Systematic Review Article

Autonomous Weapons Systems: An Analytical Review of Technological Capabilities, Operational Challenges, and Mitigation Strategies

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ABSTRACT

While substantial research has explored individual components of autonomous weapons systems (AWS), this study provides a comprehensive analysis comparing their capabilities, implementation methods, and effectiveness factors across different systems and operational contexts. This systematic literature review examines 49 studies from 2,847 initial records to investigate technological capabilities, operational challenges, and mitigation strategies that define contemporary AWS programs. The analysis shows that AWS capabilities have evolved from early automated systems to advanced platforms incorporating artificial intelligence, cutting-edge materials, and network-centric integration. Three categories of challenges primarily constrain the development of AWS: computational optimization difficulties in weapon-target assignment systems, complexities in mechanical systems integration, and limitations in materials science. The key findings suggest the effectiveness of virtual reality training systems, which achieve over 80% accuracy in military applications; advanced multi-objective evolutionary algorithms (MOEA/D-iAM2M) demonstrating superior convergence and diversity in weapon-target assignment optimization; and aluminium-carbon nanotube composite materials with enhanced ballistic protection capabilities. The findings also offer important insights for military planners and defense contractors, highlighting the importance of focusing on systems that show dependable integration and investing in communication capabilities to support network-centric warfare. Moreover, the rapid advancements in artificial intelligence (AI), materials science, and manufacturing technologies suggest an ongoing expansion of AWS capabilities, necessitating continuous research into reliability, effectiveness, and responsible deployment.

Keywords: Autonomous weapons systems; Weapon-target assignment optimization; Network-centric warfare; Advanced composite materials; Military technology

INTRODUCTION

Development and deployment of autonomous weapons systems (AWS) have surged exponentially over the last few years, with worldwide military spending on unmanned systems totalling about $12.9 billion in 2023, growing 15% annually (1). These investments are made by key military powers, such as the United States, China, Russia, and some European countries, in AWS

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capabilities, with operational deployments documented across various conflict zones from the Middle East to Eastern regions of Europe (2).

The creation, deployment, and performance of autonomous weapons systems are influenced by factors such as technological capabilities, operational needs, strategic considerations, and ethical limitations. Current studies have explored different aspects of AWS development. Lavazza (2) examined loitering munition systems and network-centric warfare integration, while Murr (3) investigated advanced manufacturing technology. Ball (4) focused on mechanical systems problems, and Yi (5) worked on computational optimization in weapon-target assignment systems, while Tsirogiannis (6) and Vidakis (7) studied recent advances in material science in composite armor and additive manufacturing.

Despite significant advancements in AWS research, a comprehensive evaluation comparing their capabilities, implementation strategies, and effectiveness drivers across different systems and operational environments remains scarce (11). While existing literature primarily addresses individual technical domains or specific AWS components (12), no systematic analysis integrates technical capabilities, operational challenges, and strategic considerations across varied system types and implementation contexts (13). This represents a critical knowledge gap given that artificial intelligence, material science, and manufacturing technology advancements have profoundly transformed the AWS development landscape (8), creating new opportunities while posing unprecedented challenges (9).

The systematic literature review addresses this research gap by providing a comprehensive comparative analysis that synthesizes technical capabilities, operational challenges, and mitigation strategies across multiple AWS domains and system types. It synthesizes findings from 49 empirical studies covering computational optimization, mechanical systems integration, and operational deployment to evaluate both the capabilities and constraints of current AWS technologies. In doing so, it aims to generate actionable insights for defence contractors, policymakers, and military planners engaged in the design and governance of autonomous systems. Specifically, this review examines current AWS capabilities, identifies key challenges that hinder their performance and deployment, and analyses the mitigation strategies and emerging technological solutions proposed within the literature. By adopting this holistic approach, the paper advances beyond previous single-domain analyses, offering a multidimensional understanding of how technological innovation, operational complexity, and strategic imperatives converge to shape the evolution of autonomous weapons systems.

LITERATURE REVIEW

Conceptual Frameworks and Contemporary AWS Evolution

The definition of autonomous weapons systems has evolved significantly with technological advancements (2), leading to various definitional constructs among military and international organizations (14). The U.S. Defence Science Board defines AWS as systems possessing the capability to act automatically (2) or govern themselves within pre-set limits (15), while the International Committee of the Red Cross provides a more operationally-focused definition (2), characterizing AWS as weapon systems that can select and attack targets without human intervention (14). Recent scholarship recognizes autonomy as existing on a continuum rather than as a binary state (16).

Lavazza (2) distinguishes between Autonomous Weapon Systems (AWS) and Semi-Autonomous Weapon Systems (S-AWS) based on the level of meaningful human control in system functioning. This dimensional approach acknowledges different degrees of human involvement across operational environments, with systems like the Samsung SGR-A1 robot platform demonstrating multiple operating modes from supervised to complete autonomy in target engagement (2).

Contemporary AWS capabilities represent a fundamental shift from conventional automated systems to sophisticated platforms integrating artificial intelligence, advanced materials, and network-centric architectures (17). The transition from mechanical automation to AI-driven autonomy marks a critical inflection point, with systems now capable of real-time decision-making in complex, dynamic environments (18).

Evolution of AWS and Current Technology

The convergence of artificial intelligence, advanced materials science (3), and manufacturing technologies has transformed AWS development paradigms (19). Modern systems incorporate machine learning algorithms for target recognition (3), advanced composite materials for enhanced protection and reduced weight, and additive manufacturing techniques enabling rapid prototyping and customized component production (20).

AI Integration

Contemporary AWS employ sophisticated algorithms for autonomous target identification and engagement (2). Loitering munition systems are an example of this evolution, with platforms like Iran's HESA Shahed 136, Russia's Geran2, and Turkey's STM Kargu incorporating infrared cameras and multi-sensor arrays for autonomous target detection in adversarial environments (22). These systems demonstrate jamming resistance through sensor fusion and autonomous decision-making capabilities.

Advanced Materials

Materials science breakthroughs have enabled new AWS capabilities through lightweight composites, enhanced protection systems, and multifunctional components (6). Aluminum-carbon nanotube composites and ceramic-polymer hybrid materials provide superior ballistic protection while reducing system weight, enabling greater mobility and endurance (7).

Manufacturing Revolution

Additive manufacturing has revolutionized AWS development by enabling rapid prototyping, customized components, and on-demand production of complex geometries that were previously impossible with traditional manufacturing (3). This capability supports modular system designs and field-deployable manufacturing for maintenance and upgrades.

