment testing for HEL weapon systems poses unique challenges, particularly regarding airborne engagements. Inadvertent laser irradiation of orbiting satellites can be dangerous, necessitating stringent safety protocols. To mitigate these risks, centralized laser clearinghouse authorization protocols are mandated prior to any above-horizon firing during testing, training, or maintenance activities. This inherent constraint contrasts with conventional kinetic weapon system testing, potentially limiting the scope of HEL weapon system operational capability evaluations and potentially delaying the comprehensive understanding of system strengths and limitations until post-deployment phases (GAO, 2023).

Defense Industrial Base: The limited adoption of HEL weapon systems within the defense industrial base is primarily attributed to the absence of clear and sustained commitments from the DoD regarding future procurement. Unlike other emerging technologies with established commercial applications, key optical components for HEL weapon systems lack a commercial market, posing significant financial risks for industry partners. Consequently, industry representatives emphasize the vital role of a robust demand signal from the DoD to incentivize significant internal investments in HEL development. Furthermore, the current high development costs per unit are intrinsically linked to the relatively small number of initial development efforts. Large-scale production of HEL weapon systems could potentially mitigate these costs through economies of scale (GAO, 2023).

Battle Management: Battle management encompasses the decision-making process for commanders across all levels of conflict, guided by the information available to them. In pursuit of operational objectives, commanders evaluate various factors when selecting weapon systems, often prioritizing rapid decision-making, especially when dealing with extensive data. The utilization of HEL weapon systems by commanders will entail a thorough assessment of their advantages, including cost-effectiveness, and constraints, such as time constraints related to target engagement. HEL weapon systems may not possess the same range capabilities as kinetic weapon systems, which can complicate the decision-making process regarding when and how to deploy them as layered defense capability (GAO, 2023).

Tactics, Techniques, and Procedures (TTPs): HEL weapon systems necessitate the development of new TTPs. These processes guide how military personnel utilize a specific technology operationally. Unlike TTPs of traditional kinetic weapon systems, which require minimal changes in use and are well understood, HEL weapon systems demand a fundamental reevaluation of tactics. The tactics envisioned by developers may not align with how warfighters would employ the system, prompting the need for tactical revisions and potentially design adjustments. The development of TTPs for HEL weapon systems across a wide range of applications is an ongoing process (GAO, 2023).

Maintainability: The internal components of HEL weapon systems possess a high degree of sensitivity, necessitating specialized clean room environments for maintenance and repair procedures. This susceptibility was exemplified by a deployed HEL weapon system experiencing operational complications related to battery charging and cooling, ultimately requiring its return to the manufacturer in the United States for rectification. This incident resulted in a reduction in system availability, a critical factor in the efficacy and operational readiness of weapon systems. The development of robust and efficient maintenance and sustainment processes for deployed weapon systems is a paramount responsibility, as the ease of maintenance and repair significantly influences decision-making processes during the evaluation and selection of different technology options (GAO, 2023).

User Safety Concerns: Concerns regarding user safety within the context of HEL weapon systems have been voiced by several officials within the DoD and various military departments. These concerns primarily stem from apprehension surrounding potential biological effects, specifically the risk of personnel sustaining irreversible visual damage due to laser exposure. To address these concerns and ensure the well-being of personnel, the DoD has implemented robust safety measures, including the establishment of a comprehensive Joint Services Laser System Safety (LSS) review process. This framework encompasses rigorous testing protocols and stringent safety regulations designed to mitigate potential risks associated with HEL operation. Furthermore, the DoD has recognized the crucial role of user education in alleviating anxieties and fostering the adoption of this emerging technology. Through comprehensive training programs and open communication channels, the DoD aims to cultivate a culture of safety and understanding within the ranks, facilitating the successful integration of HEL weapon systems into operations (GAO, 2023).

Summary

The literature review reveals that HEL DE technology has been developed since the 1950s and that currently solid-state fiber laser technology has military utility due to excellent beam quality, high efficiency, compact size, and robust thermal management. The state of U.S. military HEL weapon systems development is very active across the Air Force, Army, and Navy. HEL weapon systems implementation has distinct benefits and limitations. The current focus on C-sUAS is driving increased JCO interest in HEL weapon systems. The DoD is pursuing multiple research and development efforts to address the challenges of fielding HEL weapon systems. The next section will provide the research methodology supporting this study.

