Journal of Aeronautics and Space Technologies
17(Special Issue) (2024) 182-207
Journal Homepage: jast.hho.msu.edu.tr

RESEARCH ARTICLE

Drone Wars 3D: A Game-Based Simulation Platform for Testing Aerial Defence Strategies Against Drone Swarms

Drone Wars 3D: Drone Sürülerine Karşı Hava Savunma Stratejilerini Test Etmeye Yönelik Oyun Tabanlı Simülasyon Platformu

Gökhan Karadeniz[1], Ahmet Ozcan[2], Mehmet Bayram[3], Gökhan Ince[1*]

[1] Istanbul Technical University, Faculty of Computer and Informatics Engineering, Game and Interaction Technologies, 34469 Istanbul, Türkiye,
[2] National Defence University, Atatürk Strategic Studies and Graduate Institute, Department of Computer Engineering, 34334 Istanbul, Türkiye
[3] National Defence University, Atatürk Strategic Studies and Graduate Institute, Department of Industrial Engineering, 34334 Istanbul, Türkiye

Received: *November 21, 2023* ***Revised:*** *March 12, 2024* ***Accepted:*** *March 20, 2024*

Abstract
Unmanned aerial vehicles (UAVs), commonly referred to as "drones", have received a notable surge in recent years, particularly within military contexts. In this study, a simulation platform was developed to assess the viability of employing drone swarms as a defensive mechanism against opposing drones. The study encompasses diverse tactical approaches including the arrangement of attacking and defending drones, the role of drone launchers, and the critical factors of detection and response time. The results show the effectiveness of drone swarms, machine guns, anti-aircraft guns, laser guns and surface-to-air missiles against swarms of attacking drones. The findings provide a comprehensive insight into the potential performance of these countermeasures, laying the groundwork for the formulation of effective defence strategies against the emerging threat of drone swarms.

Keywords: Drone, Swarm, Defence, Simulation, Unity, Game, Serious Game

Öz
Yaygın olarak "dron" olarak adlandırılan insansız hava araçları (İHA), son yıllarda özellikle askeri alanlarda kayda değer bir yükseliş göstermiştir. Bu çalışmada, dron sürülerinin rakip dronlara karşı bir savunma mekanizması olarak kullanılmasının uygulanabilirliğini değerlendirmek için bir simülasyon platformu geliştirilmiştir. Çalışma, saldıran ve savunan dronların düzenlenmesi, dron fırlatıcılarının rolü ile tespit ve tepki süresi gibi kritik faktörler de dahil olmak üzere çeşitli taktiksel yaklaşımları kapsamaktadır. Sonuçlar, dron sürülerinin, makineli tüfeklerin, uçaksavarların, lazer silahlarının ve hava savunma füzelerinin saldıran dron sürülerine karşı etkinliğini göstermektedir. Bulgular, bu karşı önlemlerin potansiyel performansına ilişkin kapsamlı bir bakış açısı sağlayarak, ortaya çıkan dron sürüleri tehdidine karşı etkili savunma stratejilerinin oluşturulmasına zemin hazırlamaktadır.

Anahtar Kelimeler: Drone, Sürü, Savunma, Simülasyon, Unity, Oyun, Ciddi Oyun

*Corresponding Author
E-mail: gokhan.ince@itu.edu.tr

1. INTRODUCTION

The utilization of Unmanned Aerial Vehicles (UAVs), commonly referred to as "drones", has experienced a notable surge in recent years, particularly within military contexts. This discernible trend can be attributed to the diminishing costs, heightened reliability, and intrinsic features such as maneuverability, autonomy, and ease of deployment associated with drones. A noteworthy development in this domain is the concept of drone swarms, wherein a collective of cooperating drones pursues a shared objective. The versatility of drone swarms across various domains, including air, land, sea, and space, amplifies both their significance and potential risks.

This research endeavors to assess the viability of employing drone swarms as a defensive mechanism against opposing drone swarms. Our focal point is a specific scenario involving the protection of power lines against incursions by hostile drone swarms. Traditional weaponry may prove inefficient in countering such attacks due to the extensive distribution of power line poles. Additionally, an assault on a singular power line pole might not inflict substantial damage on the adversary; however, compromising a significant portion of these poles could yield catastrophic consequences. The feasibility and cost-effectiveness of utilizing drones for this purpose emphasize the necessity to explore alternative defence mechanisms against drone swarms, underscoring the significance of our study.