Network-Centric Integration

Modern AWS operate as nodes within larger network-centric warfare architectures rather than standalone platforms. Integration with Advanced Battle Management Systems (ABMS) enables information superiority through data fusion, analysis, and optimization processes (2). This paradigm shift reflects the evolution towards system-of-systems approaches, where AWS effectiveness is amplified through networked operations.

Directed Energy Integration

The maturation of directed energy weapons represents another significant technological advancement (12). Laser-based systems provide light-speed engagement capabilities with minimal collateral damage (1) and enhanced operational stealth compared to kinetic weapons (21). These systems have evolved from laboratory demonstrations to near-operational deployment, with major defence contractors investing substantially in development programs.

Technical Challenges

Existing studies highlight major technical issues in AWS development (27), among which computational optimization is a key challenge, especially in weapon-target assignment (WTA) systems (28). According to Yi (5), conventional WTA models have focused on attack performance and weapon cost without effectively incorporating reliability factors. This leaves key gaps where assignments made solely based on damage potential and cost criterion could be ineffective for mission success (28).

Another key challenge is the integration of mechanical systems (29), as studied by Ball (4), who cites accuracy limits in dynamic modelling. He observes that earlier studies omitting weapon-based dynamic characteristics did not reconcile planned and trial outcomes for weapon dislocation during firing operations (4). The study demonstrates that four-degree-of-freedom models provide higher accuracy for analyzing weapon casing displacement compared to simplified methods (30).

Furthermore, virtual reality training systems have become essential enabler technologies (30). Steven (8) demonstrates how virtual reality platforms achieve over 80 percent accuracy in military training applications (31) and reduce stress-related performance failures in soldier training scenarios (8). The systems integrate wearable sensor networks and big data analytics to track overall performance (33).

Despite extensive literature on autonomous weapons systems, there are limited comprehensive analytical frameworks (9) that consider technical, operational, strategic, and ethical factors (32) altogether. This analytical review fills these gaps by exploring AWS development (9) in various dimensions and offering a systematic understanding of the evolution and future trends regarding autonomous weapons systems (32).

METHODS AND MATERIALS

Research Design

The study employs a systematic literature review to explore the current development of autonomous weapons systems, implementation challenges, and prospects following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (50).

A complete literature search was conducted across numerous theoretical records to ensure broad coverage of AWS-related research. The primary databases included the Institute of Electrical and Electronics Engineers

(IEEE) Xplore Digital Library, Journal Storage (JSTOR), Science Direct (Elsevier), Springer, and Google Scholar. The exploration approach employed free-text keywords with Boolean operators to combine search terms effectively.

The literature search used primary terms including "autonomous weapons systems," "lethal autonomous weapons," "AWS," "unmanned combat systems," and "robotic weapons." Secondary terms included "weapon-target assignment," "military robotics," "autonomous targeting," "unmanned military systems," and "combat automation." This strategy captured core AWS concepts, terminology variations, and related technologies to ensure comprehensive coverage of relevant research domains.

Inclusion and Exclusion Criteria

Table 1 shows the inclusion/exclusion criteria used for the search. These systematic criteria were applied during the four-stage study selection process for the literature review on autonomous weapons systems.

Study Selection Process

Study selection followed a systematic four-step process. Database searches yielded about 2,847 potentially relevant records, which were reduced to 2,156 after removing duplicates. The screening of titles and abstracts narrowed the pool to 487 records for full-text review, resulting in 49 studies included in the final analysis. The research papers were then grouped by main focus area, such as technical development, operational deployment, and policy analysis, to guarantee balanced representation across AWS research areas (Figure 1).

Data Extraction and Analysis Framework

A systematic data extraction framework collected essential information from the included studies. The framework included study details such as author(s), year of publication, study type, research methodology, sample size, and geographic location. Technical specifications involved AWS capabilities described, technological methods, performance measures, test environments, and validation procedures. Challenges and limitations addressed technical and operational constraints, policy implications, and mitigation measures. The analysis employed a narrative synthesis method, which is suitable for the heterogeneous methodologies and research questions of the included studies, aligning with established guidelines for analytical reviews in defence studies and technology assessment literature.

A. Stage 1: Initial Screening

Initial database searches yielded approximately 2,847 potentially relevant records. Duplicate records were identified and removed using both automated tools and manual verification, resulting in 2,156 unique records for screening.

B. Stage 2: Title and Abstract Screening

A title and abstract screening was conducted using the predetermined inclusion and exclusion criteria. This stage resulted in 487 records advancing to full-text review.

Table 1. Inclusion and Exclusion Criteria for Study Selection

Criterion	Inclusion Criteria	Exclusion Criteria
Temporal scope	Published between 2020 and 2024	Published before 2020
Language	Published in English	Other languages
Content relevance	Addressed autonomous weapons systems, related technologies, or directly applicable technical challenges	Focused solely on civilian applications without military relevance
Publication type	Peer-reviewed journal articles, conference proceedings, technical reports from recognized institutions, and policy documents from authoritative sources	Lacked peer review or institutional authorization
Disciplinary scope	Engineering, computer science, materials science, military studies	Addressed only theoretical possibilities without empirical grounding or technical specificity
Geographic scope	International coverage with no geographic restrictions	
Access limitation	Full text available through institutional subscriptions or open access repositories	Full text unavailable through institutional subscriptions or open access repositories