Research Methodology

Statement of Purpose

The purpose of this qualitative study is to explore the solid-state HEL DE Technology and its application as C-sUAS weapon systems in the U.S. Army.

Research Questions

1. What is solid-state HEL DE technology?
2. What is the state of HEL weapon systems development in the U.S. military?
3. What characteristics are associated with implementing HEL weapon systems?
4. What are the advantages and challenges of using HEL specifically as C-sUAS weapon systems in the U.S. Army?
5. What challenges are current research and development efforts aiming to address for HEL weapon systems?

Research Methodology

The research for this study was broken down into three areas. The first area described the physics of laser, history and its progress into solid-state Fiber technology. The second area shared the literature on the state of U.S. military development for HEL weapon systems and identified the characteristics of implementing HEL weapon systems. The third area focused on the different types of sUAS and the advantages and challenges in using HEL as C-sUAS weapon systems. The literature review also shared the current research and development efforts addressing several HEL weapon system challenges.

This research paper utilized a qualitative methodology. Qualitative research thrives when the research problem remains shrouded in ambiguity. Its strength lies in its ability to inductively explore and illuminate the inherent structure, processes, and meanings within a phenomenon, allowing researchers to unveil and define the very variables that frame the investigation (Creswell & Guetterman, 2021). This qualitative research is limited to publicly released information and is governed by classification concerns. Notably, data collection for this qualitative research does not contain interviews with HEL and C-sUAS subject matter experts.

The author used multiple databases including U.S. Army publications website, DTIC, Google Scholar, Lawrence Technical University Library, EBSCOhost, and ProQuest to complete the research. Search terms included “Laser”,” Fiber Laser”, “Directed Energy Weapons”, and “Drones”. The search results were filtered to only include articles with full text availability that were peer-reviewed. Additionally, numerous excerpts, books, and articles were reviewed to limit the research to the most relevant information related to HEL and C-sUAS. The research questions served to guide the collection of data from these sources. A thematic analysis synthesized the collected data to answer the research questions and integrated the information across multiple sources to arrive at findings and relevant conclusions in using HEL as C-sUAS weapon systems. The research maintained a limited scope for DE technologies to Solid-State HEL and air defense weapon systems to C-sUAS in the U.S. Army.

Summary

This section outlined the research methodology, data collection methods, and analysis methods, as well as illustrated the weaknesses associated with the research. Numerous databases and relevant search terms were used to answer the research questions. The data was analyzed through qualitative methods to describe the state of HEL weapon systems development and use as C-sUAS weapon systems. The next chapter presents the findings of qualitative analysis and whether they support this research's premise.

Findings

Introduction

This section presents the key findings derived from the review of relevant literature, meticulously aligned with the research questions set forth at the outset. These findings constitute the cornerstone for the subsequent discussion of conclusions and recommendations.

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Results

As a result of the qualitative analysis, various findings were revealed. The current Russian-Ukrainian battlespace represents a historic shift in warfare tactics and technology, marked by intensive use of drones to date (Franke, 2023). Recognizing the inevitability of drone usage in the current and future battlespace, the U.S. military is actively seeking solutions with a common architecture to address present and anticipated drone threats (DoD, 2021).

Laser systems have made significant progress over the years. Solid-state fiber laser systems provide excellent beam quality, high efficiency, compact size, and robust thermal management. By combining multiple fiber gain modules using spectral beam combining, fiber lasers have achieved kW-class output powers providing potential for a weapon system capable of cost-effective interdiction of sUAS (Dawson et al., 2008).

With an annual budget of $1 billion, the U.S. military is pushing forward with developing directed-energy weapon systems, including HEL weapon systems. All three services – Air Force, Army, and Navy – are currently developing and testing multiple HEL weapon systems. However, a limited number of HEL weapon systems are currently fielded in an operational environment.

The implementation of High Energy Laser (HEL) weapon systems offers distinct benefits, including swift engagement times due to the speed of light, low cost per shot as the cost mainly involves converting electrical energy to light energy, and precision engagement, as the laser beam's irradiation area can range from several millimeters to several inches in diameter. Additionally, High Energy Laser (HEL) weapon systems potentially have a large magazine depth, as the capacity for fire depends on sufficient electrical power and thermal management. They also offer graduated responses, as HEL weapon systems can provide a spectrum of functions beyond target destruction.