The study encompasses diverse tactical approaches, each delving into distinct facets of the problem, including the formation of attacking and defending drones, the role of drone launchers, and the critical factors such as detection and response time. The originality of this study is in the innovative application of drone swarms as a distributed means of both attack and defence roles, with the formulation of varied offensive and countering strategies. Furthermore, this study highlights the adaptability of drone swarm technology and demonstration of unique suitability for the scenario of targeted widely distributed power line infrastructure, a scenario not amenable to conventional weaponry.

The primary contributions of this study to the literature are as follows:

- Examination of diverse defense strategies using drone swarms, in a serious game setting
- Effectiveness demonstration of proposed swarm model over traditional weaponry for the distributed infrastructure protection problem
- Cost-effectiveness and feasibility analysis of drone utilization for air defense tactics

The rest of the paper is organized as follows. In Section 2, previous studies in the literature were laid out. In Section 3, the developed original simulation platform is described in detail. In Section 4, different experiments are performed, and the results obtained from these experiments are provided. Finally, in Section 5, the benefits are summarized, the results of the study and possible future work are discussed.

2. RELATED WORK

In recent times, there has been a notable upsurge in the scrutiny of drone swarms, as evidenced by the burgeoning body of literature. An examination on Web of Science (WOS) using the keyword "drone swarms" unveiled a discernible pattern: 14 studies identified between 2001 and 2010, 43 studies from 2011 to 2015. However, the research interest in this domain witnessed a substantial surge with 418 studies conducted between 2016 and 2020, followed by a noteworthy escalation to 488 studies in the brief span from 2021 to 2023 [1]. The ascending trajectory is visually depicted in Figure 1.

Contemporary research in this field predominantly revolves around two principal facets: the development of swarm formations and the formulation of control algorithms for drone swarms. Aloui et al. introduced a modeling language dedicated to the creation of drone swarms, facilitating the modeling of tasks, hardware, and architecture. By seamlessly integrating this language into the Robot Operating System (ROS), they could conduct tests in either real-world scenarios or simulated environments. In their specific investigation, Aloui et al. applied this modeling approach to simulate a surveillance mission [2]. Lukina et al. delved into research on formation control and tracking using the OpenUAV simulator, a platform tailored for Unmanned Aerial Vehicles (UAVs). OpenUAV's primary objective is to streamline the setup process for both single and multi-UAV simulations, thereby easing testing procedures [3]. Chen et al. proposed an algorithm specifically designed to generate robust and efficient consensus in large-scale drone swarms, applicable to formations with a leader or leaderless swarms [5]. While a considerable portion of drone swarm studies revolves around swarm creation, formation, and control, there is also exploration into innovative applications. For instance, Kallenborn investigated the utilization of drone swarms in the realm of information warfare [6]. Additionally, Jeong et al. developed a device for controlling drone swarms using brain signals, evaluating its efficacy through simulation in the MATLAB environment [7].

The conception and planning of missions for UAV swarms represent a complex undertaking. However, simulations provide a cost-effective avenue for conducting realistic tests before progressing to field trials. Mairaj et al. underscored the significance of drone simulators, elucidating essential features and offering comparative insights into various drone simulation programs [8]. The limited availability of swarm-enabled simulators underscores a notable gap in the field. Soria et al. contributed to simulation studies on drone swarms by creating a MATLAB-compatible drone simulator, delving into swarm algorithms and their computational aspects [9]. In an alternative approach, Jeroncic devised a drone swarm simulator within the Unreal Engine 4 environment [10]. Kumar's research introduced an AI learning algorithm for drone swarm path planning and formation within a simulated environment, encompassing diverse search and rescue scenarios [11]. Meanwhile, Devgan et al. presented a surveillance and monitoring system based on the Unity game engine, incorporating drone swarms. This system, augmented with virtual reality support, facilitates the segregation and subsequent aggregation of formation-flying drones for specialized surveillance [12]. Bhamu et al. have carried out a serious game based study with UNITY to design and test drone swarm algorithms. In the relevant study, a method to ensure the continuity of herd behavior was proposed using image processing and machine learning techniques for environments where GPS is not effective[13].