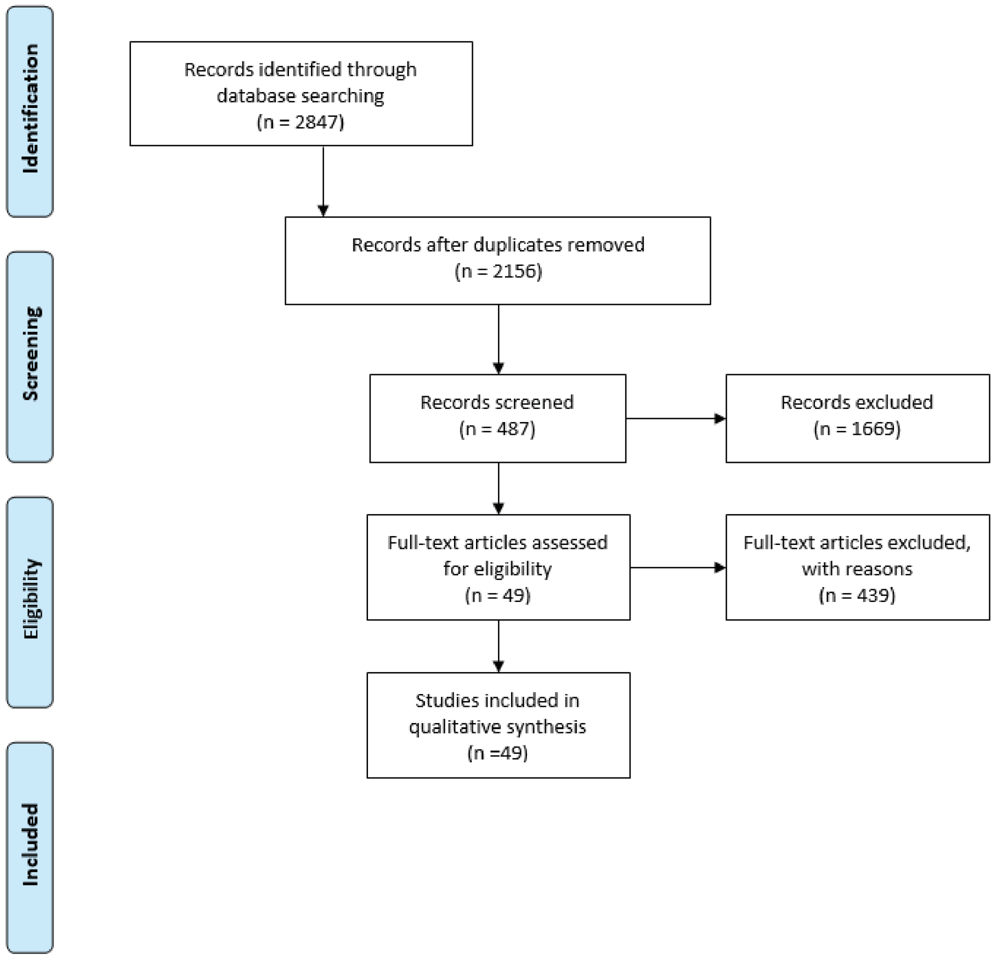

Figure 1. PRISMA Flow Diagram for Study Selection Process. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram illustrating the systematic study selection process for the literature review on autonomous weapons systems.

C. Stage 3: Full-Text Assessment

Full-text articles were retrieved and assessed for final inclusion. Studies were categorized by primary focus area (technical development, operational deployment, policy analysis, materials science) to ensure balanced coverage across AWS research domains. This process yielded 49 studies for final inclusion in the analytical review.

RESULTS AND DISCUSSION

Directed Energy Weapons and Advanced Targeting Systems

Directed energy (DE) weapons represent a paradigm shift in autonomous weapons technology, employing concentrated electromagnetic energy to incapacitate, injure, or destroy enemy targets. Ahmed (1) explains that directed energy systems utilize electromagnetic energy and nuclear or atomic particle formation, with DE weapons having evolved from laboratory bases to near-operational levels over decades of technological progress. The evolution from the first laser demonstration in 1960 at California's Hughes Research Lab required nearly half a century to achieve military-suitable applications, now offering unparalleled capabilities in coherence, high monochromaticity, and incredible power achievement (1).

The laser-based AWS provides significant advantages over traditional kinetic weapons (1), including light-speed transmission enabling instant target engagement upon detection (21), beam-directed energy for minimal collateral damage, and enhanced operational stealth compared to conventional systems (14). These surgical weapons offer precise target-point selection with high initial installation costs but low engagement operation costs, versatile deployment capabilities, and gradient effects between non-lethal and destructive applications.

The transition to laser-based systems addressed technological limitations of radio frequency coupled with digital signal processing systems from the 1970s to 1990s, which became insufficient for increasing data capacity requirements in electronic warfare, wider spectrum communications, and broadband radar systems (1). Laser technology provides superior alternatives for managing extensive capabilities and dynamic range processing needs in real-time military applications.

Major defence contractors, including Lockheed Martin, Northrop Grumman, Raytheon, BAE Systems, and Boeing provide substantial support for laser weapons development (1). China, Russia, Japan, and Germany conduct extensive research toward offensive laser technology applications, though no systems have been publicly cleared for battlefield deployment.

Network-Centric Warfare Integration

Contemporary AWS development focuses on integration with Advanced Battle Management Systems (ABMS) that achieve operational effectiveness through information superiority. Lavazza (2) defines ABMS as next-generation command and control systems aimed at attaining warfare superiority by delivering the correct information arrays at appropriate times and locations through data fusion, analysis, and optimization processes. These systems represent fundamental shifts into network-centric operational paradigms originally designed by Soviet Marshal Nikolai Vasilyevich Ogarkov and later adopted by Admiral William Owens, targeting the systematic integration of computer technologies, communications, and information to enable more effective combat operations (2).

Autonomous Defence Integration

Anti-ballistic missile systems (ABMS) demonstrate mature autonomous performance with reduced human involvement. ABMS such as long-range platforms S-500/S-400 or Patriots and mid-to-short-range systems including Buk3/Pantisir S2, S350 Vityaz operate independently of constant human observation, rapidly engaging targets within radar detection ranges (2). These defensive autonomous weapons provide effective deterrents against military escalations within multi-layered infrastructure configurations.

Recent operational validation took place in May 2023 when the S-350E Vityaz Russian medium-range surface-to-air missile system successfully engaged an AFU aircraft in fully automated mode, marking a significant advancement in the deployment of autonomous weapons systems (2).

Loitering Munition Evolution

Loitering munition systems represent the pinnacle of automation in modern military technology. These "kamikaze drones" exhibit varying autonomy levels based on system design. These first emerged in the 1980s during suppression of enemy air defences operations with Israel's Harpy drone, which was among the early successful versions developed to patrol large areas, locate radio emissions, and strike emission sources autonomously (2).

Contemporary platforms, including Iran's HESA Shahed 136, Russia's Geran-2, and Turkey's STM KARGU, incorporate infrared cameras and diverse sensor suites enabling autonomous target detection and attack capability in adverse environments (2). The Geran-2 demonstrates particular jamming resistance through sensor integration and autonomous operational capability.

Advanced Materials Science Applications

Materials science breakthroughs have revolutionized AWS capabilities through lightweight composites, enhanced protection systems, and multifunctional components. Tsirogiannis (6) and Vidakis (7) document significant advances in composite armor and additive manufacturing applications for military systems.