However, there are limitations in implementing HEL weapon systems like constraint by line of sight due to light's inability to bend with the earth's curvature. Additionally, the ability to focus is constrained by the size of optical lenses and mirrors, which determines the aim point distance to target. The atmospheric absorption of light energy and thermal blooming, due to heating effect of the air, leads to reduced energy (kW/cm^2) on the target. Furthermore, HEL weapon systems are sensitive to contaminants or debris which can result in hot spots on optical lenses or mirrors. The literature review does not share energy key performance parameters and sustainment key performance parameters that might drive employment limits. However, the magazine depth in the operational world will be impacted by power supply (batteries/generators) availability and optical lens and mirror reliability, maintainability, down time and supply chain.

Group 1-3 UAS, classified as small Unmanned Aircraft Systems (sUAS), are the focal point of Counter-small Unmanned Aircraft Systems (C-sUAS) efforts. Established in 2020, the Joint Counter-small Unmanned Aircraft Systems Office (JCO) plays a pivotal role in coordinating and directing these activities, with its core mission being to lead, synchronize, and guide joint initiatives. As part of its mandate, the JCO is currently evaluating High Energy Laser (HEL) weapon systems as a potential C-sUAS capability. HEL weapon systems offer a number of advantages over traditional C-sUAS methods, such as kinetic weapon systems and electronic warfare. Advantages include precision, as lasers can be focused on a very small area; speed, as lasers travel at the speed of light; and cost-effectiveness, as lasers are relatively inexpensive to operate. However, when used as C-sUAS weapon systems, HEL must overcome challenges related to the detection and discrimination of small UAS, atmospheric attenuation, and maintenance of sensitive components.

Current research and development efforts are aiming to address several challenges associated with HEL weapon systems. These include issues related to testing limitations, the defense industrial base, space, weight, and power, maintainability, battle management, TTPs, and user safety concerns.

Summary

This section presents the research findings gleaned from a comprehensive review of relevant literature, focusing on the potential of HEL weapon systems as a cost-efficient countermeasure to drone attacks. While acknowledging inherent challenges and limitations, the findings provide insightful answers to the initial research questions while paving the way for further exploration. The subsequent section will present the conclusions derived from this study, accompanied by specific recommendations and the identification of several promising areas for additional research.

Conclusions and Recommendations

Introduction

The following section presents the conclusions, recommendations, and potential avenues for further research derived from this study. The dynamic nature of Directed Energy technologies might necessitate the reevaluation of the assumptions and conclusions presented herein, due to potential technological advancements in the foreseeable future.

Conclusions

The following are six conclusions derived as a result of the research.

1. The primary conclusion from this study is that Solid-state fiber laser technology shows strong potential as the core of an effective HEL weapon system for defense against small drone threats, based on beam quality, high efficiency, power scaling capability, and thermal management. Multiple sources highlighted the benefits of the technology, including high efficiency in converting electricity to light for lasing, the ability to manage waste heat effectively, and near diffraction-limited beam quality. These strengths enable the modular scaling to higher power levels necessary for an operational C-sUAS laser weapon system. The promise exists for a robust, easily maintainable HEL weapon system capable of defeating small drone targets.
2. The U.S. military views HEL weapon systems as a promising capability for countering drone threats and is actively developing and testing HEL prototypes across the Air Force, Army, and Navy. The funding and prototype development across services indicate a consensus on the need and priority for such systems. However, the literature review found limited examples of fielding to date. This highlights the remaining development and integration challenges to transition the promising prototypes into deployed weapon

systems. These challenges include developmental costs, power demands, thermal management, and platform space constraints.