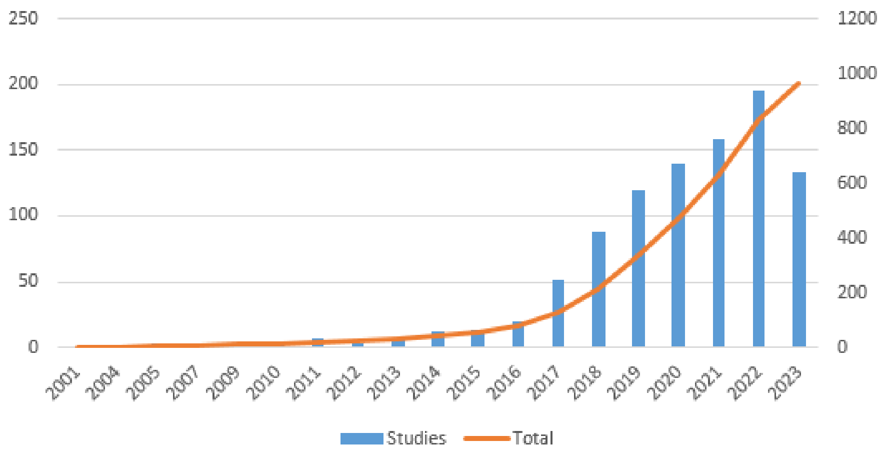

Figure 1. WOS number of studies with keyword “drone swarms”.

Serious games offer a significant advantage for planning and problem-solving by enabling the experimentation of various strategies and tactics within a competitive and dynamic environment, shaped by the controlled conditions of the game's framework [14]. In the military domain, where devising new systems and approaches against emerging threats is paramount, numerous studies on drone swarms and their simulations have been conducted. Mittal and Davidson advocated for the use of wargaming simulations to explore novel threat and defence approaches in response to technological developments, emphasizing the advantages of integrating modeling simulation and wargaming [15]. A military perspective on drone swarm simulation and wargaming is evident in various academic studies. Edwards, in a thesis, simulated a laser weapon on a ship defending itself against a swarm of drones, delving into wargaming simulations with machine learning support and their outcomes [16]. Laarni et al., through collaboration with the Finnish Defence Forces, elucidated and executed a concept counter-drone swarm attack simulation [17]. Williams contributed to the field by providing a simulation in the Java language, following a theoretical study on attacking parallel targets with swarm weapons [18].

3. SIMULATION PLATFORM

The simulation platform developed for this study, named "Drone Wars 3D", presents distinctive advantages by leveraging a gaming engine and adopting a fully three-dimensional (3D) framework. Notably, this platform empowers users with the ability to choose from a variety of pre-loaded artificial terrains, including mountainous or plains landscapes. Additionally, it facilitates the importation of custom height-map data, allowing for the creation of real-world terrains through the input of geographical coordinates. The scenarios subjected to testing are fully customizable, enabling users to configure drone properties such as physical dimensions, movement capabilities, explosion effects, as well as swarm specifications encompassing count, formation, and deployment locations. The modular framework of Drone Wars 3D broadens the array of available agent types, providing users with comprehensive control. The simulation can be paused to accommodate adjustments, and a detailed report file documenting each destruction event is generated, facilitating thorough result evaluation. Figure 2 shows the general flow of the experiments.

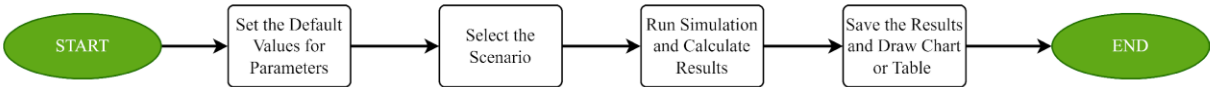

Figure 2. Flow diagram of the experiments.

In essence, Drone Wars 3D seamlessly integrates the flexibility and user-friendliness characteristic of a Real-Time Strategy (RTS) game with the reliability inherent in simulations. Consequently, it serves as a robust research platform for the development of methodologies focused on defending against drone swarms.