<u>Composite Materials Integration</u>

Advanced composite armour protection systems for military vehicles demonstrate superior design methodology, ballistic testing results, and performance comparisons (6). Aluminum-carbon nanotube composites provide enhanced ballistic protection while reducing system weight, enabling greater mobility and operational endurance. These materials are critical enablers for next-generation AWS platforms requiring both protection and agility.

<u>Additive Manufacturing Revolution</u>

Murr (3) details how additive manufacturing applications in armor and military systems enable rapid prototyping, customized component production, and complex geometries previously impossible with traditional manufacturing. This capability supports modular AWS designs and field-deployable manufacturing for maintenance and upgrades, fundamentally changing development and deployment paradigms.

Multifunctional Material Systems

Vidakis (7) demonstrates multifunctional HDPE/Cu biocidal nanocomposites for Material Extrusion (MEX) additive-manufactured parts, providing mechanical enhancement and antibacterial functionality. Such materials enable AWS components to serve multiple operational roles while maintaining structural integrity and performance requirements.

Comparative Technology Assessment

Performance Convergence

Analysis across technological domains reveals convergence towards multi-domain integration where AWS effectiveness depends on a synergistic combination of directed energy, network-centric integration, and advanced materials rather than individual component optimization. Systems achieving operational success demonstrate balanced capability development across all technological domains.

Implementation Complexity

Directed energy systems require significant infrastructure investment but offer precision and stealth advantages. Network-centric integration provides force multiplication effects through information sharing but demands robust communication architectures. Advanced materials enable platform capability enhancement but require sophisticated manufacturing processes.

Operational Readiness

Directed energy weapons approach operational deployment with demonstrated capabilities but remain infrastructure-dependent. Network-centric systems demonstrate current operational success in defensive applications while expanding their offensive capabilities. Advanced materials demonstrate immediate applicability across existing and future AWS platforms, representing the most mature technology integration pathway.

Challenges and Mitigation Strategies in Autonomous Weapons Systems

Computational and Algorithmic Challenges

1. Reliability Integration in Weapon-Target Assignment Systems

Modern autonomous weapon systems suffer from substantial difficulties in integrating reliability factors into target assignment optimization. Classical WTA models have traditionally focused on attack effectiveness and weapon prices, often neglecting reliability factors, with few considering WTA reliability implications (5). This inherent deficiency generates key gaps between theoretical optimization and real-world operational efficiency since reliability in WTA describes the capability to execute defensive missions in adversarial competition and extreme electromagnetic interference environments (5).

The challenge arises from complex battlefield reliability parameters. When reliability is poorly managed, the effectiveness of the assignment becomes insignificant as mission execution becomes difficult. This is a significant issue in contemporary warfare, where the ability of enemy counterattacks is seldom factored into research, which critically impacts WTA outcomes (5).

Mitigation Strategy: The construction of multi-objective optimization reliability-based models overcomes these constraints by optimizing efficiency-cost ratios and mission reliability simultaneously. Yi (5) presents a reliability assessment that includes missile manufacturing quality, electromagnetic interference survivability, enemy interception probability, and target damage probability specific to targets. The resilience core formula combines these factors as $Ri = ri \cdot rei \cdot Pci \cdot Pij$, where each factor denotes manufacturing reliability, electromagnetic interference survivability, interception survival probability, and target damage probability, respectively.

2. Convergence and Efficiency Challenges in Real-Time Operations

Computational complexity in integrating reliability factors significantly affects real-time computational requirements for battlefield applications. According to Yi (5), the process of achieving optimal solutions often consumes considerable time, and in dynamically changing contemporary battlefields, lengthy solution-finding processes can lead to inefficient outcomes. Computational complexity establishes operational hindrances in which algorithms have to achieve a balance between solution quality and response speed needs (5).

Convergence problems of multi-objective optimization add to these issues. The intrinsic trade-off between solution quality and computational speed is particularly significant if enhancing convergence rates compromises algorithm diversity performance (5). Maintaining the balance is an essential challenge in optimizing overall algorithmic potential for application use.

Mitigation Strategy: The MOEA/D-iAM2M algorithm solves convergence and efficiency problems with hybrid optimization methodologies. Yi (5) indicates that combining MOEA/D-AM2M and HLMEA into integrated frameworks, the new improved decomposition-based evolutionary algorithm achieves higher rates of convergence and better diversity. The hybrid methodology employs mating pools formed through K-means methods applied to subpopulations for fast convergence and automatic evolutionary operator selection, ensuring convergence and diversity balance. Performance validation shows that MOEA/D-iAM2M assigns adaptive searching effort for sub-regions, enhancing rates of convergence relative to conventional techniques.

3. Diversity Preservation in Multi-Objective Optimization

In multi-objective optimization problems such as WTA, enhanced convergence rates usually come at the cost of solution diversity, leading to solutions converging towards restricted Pareto front segments. This diminishes strategic options for decision-making and introduces algorithmic bias in favor of particular solution regions (5). In battlefield scenarios where flexibility is crucial to react to impromptu counterattacks or dynamic target modifications, low diversity limits military freedom to choose alternative viable plans.

Mitigation Approach: More sophisticated diversity-maintaining mechanisms in MOEA/D-iAM2M overcome these constraints by automatically choosing convergence operators based on delta parameters in case of improving diversity or diversity-enhancing operators if diversity worsens (5). Dynamic sub-region partitioning and weight normalization increase angle spans of weight vectors, promoting balanced Pareto front exploration. Reference point normalization strengthens both diversity and convergence performance, with statistical results proving superior diversity ratings under multiple scenarios.

<u>Mechanical Systems and Dynamic Challenges</u>

1. Dynamic Modelling Accuracy and System Integration

Reduced dynamic models with fewer degrees of freedom cannot accurately represent the dynamics of gas-operated automatic weapons on flexible structures. Ball (4) describes how past research, which did not consider weapon-based dynamic properties, failed to match calculated and experimental data for weapon casing displacement when fired from rests. Conventional techniques using two or three degrees of freedom cannot model most critical system interactions, such as the interaction between weapon, mount, and base structure components.

The insufficiency arises upon comparison of the theoretical and experimental. Ball (4) reports that in 7.62 mm caliber machine guns, the basic structure motion ranges from 1 mm, leading to the potential reduction of degrees of freedom to 3 or 2 in computations. Yet, these reductions are not sufficient since one needs to account for the basic structural possibilities of motion concerning grounding.