3. HEL weapon systems offer significant advantages in speed, operation cost effectiveness, precision and graduated response over traditional kinetic weapons for C-sUAS missions. Benefits are centered around speed of light engagement, lower cost per shot, precision, and flexible options between disabling and destroying targets.
4. The limitations of HEL weapon systems persist with adverse weather conditions, component fragility, and platform integration challenges. Weaknesses highlighted include factors that degrade laser effectiveness, such as drag from moisture or particles in the air, and blooming or defocusing effects over long distances due to thermal heating. Additionally, field maintenance and repair of sensitive optics remains a concern for achieving reliable operational capability.
5. While the services have historically pursued separate development activities, the Joint Staff has mandated a unified approach to fielding C-sUAS systems. This approach aims to channel investments, prevent duplication, and enhance future joint interoperability of fielded systems. The JCO will play a pivotal role in assessing and integrating service-led high energy laser efforts within a common C-sUAS ecosystem architecture. This unified governance model should serve as an example for how to approach other future contested domains.
6. Current R&D efforts are focused on addressing integration challenges related to size, weight and power demands along with improving testing, sustainment, battle management integration and user adoption. However, major constraints hindering transition to broader HEL fielding include initial developmental costs, dealing with

significant waste heat dissipation, adapting and hardening sensitive optics around different environments.

Recommendations

The following are the six recommendations informed by the research.

1. The U.S. Army, in coordination with the JCO, should continue advanced development and operational testing of HEL weapon systems for C-sUAS capabilities. This effort should focus on platform integration, refining of tactics and procedures and user familiarization. To build confidence for wider HEL C-sUAS weapon systems adoption, the U.S. Army should integrate them into battalion-level field exercises, quantify performance against surrogate targets, and expose brigade combat teams to employment concepts. Live-fire operational tests will prove system efficacy and surface integration issues.
2. Further research into extending lasing duration and improving optical components' durability and environmental robustness will enhance operational employment of HEL C-sUAS weapon systems. Maturing HEL technology, including advancements in battery storage density, mobile power generation, and adaptive optics, should remain a priority. These advancements are crucial to fulfilling the promise of HEL weapon systems against drone threats.
3. In parallel with developing materiel solutions, the U.S. Army should assess distributed lethality options, multi-domain fire control connectivity, airspace deconfliction requirements and human factors to prevent blinding friendly optics. Realistic training events, with scalable drone threat surrogates, are needed to develop and refine HEL-specific tactics, techniques, and procedures (TTPs) for Army field manuals.

4. Test ranges and test organizations should streamline overly prohibitive C-sUAS HEL testing restrictions which negatively impact realism. Policies should adopt a risk management approach like laser safety certifications.
5. As individual HEL C-sUAS prototypes mature, the Army should conduct program alignment reviews to ensure interoperability. This includes interfaces, message sets, network transport layers, data formats, timing services, application layer standards, and information assurance levels. Such guidance is imperative to prevent divergence and enable flexible assignment of HEL weapon systems between platforms.
6. The services, in coordination with the JCO, should consider expanding their long-term acquisition strategy with funding. This will encourage the defense industrial base for broader investments in HEL technologies necessary for affordable scale-up in HEL optical components, beam directors, thermal management and system integration.

Areas for Future Research

The following are areas for future research on DE technology and weapon systems –

1. Laser DE Technology for other Air Defense applications.
2. High-Power Microwave DE Technology.
3. Use of machine learning and artificial intelligence to improve detection, acquisition, pointing, and tracking algorithms used in DE weapon systems.
4. Ethical and legal considerations surrounding the use of DE weapon systems in air defense.
5. Development of Doctrine, Organization, Training, Leadership, Personnel, Facilities and Policies (DOTLPF-P) required for operating DE weapon systems (materiel solution), highlighting similarities and differences from traditional air defense weapon systems.
6. State of DE weapon systems and drone development among allies and adversaries.

Summary

This qualitative study was aimed towards the solid-state HEL DE Technology and its application as C-sUAS weapon systems in the U.S. Army. The research described the development of high energy lasers; the advent of solid-state fiber laser and multiple fiber gain modules which resulted in sufficient power to utilize them for military application. The study explored the state of HEL weapon systems development in the U.S. military and their benefits and limitations. The study explained the categories of UAS, the role of JCO in the DoD and the advantages and challenges of using HEL as C-sUAS weapon systems. Finally, the study looked at several HEL weapon system challenges being addressed by current research and development efforts.

Witnessing the extensive drone warfare in Russia-Ukraine, the U.S. military is acutely aware of the need for adaptable countermeasures. With drone fleets burgeoning on all sides, air defense systems and jamming techniques are becoming integral to modern warfare. However, these conflicts, characterized by remote engagements and miles-wide battlefields, necessitate innovative solutions beyond traditional defense methods. DE weapon systems, particularly HEL, are emerging as one of the potential stars of the U.S. Army's modernization efforts, offering a precise and agile response to the ever-evolving drone threat.