The simulation platform assumes a pivotal role in this research by enabling thorough analysis and evaluation of diverse defence measures against drone swarms. This section will, therefore, provide a summary of the simulation model and its constituent elements. Furthermore, an in-depth examination of various mission types and terrain configurations employed in the simulation will be conducted. Finally, the entities within the simulation, including drones, swarms, machine guns, anti-aircraft guns, surface-to-air missile launchers, and laser weapons, will be elucidated, with their features comprehensively assessed.

3.1. Overview

"Drone Wars 3D" functions as a comprehensive drone swarm defence simulation platform, built on the Unity game engine. Its primary purpose is to develop and assess various scenarios involving diverse types of drone swarms and countermeasure actors. Taking inspiration from RTS games, this platform facilitates the exploration of tactics and formations for defending against opposing drone swarms. Figure 3 provides a high-level overview of the simulation.

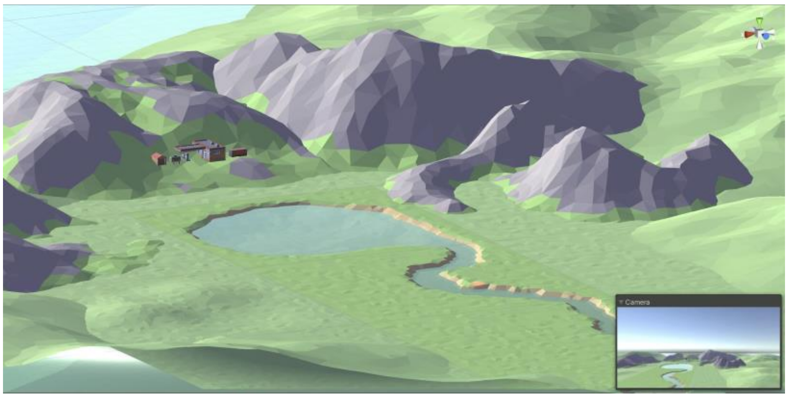

Figure 3. Drone Wars 3D has a RTS game-like view and controls.

In Figure 4, the simulation's drones are depicted, equipped with passive sensors and directed by an operator to follow specific routes and assume predetermined positions in new formations. Notably, these drones are designed to be jamming resistant, similar to military-grade drones, setting them apart from consumer-grade counterparts [19]. However, it is important to note that they lack armor and are entirely eliminated upon impact. Throughout their functional lifespan until destruction, all drones are considered fully operational. The simulation assumes that the drones possess the capability to identify hostile drones within their detection range. It is essential to highlight that the simulation excludes environmental elements such as wind, air drag, smoke, dust, and explosions.

Upon the destruction of an actor within the simulation, the event is meticulously recorded in a file for subsequent analysis. Key parameters recorded for each destroyed actor include type, name, side, parent actor, position, destroyer actor, destroyer actor position, destruction kind (direct hit or secondary impact), and time. This detailed recording mechanism enables a thorough examination of simulation events and outcomes.

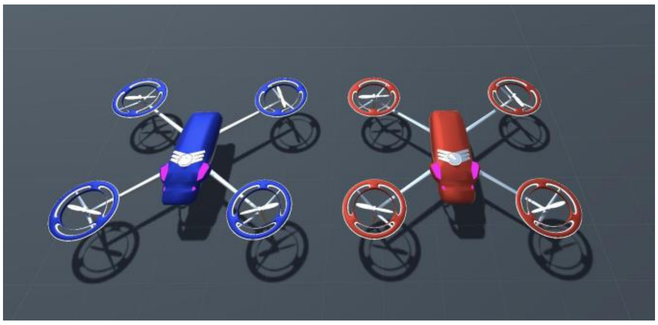

Figure 4. Graphical models of blue and red drones.

3.2. Mission Types

The mission types integrated into Drone Wars 3D are derived from a comprehensive analysis of general swarm robotics tasks, as detailed in [20]. The simulation platform enables the assignment of drone swarm agents to various tasks, providing a versatile range of mission types, including:

1. Attacking a Point Target: In this mission type, the swarm's drones are directed to assail a fixed location or object, such as specific coordinates or a weapon.
2. Attacking an Area Target: This mission involves instructing the swarm's drones to attack a specified region or zone rather than a precise location, broadening the scope of their offensive capabilities.
3. Attacking a Detectable Target: The swarm's drones are tasked with seeking and engaging a specific type of target in this scenario, showcasing the adaptability of the swarm in identifying and neutralizing distinct threats.
4. Constructing an Air Shield with Drones: This mission type entails commanding the drones in the swarm to form a protective barrier in the air, essentially creating an aerial shield for defensive purposes.
5. Defending Against Incoming Enemy Swarms: In this mission, the swarm's drones are programmed to engage and neutralize a hostile swarm of drones, exemplifying a defensive strategy against incoming threats.