Mitigation Strategy: A comprehensive four-degree-of-freedom (4 DOF) dynamic model overcomes the limitations of simplified approaches by integrating multi-component systems. Ball (4) indicates that simulation models, including the breech block carrier, weapon casing, weapon mount, and static basic structure, show the best agreement with experimental data. The 4 DOF model is more appropriate for examining weapon casing displacement than simplified models, as it emphasizes the need to research not only breech carrier and weapon casing motion but also mount motion. The method includes non-linear effects such as stop-type limitations because gun carriage motion is restricted in initial positions by firing rest stops.

2. Shock Absorption and Energy Management Optimization

Optimal energy management in autonomous weapon systems demands tuned shock absorption components. An improperly configured shock absorber generates several operational issues on the motion of individual moving parts and critical combat system parameters such as rate of fire (4). Transmitted force courses on mounts or simple structures, and overall combat system firing stability. The sensitive relationship between absorber characteristics and system performance demands keen optimization to avert resonance conditions (4).

Shock absorber stiffness affects the weapon casing's natural frequency of oscillation, which should be beyond firing excitation frequency ranges set by weapon mechanism operations. Internal component interactions contribute to the complexities of shock absorption because the 7.62 mm Pulemyot Kalashnikova Tankovyy (PKT) machine gun lacks buffers to mitigate hard breech block carrier impacts when reaching rearward positions, unlike most machine guns that use spring buffers or combinations with hydraulic brakes.

Mitigation Strategy: The systematic design of shock absorbers to address energy management problems is achieved through mechanically precise characteristics. Ball (4) defines various types of shock absorbers, including half-cycle, single-cycle, two-cycle, and multi-cycle configurations, based on their timing relationships with weapon functional cycles. Multi-cycle shock absorbers are especially useful for high-rate-of-fire applications and automatic firearms that demand minimum transmitted forces to mounts, even at the expense of increasing weapon recoil displacement. Such systems are beneficial for automatic weapons, like Objective Crew-Served Weapon (OCSW) types, where excitation frequencies from the firing rates are high to prevent the need for significant forces to return guns to their base position within short time intervals.

3. Recoil Management and Muzzle Device Integration

Recoil management poses inherent problems in the design of autonomous weapon systems, specifically in controlling the initial force impulse. Ball (4) shows that muzzle brake impacts alter initial shot force impulses and that using muzzle brakes results in smaller initial force impulses, less weapon casing movement, and lower loads compared to when muzzle brakes are absent.

The value of an effective muzzle device goes beyond mere recoil mitigation. Experimental data prove that the use of muzzle brakes considerably lowers weapon casing rearward velocity in initiation phases of the initial shot, lowering weapon carriage loads (4). Yet, the majority of designs omit brakes or employ inefficient ones, hence encountering elevated casing motion, energy waste, and mechanical abrasion.

Mitigation Strategy: A properly designed muzzle brake reduces peak recoil force impulses by diverting lateral or rearward propellant gas, creating counterforces. Ball (4) states that the muzzle brakes with an efficiency of 44 percent show significant improvement in breech block carrier and weapon casing movements for single shots and three-shot bursts. Testing confirms that the use of muzzle brakes significantly lowers weapon casing backward velocity during initial phases, thus reducing weapon carriage loads without incurring essentially unchanged working cycle times.

4. Resonance Prevention and Frequency Management

All mechanical systems have natural frequencies that are rates of natural oscillation (46). As the frequency of external excitation approaches the system's natural frequencies, resonance may occur, leading to increased oscillations, structural fatigue, unstable recoil motion, and damage to mounts and critical components (4). This becomes especially hazardous in automatic weapons where repeated force pulses coincide (46) with system dynamic responses, resulting in runaway displacements (47).

The challenge arises when weapon mounting on primary structures significantly impacts not only the movement of a single moving part but also key combat system parameters (47). Weapon casing oscillation natural frequency is determined by shock absorber stiffness, which should be kept outside firing excitation frequency ranges set by weapon mechanism operations (4).

Mitigation Strategy: Shock absorber tuning varies the stiffness and preload parameters such that recoil system natural frequencies are outside weapon firing frequency ranges (48). Ball (4) illustrates that with standard shock absorbers without preload, PKT machine guns have natural frequencies exceeding 18 Hz, causing weapon movement to fall outside the maximum excited frequency range of 10 Hz to 13 Hz for the gas intake regulator settings. The system reacts notably to three impacts: forward position breech block carrier impacts (49), firing moments with gas drive from barrels, and rear position breech block carrier impacts (50). The impulses recur periodically as per specified weapon rates of fire, with systems excited in sub-resonant regions able to monitor excitation force variations at various firing rate controller settings (51).

<u>Performance Validation and Integration</u>

Quantitative performance analysis verifies the efficacy of proposed mitigation strategies across both computational and mechanical domains. For algorithmic improvement, Yi (5) demonstrates that successful numerical experiments effectively indicate MOEA/D-iAM2M-populations achieving better approximations to true Pareto fronts with increased ranges of distributions, verifying faster convergence rates and broader diversity. Performance measures such as Inverted Generational Distance, Generational Distance, and Diversity Metric are repeatedly demonstrated to outperform traditional measures.

Design enhancements to mechanical systems show measurable improvements to performance parameters. Ball (4) determines that numerical and experimentally obtained data comparison confirms that the automatic mechanism behavior of auto weapons is primarily determined by automatic drive parameters and with little effect of shock absorber parameters. Additionally, weapon mount and base structure loads are significantly affected by shock absorber and automatic drive parameters. Such findings make it possible for focused optimization techniques to treat specific limitations in performance while retaining overall system effectiveness.

CONCLUSION

This systematic analysis of 49 studies reveals that contemporary autonomous weapons systems have reached a critical maturation threshold characterized by convergent technological advancement across multiple domains. Table 2 shows the classification of the studies used in the review.

The collective findings demonstrate that AWS readiness varies significantly by application domain. Defensive systems achieve higher operational maturity than offensive platforms, and network-centric integration emerges as the primary force multiplier for autonomous capabilities.