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Appendix A – Glossary of Acronyms

ADAR ....Air Defense Artillery Regiment

AFRICOM ....Africa Command

AFRL ....Air Force Research Laboratory

AMP-HEL............Army Multi-Purpose High Energy Laser

ASCM ....Anti-Ship Cruise Missiles

C-sUAS................Counter-small Unmanned Aircraft Systems

CENTCOM..........Central Command

CRS......................Congressional Research Service

DE ....Directed Energy

DE M-SHORAD..Directed Energy Maneuver-Short Range Air Defense

DJI........................Da-Jiang Innovations

DoD......................Department of Defense

DOTmLPF-P........Doctrine, Organization, Training, materiel, Leadership, Personnel, Facility - Policy

DTIC ....Defense Technical Information Center

EO ....Electro-Optic

GAO.....................Government Accountability Office

HELCAP..............High Energy Laser Counter Anti-ship cruise missiles Program

HELIOS ....High Energy Laser with Integrated Optical dazzler and Surveillance

HEL......................High Energy Laser

HELWS................High-Energy Laser Weapon System

IFPC-HEL............Indirect Fire Protection Capability-High Energy Laser

INDOPACOM .....Indo-Pacific Command

ISR ....Intelligence, Surveillance, and Reconnaissance

JCO ....Joint Counter-small Unmanned Aircraft Systems Office

JUAS CoE............Joint Unmanned Aircraft Systems Center of Excellence

kW........................Kilowatt

kW/cm^2 ....Kilowatt per square centimeters

LSS.......................Laser System Safety

OSD......................Office of the Secretary of Defense

P-HEL ....Palletized-High Energy Laser

R&D.....................Research and Development

SHiELD................Self-Protect High-Energy Laser Demonstrator

SNLWS................Surface Navy Laser Weapon System

SSL-TM ....Solid-State Laser Technology Maturation

sUAS....................small Unmanned Aircraft Systems

SSL-TM ....Solid-State Laser Technology Maturation

TTP ....Tactics, Techniques, and Procedure

UAS......................Unmanned Aircraft Systems

USSOCOM ..........U.S. Special Operations Command

Appendix B – Author Biography

Mr. Tarun Gupta most recently served as the Acting Director for the Directed Energy Project Office (DEPO) within the Army Rapid Capabilities and Critical Technologies Office (RCCTO), Redstone Arsenal, Alabama from April 2022 through July 2023. In this role, Mr. Gupta was responsible for oversight and execution of development, prototyping, test, evaluation, procurement, and fielding of Army Directed Energy technologies and capabilities that address near-term and mid-term threats, consistent with the Army's modernization priorities. In addition to delivering Directed Energy prototype weapon systems, Mr. Gupta also provided oversight on the coordination and alignment of the Army's Directed Energy Science and Technology (S&T) portfolio. He served as the Deputy Director for the DEPO from November 2019 until April 2022.

Prior to joining the Army, Mr. Gupta served as the Deputy Director for Test Planning & Design at the Missile Defense Agency. He was responsible for planning and designing an executable Ballistic Missile Defense System (BMDS) test program for the Agency based on engineering analysis of developmental and operational test requirements. This included the development and annual publication of an Integrated Master Test Plan (IMTP), aligned to the President's Budget submission, detailing the strategic test plan for the Agency. He was also responsible for the Agency's test baseline management and configuration control and for pre- and post-test analysis activities supporting Flight and Ground tests. Mr. Gupta held various leadership roles during his tenure with the Missile Defense Agency from March 2010 until November 2019.

Mr. Gupta has served in the Federal Government for the last 14 years. Prior to this, he held a career in the Automotive Industry – Chrysler, Siemens VDO, and Continental Automotive – in Alabama for 15 years. He holds a bachelor's and master's degree in electrical engineering from Auburn University in Auburn, Alabama. He is a Defense Acquisition Corps member. He was inducted as a member of the Honorable Order of Saint Barbara in 2022 and received the Department of the Army Meritorious Civilian Service Medal in 2023.