These mission types collectively cover a spectrum of tactical scenarios, enabling a thorough exploration of the capabilities and effectiveness of drone swarms in diverse situations within the simulation. Such versatility allows for a nuanced analysis of swarm behavior and performance across various mission objectives, contributing to a comprehensive understanding of their potential applications and limitations in defence scenarios.

3.3. Terrain

To mitigate processor utilization, the simulation in Drone Wars 3D incorporates a selection of pre-loaded artificial terrains. While users have the option to generate location-specific terrains by inputting geographic coordinates, this study has opted for pre-loaded flat terrains for the sake of determinism. This decision eliminates the need for drone swarms to possess obstacle-avoidance capabilities and minimizes the influence of environmental factors on the simulation.

The use of predetermined flat terrains contributes to a more controlled and predictable experimental environment, aligning with the specific objectives of this study. By opting for flat terrains, the simulation ensures a consistent and stable testing ground, allowing for a focused examination of drone swarm behaviors, tactics, and defensive strategies without the added complexity introduced by varied topography. This approach facilitates a more direct exploration of the factors relevant to the study's objectives, optimizing the simulation for the specific research goals in question.

3.4. Actors

Drone Wars 3D intricately simulates the interactions among diverse entities, encompassing drones, swarms, machine guns, anti-aircraft weapons, laser guns, and surface-to-air missile launchers. This section provides a comprehensive exploration of each actor, elucidating their functionalities, attributes, constraints, and behaviors within the simulation.

Table 1. Drone model properties.

Properties	Unit	Info
Physical dimensions	m	Length along the x, y, and z-axis.
Maximum elevation	m	Maximum altitude the drone can reach
Detection range	m	Distance a drone can detect other drones
Top speed	m/s	The maximum speed the drone can reach when moving
Acceleration	m/s^2	Drone's velocity change rate
Top speed-upward	m/s	Maximum upwards speed of the drone
Acceleration-upward	m/s^2	Maximum upwards acceleration of the drone
Explosion attributes	Explosion model array	Property including four parameters for post-explosion decision making
Blast radius (Explosion attribute)	m	Effective radius of explosion
Hit rate (Explosion attribute)	m	Hit rate in the effective radius of the explosion
Chance of explosion when destroyed	%	The rate if the destroyed drones also explode
Minimum distance to detonate	m	The distance a drone must get close to an enemy drone to self-destruct

The drones in the simulation serve as fundamental models for swarms, operating as autonomous agents with features detailed in Table 1. Users, prior to the initiation of the simulation, possess the capability to initialize and deploy swarms globally, allowing for the creation of diverse scenarios. In instances where swarm initialization becomes necessary during an ongoing simulation, this task must be undertaken by a drone launcher agent within the confines of its designated capabilities. It is noteworthy that all swarms share identical properties, as outlined in Table 2. Figure 5 provides visual representations of various formation types.

This detailed characterization of drone and swarm attributes forms the foundation for understanding their roles and behaviors within the simulation, facilitating a nuanced analysis of their interactions and performance in diverse scenarios.

Table 2. Swarm model properties.

Properties	Unit	Info
Side	blue/red	Property that indicates which side the herd belongs to. (Blue for defending,Red for attacking)
Drone type	drone model	Type of drone contained in the swarm
Drone count	number	Total number of drones in the swarm
Spacing x, Spacing y, Spacing z	m	Distance between drones in each direction

Count x, Count y, Count z	number	Number of drones of all dimensions in the swarm
Mission type	-	Type of the mission
Formation type	-	Shape of the swarm (cube, prism, pyramid, wedge, and v-shaped)
Angle	degrees	Angle of formation (wedge and v-shaped)
Direction	degrees	Direction of the swarm around the y-axis

(a) (b) (c)

Figure 5. Formation type samples, (a) cube formation, (b) pyramid formation, (c) wedge formation.