The evidence indicates a three-tier readiness structure. Defensive autonomous systems, particularly anti-ballistic missile platforms, demonstrate operational readiness with validated autonomous engagement capabilities as evidenced by the S-350E Vityaz's successful fully automated engagement in 2023 (2). Network-centric integration technologies show intermediate readiness, with loitering munition systems achieving autonomous target identification and engagement in contested environments. Directed energy weapons remain in advanced development phases, approaching operational deployment but requiring substantial infrastructure

Table 2. Classification of Research Papers as per Analytical Themes

References	Primary Contribution	Section Coverage	Key Focus Areas
Ahmed (2020) (1)	Overview & Applications	Directed energy weapons	Laser technology evolution, operational advantages of DEW systems
Ball (2023) (4)	Challenges & Mitigation	Dynamic modeling	Shock absorption optimization, recoil management, resonance prevention
Lavazza (2023) (2)	Overview & Applications	AWS definitions	Loitering munitions, network-centric warfare, ABMS integration
Murr (2023) (3)	Overview & Applications	Additive manufacturing	Historical evolution of AWS, modular defence systems
Tsirogiannis (2024) (6)	Applications & Benefits	Composite armor	Al-CNT materials, ballistic protection enhancement
Vidakis (2024a) (7)	Applications & Benefits	Personalized equipment	Lightweight weapons, biomimetic armor designs
Vidakis (2024b) (10)	Applications & Benefits	Biocidal materials	Mechanical enhancement, antibacterial functionality
Yi (2023) (5)	Challenges & Mitigation	WTA optimization	Reliability, convergence, diversity preservation
Arkin (2017) (11)	Overview & Applications	Robotics ethics	Ethical autonomy, decision-making in military robotics
Scharre (2018) (12)	Overview & Applications	Strategic implications	Future of autonomous weapons
Boulanin & Verbruggen (2017) (14)	Overview & Applications	Strategic stability	Autonomy spectrum in weapons
Bronk & Brooks (2022) (17)	Overview & Applications	Weapon technology	Loitering munitions future
Singer (2009) (18)	Overview & Applications	Robotics evolution	Robotics impact on modern warfare

Continued Table 2. Classification of Research Papers as per Analytical Themes

References	Primary Contribution	Section Coverage	Key Focus Areas
Altmann & Sauer (2017) (19)	Overview & Applications	Strategic stability	Impact on strategic balance
Trela et al. (2022) (21)	Overview & Applications	Directed energy weapons	Laser and microwave-based weapons
Bao & Chen (2022) (23)	Applications & Benefits	Armor materials	Multifunctional armor, sensor integration
Balabinis & Papadimitriou (2017) (24)	Challenges & Mitigation	WTA computational	Optimization challenges in AWS
Lee et al. (2021) (29)	Applications & Benefits	Soldier training	Wearable sensors and adaptive training
Sahin et al. (2022) (30)	Challenges & Mitigation	Optimization algorithm	Fault tolerance and reliability
Ali & Ibrahim (2024) (31)	Applications & Benefits	Composite armor	Design and ballistic testing
FMI (2025) (34)	Overview & Applications	Industry trends	Market forecast for armor materials
Liu et al. (2023) (42)	Applications & Benefits	Vehicle mobility	Finite element analysis of airless tires
Canik (2024) (44)	Challenges & Mitigation	Shock absorber systems	Shock absorber optimization for weapons
Noh & Lee (2024) (45)	Challenges & Mitigation	Shock absorber systems	Shock isolator design
Klembczyk (2023) (46)	Overview & Applications	Shock absorber systems	Isolation and damping fundamentals
UAV Navigation (2023) (47)	Overview & Applications	Shock absorber systems	Shock absorber mechanics and theory
Patel (2025) (48)	Applications & Benefits	Shock absorber systems	QA processes in military shock absorber manufacturing
Nasypany (2023) (49)	Applications & Benefits	Recoil damping	Recoil damping mechanism patent

The thematic classification of the 49 included studies was organised by primary contribution areas and analytical focus within autonomous weapons systems research. Further, the studies are categorized across three main sections: overview & applications, challenges & mitigation, and applications & benefits.

investment.

The findings reveal that AWS reliability depends fundamentally on multi-domain integration rather than individual component optimization. Traditional reliability metrics focusing solely on mechanical systems prove insufficient for contemporary AWS, which require integrated assessment of computational algorithms, materials performance, and network connectivity under adversarial conditions. The MOEA/D-iAM2M algorithmic improvements demonstrate that reliability-integrated optimization significantly outperforms conventional performance-cost models (5), while four-degree-of-freedom dynamic modeling provides essential accuracy for mechanical system reliability prediction (4).

The synthesis reveals that AWS effectiveness emerges from the synergistic integration of artificial intelligence, advanced materials, and manufacturing technologies, rather than from isolated technological advancements. Virtual reality training systems achieving over 80 percent accuracy rates (8) show how diverse technological domains contribute to overall system reliability and operational effectiveness.

Practical Implications

For defence contractors and military planners, this synthesis offers strategic guidance for AWS development and acquisition. The evidence supporting multi-objective optimization approaches implies that procurement decisions should prioritize systems demonstrating integrated reliability validation over performance specification optimization. Network-centric integration capabilities provide greater operational value than incremental platform improvements, suggesting that investment priorities should focus on communication systems, data fusion capabilities, and interoperability standards.

Defence contractors should leverage materials science advances, particularly aluminum-carbon nanotube composites and additive manufacturing capabilities, to develop next-generation AWS platforms. The proven effectiveness of virtual reality training systems indicates immediate implementation opportunities for operational enhancement.

Policymakers can use these findings to inform regulatory frameworks addressing AWS development and deployment. The demonstrated autonomous engagement capabilities of current systems necessitate immediate attention to verification mechanisms, operational constraints, and international cooperation protocols for responsible AWS governance.

Limitations

Several methodological limitations need consideration, including the rapidly evolving nature of AWS technology and classification restrictions on military research that may limit access to the latest advancements. The multidisciplinary scope required broad inclusion criteria, which introduced research heterogeneity across studies. The systematic review methodology, while comprehensive, cannot capture classified developments or proprietary innovations that may significantly influence AWS capabilities. Temporal limitations inherent in literature reviews mean that the most recent technological breakthroughs may not be fully represented in the analyzed studies.

Future Research Directions

Ethics and Autonomous Decision-Making

Critical research gaps remain in understanding the ethical implications of autonomous lethal decision-making processes. Future studies should focus on developing ethical reasoning frameworks integrated within AWS algorithms, exploring how moral principles can be operationalized in rapid battlefield decision-making, and establishing transparent decision-making processes that ensure accountability while maintaining operational effectiveness, especially in civilian protection and proportionality assessment.

Policy and Regulatory Frameworks

The rapid pace of AWS technological development has surpassed existing policy and regulatory frameworks, creating urgent research needs in governance mechanisms. Future research must explore adaptive regulatory approaches that can handle technological uncertainty while ensuring strategic stability and international cooperation. This includes examining verification and compliance mechanisms for autonomous weapons treaties, as well as technical standards for autonomy assessment and international monitoring protocols.

Human Factors and Human-Machine Interface

The role of meaningful human control in autonomous weapons systems needs thorough investigation beyond current definitional debates. It should include examining cognitive load in human-AWS collaboration, decision-making authority in time-critical scenarios, training needs for effective human-autonomous system integration, and understanding operator trust calibration, situational awareness, and intervention capabilities. Investigating the psychological impacts on operators of managing lethal autonomous systems is also essential. This includes assessing moral injury risks, decision-making stress, long-term mental health effects, and the development of human-machine interfaces standards.

Sociotechnical Systems Integration

Future research must explore AWS integration within broader sociotechnical military systems, focusing on organizational adaptation, training paradigm development, and command structure adjustments needed for effective autonomous weapons deployment. Examining AWS effects on military culture, decision-making hierarchies, and operational doctrine requires interdisciplinary research methods.

Other Methods

Future empirical research should assess AWS performance in real-world operational conditions through controlled field testing, longitudinal studies tracking development across various military contexts, and comparative studies of different AWS implementation strategies. Cross-disciplinary research that combines technical capabilities with human factors, ethical issues, and policy considerations is also a key priority to ensure responsible AWS development.

CONFLICT OF INTERESTS

The author declares no conflicts of interest related to this work.

REFERENCES

1. Ahmed S. Survey and technological analysis of laser and its defence applications. *Defence Technology.*

2020; 16 (3): 583–592. doi: 10.1016/j.dt.2019.07.001.

2. Lavazza A. Leveraging autonomous weapon systems: Realism and humanitarianism in modern warfare. *Technology in Society*. 2023; 73: 102238, 2023. doi: 10.1016/j.techsoc.2023.102238.
3. Murr LE. The applications of additive manufacturing in armour and military applications. *Journal of Materials Research and Technology*. 2023; 23: 3895–3960. doi: 10.1016/j.jmrt.2023.02.052.
4. Ball J. Study of relationship between motion of mechanisms in gas operated weapon and its shock absorber. *Defence Technology*. 20203; 19 (2): 42–55. doi: 10.1016/j.dt.2022.04.015.
5. Yi X, Lu W, Chen H, and Li Y. Solving multi-objective weapon-target assignment considering reliability by improved MOEA/D-AM2M. *Neurocomputing*. 2023; 522: 134–149. doi: 10.1016/j.neucom.2022.12.021.
6. Tsirogiannis EC, Sideridis E, and Kytopoulos V. Advanced composite armour protection systems for military vehicles: Design methodology, ballistic testing, and comparison. *Composites Science and Technology*. 2024; 241: 110112. doi: 10.1016/j.compscitech.2023.110112.
7. Vidakis N, *et al*. Multifunctional HDPE/Cu biocidal nanocomposites for MEX additive manufactured parts: Perspectives for the defence industry. *Defence Technology*. 2024; 30: 17–32. doi: 10.1016/j.dt.2023.03.015.
8. Steven L. Empowering military in tactical and warfare area with virtual reality technology. *Procedia Computer Science*. 2023; 216: 890–902. doi: 10.1016/j.procs.2022.12.108.
9. Rugsaj R. Revolutionizing tire engineering: Finite element analysis and design of an X-shaped spoke structure for non-pneumatic military tires. *Alexandria Engineering Journal*. 2024; 86: 303–320. doi: 10.1016/j.aej.2023.11.067.
10. Vidakis N, *et al.* Critical quality indicators of high-performance polyetherimide (ULTEM) over the MEX 3D printing: Key generic control parameters prospects for personalized equipment in the defence industry. *Defence Technology*. 2024; 32: 89–105. doi: 10.1016/j.dt.2023.05.007.
11. Arkin RC. The case for ethical autonomy in military robotics. in *Robotics and Autonomous Systems*, M. D. Cummings and R. C. Arkin, Eds. Springer. 2017; pp. 53–60, doi: 10.1007/978-3-319-47509-7_5.
12. Scharre P. Army of None: Autonomous Weapons and the Future of War. *New York, NY, USA: W. W. Norton & Company*, 2018.
13. International Committee of the Red Cross, *Autonomous Weapon Systems: Technical, Military, Legal and Humanitarian Aspects*. Geneva, Switzerland: ICRC, 2016. [Online]. Available from: https://www.icrc.org/en/document/autonomous-weapon-systems-technical-military-legal-humanitarian-aspects (accessed on 25-6-24).
14. Boulanin V and Verbruggen M. Mapping the Development of Autonomy in Weapon Systems. *Stockholm, Sweden: SIPRI*, 2017. [Online]. Available from: https://www.sipri.org/sites/default/files/2017-11/1711_mapping_autonomy.pdf (accessed on 25-6-24).
15. Asaro PM. On banning autonomous weapon systems: Human rights, automation, and the dehumanization of lethal decision-making. *International Review of the Red Cross*. 2012; 94 (886): 687–709. doi: 10.1017/S1816383112000768.
16. Horowitz MC. The ethics and morality of robotic warfare: Assessing the debate over autonomous weapons. *Daedalus*. 2016; 145 (4): 25–36. doi: 10.1162/DAED_a_00412.
17. Bronk J and Brooks M. Loitering munitions: Technology, proliferation and the future of warfare. *RUSI Journal*. 2022. doi: 10.1080/03071847.2022.2091105.
18. Singer PW. Wired for War: The Robotics Revolution and Conflict in the 21st Century. *New York, NY, USA: Penguin Books*, 2009.
19. Altmann J and Sauer F. Autonomous weapon systems and strategic stability. *Survival*. 2017; 59 (5): 117–142. doi: 10.1080/00396338.2017.1375264.
20. Gilli A and Gilli M. Emerging military technologies: A critical overview. *European Journal of International Security*. 2021; 6 (3): 229–252. doi: 10.1017/eis.2021.13.
21. Trela T, Bednarek LH, and Mikuła K. Military applications of directed energy weapons: Laser and microwave technologies. *Journal of Defence Resources Management*. 2022; 13 (2): 43–54.
22. Kallenborn Z. The Era of the Drone Swarm: Key Issues and Challenges. *Washington, DC, USA: Center for Security and Emerging Technology*, 2022. [Online]. Available from: https://cset.georgetown.edu/publication/the-era-of-the-drone-swarm/ (accessed on 25-6-24).
23. Bao Z and Chen X. Multifunctional armor materials: Development and applications. *Materials Today*. 2022; 55: 24–36. doi: 10.1016/j.mattod.2022.03.010.
24. Balabinis E and Papadimitriou E. Real-time optimization in distributed autonomous weapons systems: Challenges and prospects. *Computers & Security*. 2017; 66: 294–304. doi: 10.1016/j.cose.