(a) (b) (c)

Figure 6. Graphical model samples, (a) machine gun, (b) anti-aircraft gun, (c) laser weapon.

Table 3. Properties of the Machine Gun (MG), Anti-Aircraft Gun (AAG), Surface-to-Air Missile Launcher (AAML) and Laser Weapon (LW).

Properties	Unit	Actor/Actors
Fire rate	number (per minute)	MG, AAG, SAML
Range	meters	MG, AAG, SAML, LW
Hit points	1≤N≤100	MG, AAG, SAML, LW
Bullet destroy	boolean	MG
Engagement time	seconds	MG, AAG, SAML
Min-Max shooting angles	degrees	MG, AAG, SAML, LW
Fragment count	number	AAG
Fragment range	meters	AAG
Explosion attributes	explosion model array	SAML
Explosion distance	meters	SAML
Target destruction time	seconds	LW

A Machine Gun (MG) in Drone Wars 3D is characterized as a rapid-firing direct-fire weapon with adjustable properties, including fire rate, range, hit points, bullets destroy option, engagement time, shooting angles, bullet velocity, and count. The Machine Gun serves as a versatile tool within the simulation, providing users with the flexibility to fine-tune its parameters based on specific requirements. An Anti-Aircraft Gun (AAG), another weaponry option in the simulation, is a contemporary artillery armament that distinguishes itself from a machine gun by dispersing destructive fragments upon hitting the target within a specified fragment range. While this feature sets it apart, other properties of the Anti-Aircraft Gun remain consistent with those of the machine gun, allowing for a seamless integration of both weapon types within the simulation. The Surface-to-Air Missile Launcher (SAML) represents another formidable weapon in the simulation, launching pre-loaded missiles that detonate after covering a set distance or upon striking a target. The explosion distance is fixed, and properties are shared with drones, ensuring a cohesive interaction between different entities within the simulation. The Laser Weapon, a distinctive addition to the arsenal, has the capability to burn a target if latched on for a specific duration. The target destruction time represents the time needed to lock on and destroy the designated target. Other properties of the Laser Weapon align with those of the machine gun, maintaining a consistent framework for user interaction. Figure 6 provides a graphical representation of the actor models and Table 3 provides properties of the actor models.

3.5. Simulation Environment

The simulation, meticulously developed using the Unity3D game engine, places a strong emphasis on both functionality and aesthetics. Visual representations of the actors were carefully crafted to ensure an aesthetically pleasing experience for users. In alignment with real-time strategy games, the 3D game camera is adjustable, allowing for easier visual observation by dragging the cursor nearer to the screen's edges.

The Unity3D game engine interface has been effectively harnessed to enhance the simulation's flexibility. Incorporating assignable variables simplifies the process of updating parameters for all actors. This design choice facilitates the swift creation of drone swarms or any other actor with desired qualities. The simulation's dynamic nature allows for real-time adjustments, be it halting the simulation, adding or deleting actors, adjusting locations, or seamlessly resuming the simulation from the paused state.

During the simulation, a continuously updated score is prominently displayed on the screen, offering information about how many drones have successfully reached the objective. Furthermore, all pertinent data is systematically saved to a log file, ensuring a comprehensive record of the simulation's events and outcomes. This holistic approach to simulation design not only promotes ease of use but also enhances the overall analytical capabilities and user experience, contributing to a well-rounded and user-friendly research platform.

4. EXPERIMENTS AND RESULTS

This section conducts a comprehensive examination of the simulation's performance across diverse settings. This involves evaluating the efficacy of different countermeasures employed against approaching drone swarms, accompanied by an in-depth analysis of the individual performance of various actors within the simulation. The presentation of results adopts a dual approach, utilizing both quantitative data and graphical representations to offer a comprehensive understanding of the simulation's performance.

Quantitative data provides precise and numerical insights into the outcomes of the experiments, allowing for a detailed examination of the impact of various factors on the simulation. Concurrently, graphical representations enhance the accessibility and interpretability of the results, facilitating a visual understanding of trends, patterns, and key findings. This combination ensures that the reader gains a holistic view of the simulation's behavior and the implications of the tested scenarios.