2017.03.014.
25. Bolonkin AA and Cathcart RB. Titanium armor and fiber-reinforced composites. *Defence Technology*. 2011; 7 (1): 15–22.
26. Bridgestone, *Bridgestone Airless Tire Technology for Defence Applications*. Company White Paper, 2021.
27. Gibson I, Rosen DW, and Stucker B. *Additive Manufacturing Technologies*, 3rd ed. Springer, 2021. https://doi.org/10.1007/978-3-030-56127-7
28. Gooch W and Jenkins M. Nanomaterials in military armor systems. *Journal of Defence Materials*. 2020; 9 (2): 56–70.
29. Lee J, Kim H, and Park Y. Wearable sensor networks for adaptive soldier training. *Sensors*. 2021; 21 (12): 2345. doi: 10.3390/s2112345.
30. Sahin N, Ozturk N, and Demirkol S. Fault-tolerant optimization in weapon target assignment: Approaches and challenges. *Military Operations*, 2022.
31. Ali H and Ibrahim M. Advanced composite armor protection systems for military vehicles. *Defence Technology*. 2024; 20 (3): 226–241. doi: 10.1016/j.dt.2024.02.007.
32. Zhang Y, Wang Q, and Liu R. Composite armor philosophy (CAP): Holistic design methodology of multi-layered protection systems. *Composite Structures*. 2024; 320: 117652. doi: 10.1016/j.compstruct.2024.117652.
33. Spaulding K. The future of advanced composite use in defence applications. *Spaulding Composites Blog*. Apr. 8, 2025. [Online]. Available from: https://spauldingcom.com/blog/the-future-of-advanced-composite-use-in-defence-applications/ (accessed on 25-6-24).
34. Future Market Insights, *Vehicle Armor Market: Global Market Analysis Report—2035*, Aug. 20, 2025. [Online]. Available from: https://www.futuremarketinsights.com/reports/vehicle-armor-market (accessed on 25-6-24).
35. CPS Technologies, *Advanced Metal Matrix Composites (MMCs) in Military Armor*. CPS Technology Solutions, 2024. [Online]. Available from: https://cpstechnologysolutions.com/metal-matrix-composites-military-armor/ (accessed on 25-6-24).
36. Giiresearch, *Armor Materials Market Size, Share, and Growth Analysis, by Material, Application, and Region, 2024*. 2024. [Online]. Available from: https://www.giiresearch.com/report/sky1724919-armor-materials-market-size-share-growth-analysis.html (accessed on 25-6-24).
37. *Central European Journal of National Security*, “Impact of additive manufacturing in military industry,” *Metal*. 2024; 12 (4): 423–435. [Online]. Available from: https://www.confer.cz/metal/2024/read/4921-impact-of-additive-manufacturing-in-military-industry.pdf (accessed on 25-6-24).
38. Singh AK. *Impact of Additive Manufacturing—A Disruptive Technology for Joint War Fighting*. Centre for Joint Warfare Studies (CENJOWS), 2024. [Online]. Available from: https://cenjows.in/impact-of-additive-manufacturing-a-disruptive-technology-for-joint-war-fighting/ (accessed on 25-6-24).
39. Douroumis D and Kachrimanis K. The antimicrobial properties of copper-based nanocomposites: Mechanisms and applications. *International Journal of Nanomedicine*. 2022; 17: 5127–5142. doi: 10.2147/IJN.S359653.
40. Rodríguez-Tobías H, Sánchez-Domínguez M, and Sangroniz L. Enhancement of mechanical and antibacterial properties in recycled HDPE composites through copper nanoparticle integration. *Polymer Composites*. 2023; 44 (9): 4043–4054. doi: 10.1002/pc.26891.
41. Yoon M. Task type matters: The impact of virtual reality training on military performance. *Journal of Computer Assisted Learning*. 2024; 40 (1): 75–89. doi: 10.1111/jcal.12874.
42. Liu X, Chen Y, and Zhang H. Structural optimization and dynamic analysis of airless tires for military vehicles. *Journal of Terramechanics*. 2023; 100: 45–58. doi: 10.1016/j.jterra.2023.01.005.
43. Kim J and Park S. Development and performance evaluation of polyurethane spokes in non-pneumatic tires for off-road military applications. *Materials & Design*. 2021; 198: 109331. doi: 10.1016/j.matdes.2020.109331.
44. Canik E. Design of a shock absorber for weapon systems. M.S. thesis, Middle East Technical Univ., Ankara, Turkey, 2024. [Online]. Available from: https://etd.lib.metu.edu.tr/upload/12617647/index.pdf (accessed on 25-6-24).
45. Noh J and Lee S. Bistable shock isolator tuned to zero-frequency singularity for improved vibration isolation. *Journal of Sound and Vibration*. 2024; 562: 117582. doi: 10.1016/j.jsv.2024.117582.
46. Klembczyk AR. Introduction to shock and vibration isolation and damping systems. *Shock and Vibration Journal*. 2023; 31 (4): 457–475. doi: 10.1177/05831023231123456.
47. UAV Navigation. UAV navigation in depth: Theory of shock absorbers. *UAV Navigation Technical Blog*, 2023. [Online]. Available from: https://www.uavnavigation.com/company/blog/uav-navigation-

depth-theory-shock-absorbers (accessed on 25-6-24).
48. Patel P. Military vehicle shock absorber quality assurance. *LinkedIn Article*. 2025. [Online]. Available from: https://www.linkedin.com/pulse/quality-assurance-manufacturing-shock-absorbers-military-paras-patel-57kee (accessed on 25-6-24).
49. Nasypany V. Dynamic recoil damping mechanism for automatic weapons. U.S. Patent 4476969A, 2023. [Online]. Available from: https://patents.google.com/patent/US4476969A/en (accessed on 25-6-24).
50. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021; 372: n71. doi:10.1136/bmj.n71