By leveraging both quantitative data and graphical representations, the section aims to furnish a robust foundation for drawing informed conclusions regarding the simulation's performance. This multifaceted approach enhances the clarity and depth of insights, enabling a nuanced understanding of the dynamics and effectiveness of the simulated scenarios. The dual presentation method aims to cater to a diverse audience, accommodating those who may prefer either a numerical or visual interpretation of the simulation results.

4.1. Experimental Conditions

Given the simulation's capacity to encompass a broad spectrum of parameter values defining the characters, it opens the possibility of constructing an infinite number of scenario combinations for testing. This variability underscores the necessity and significance of a simulation environment for drone swarms, especially when assessing special cases. However, recognizing that the primary objective of this study is to assess the efficacy of defences against drone swarms, a selective approach is taken in choosing scenarios. The aim is to narrow down the vast array of potential combinations to specific cases that yield deterministic results, facilitating a more focused and manageable evaluation.

By strategically selecting scenarios that offer deterministic outcomes, the study ensures a more systematic analysis of defence mechanisms against drone swarms. This targeted approach allows for a more in-depth exploration of key variables and their impact on defence strategies, aiding in drawing meaningful conclusions that can be generalized to a broader context.

In essence, while the simulation environment provides the flexibility to explore a multitude of scenarios, the study strategically narrows down the selection to ensure a thorough and insightful evaluation of defence effectiveness against drone swarms. This balanced approach aims to strike a pragmatic balance between the richness of scenario possibilities and the need for focused, interpretable results.

The study adopts default values for testing unless specified otherwise. The attacking swarms are launched from a distance of 200 meters, representing a standard assault range. For consistency, the default swarm configuration is a cube-shaped collection comprising 512 drones arranged in an 8x8x8 formation, with a uniform spacing of 5 meters between each drone in all three dimensions. Each drone is equipped with collider boxes measuring 0.5 meters in width, 0.4 meters in depth, and 0.3 meters in height.

The drones move at a velocity of 4 meters per second, and their acceleration setting allows them to reach this top speed within 1 second. The minimum detonation distance is set at 0.5 meters. The default target type is an area target, signifying that the drones move collectively and maintain a constant spacing.

To prevent chain reactions, the likelihood of explosion upon destruction is set to zero. Furthermore, all hit points are set to zero, indicating that any hit results in the destruction of the actor. For reference, Table 4 provides a concise summary of these default values, offering an overview of the standardized parameters used in the testing process.

Table 4. Default values used in the experiments.

Parameter	Value	Unit
Target distance	200	m
Pole count	50	pcs
Pole spacing	100	m
Swarm count	200	pcs
Drone dimensions	0.5x0.4x0.3	m
Drone velocity	8	m/s
Drone acceleration	8	m/s
Drone upward velocity	8	m/s
Drone upward acceleration	8	m/s
Minimum distance to detonate	0.5	m
Explosion Area-I Blast Radius	1	m
Explosion Area-I Hit Rate	100	%

These default values establish a standardized baseline for testing, ensuring consistency and comparability across different scenarios within the study.

4.2. Test Scenarios

In this study, six distinct scenarios were simulated, each focusing on a unique defence technique against drone swarms. Rigorous iterations of each scenario were conducted to amass substantial data and statistics for comprehensive analysis. The selected scenarios were deliberately diversified to encompass a broad spectrum of defence tactics against drone swarms. The scenarios are outlined as follows:

- In Scenario 1, Drone Swarms versus Drone Swarms were analyzed. A baseline scenario for comparison, studying the behavior of drone swarms in a pure swarm-versus-swarm context. Initial parameters set to equal values, except for the formation, to observe mutual interactions.
- In Scenario 2, Machine Gun versus Drone Swarms were analyzed. Assessing the efficacy of machine guns, which can engage one target at a time, against drone swarms. Traditional kinetic engagement method using machine guns with varying engagement time parameters.
- In Scenario 3, Laser Weapon versus Drone Swarms were analyzed. Evaluating the effectiveness of modern laser weapons, capable of destroying one target at a time, against drone swarms. Analyzing a laser energy-based strategy with varying burn-up times due to technological advancements.
- In Scenario 4, Anti-Aircraft Gun versus Drone Swarms were analyzed. Testing the effectiveness of stationary anti-aircraft defences, considering the potential explosion of ammunition to destroy surrounding drones. Incorporating the secondary impact zone feature of anti-aircraft guns, is especially effective against dense targets like drone swarms.
- In Scenario 5, Drone Swarms and Anti-Aircraft Gun versus Drone Swarms were analyzed. Assessing the collaborative defence of drone swarms and anti-aircraft guns to explore potential synergies. Studying the combined traits of drone swarms and anti-aircraft guns to test their collective efficacy.
- In Scenario 6, Anti-Air Missile Launcher versus Drone Swarms were analyzed. Evaluating the effectiveness of surface-to-air missile launchers in defending against drone swarms, considering blast radius and missile rate. Analyzing the capability of multi-barrel missile launchers and the optimal blast radius for efficient defence.

The purpose of these scenarios was to generate data on the efficiency of various defence measures against drone swarms, offering insights into the behavior and performance of the simulation's diverse characters. The results obtained from the simulations will be used to compare the effectiveness of different defence strategies in terms of the number of drones destroyed. After the data collection, a thorough review and analysis will be conducted to assess the success of each drone swarm protection technique.

4.3. Results about Scenario 1: Drone Swarms vs. Drone Swarms

4.3.1. Defensive Success Rates

Table 5 shows the rates at which swarms of drones, denoted as Drone Swarm neutralization Rate (DSR), are neutralized when attacking an area target. Generally, the defending swarms exhibit a high level of efficacy in neutralizing the majority of invading drones before they reach their intended objective.

It is crucial to underscore that the defending drones operate as individual entities, lacking target-sharing algorithms in their swarm management and communication. This limitation is acknowledged as it falls beyond the scope of the current study.

Due to the absence of intelligent swarm behaviors such as target sharing, some defensive drones may inadvertently become victims of friendly fire or explosions, resulting in certain friendly casualties. This aspect underscores the potential for even greater effectiveness in defence if drone swarms were equipped with advanced swarm behaviors that enable intelligent target sharing among individual drones.

Table 5. Defensive success rates in Scenario 1: Drone Swarms vs. Drone Swarms.

Offence / Defence	Cube	Pyramid	Prism	Wedge	V-Shaped
Cube	97.1	89.5	96.5	94.7	93.6
Pyramid	91.8	93.2	94.9	94.1	92.4
Prism	93.6	92.0	97.3	96.7	93.6
Wedge	86.7	86.1	88.5	98.8	90.8
V-Shaped	91.8	88.9	93.8	96.1	95.3

In summary, while the defending swarms demonstrate notable effectiveness in neutralizing invading drones, the absence of target-sharing algorithms highlights a potential area for improvement. Implementing intelligent swarm behaviors could enhance the efficiency of drone swarms in defence, minimizing friendly casualties and optimizing their overall defensive capabilities.

The success of the defence strategy is contingent upon the defending swarm being positioned directly in the path of the attacking swarm. Given that the speeds of the swarms are either equivalent or closely matched, the effectiveness of defence diminishes as the distance between the defending and attacking swarms increases. Therefore, it is imperative to accurately predict the enemy's approach direction and strategically deploy the defending swarm to cover these anticipated directions. Alternatively, utilizing drone launchers to impart initial speed to the defending swarm and generating a barrage as needed can enhance defence capabilities. Recognizing the significance of drone launchers, ongoing research and development efforts are underway.

It's noteworthy that while the superiority of formations may vary, the highest value in each column aligns with the row corresponding to the same formation, creating a diagonal line. This observation suggests that defence is most efficient when the defending swarm closely resembles the attacking swarm in terms of speed and formation. In essence, aligning the characteristics of the defending swarm with those of the attacking swarm enhances overall defensive effectiveness. This insight underscores the importance of considering swarm characteristics and deployment strategies for optimizing defence success rates.

4.3.2. Effect of the Changes in Spacing on the Defensive Success Rates

Figure 7 illustrates the impact of changes in drone spacing on defensive success rates. The x-axis values represent the difference in spacing between the attacking and defending swarms. With the default spacing set at 5 meters, a value of 0 indicates that the drones in both swarms are 5 meters apart in all dimensions. Positive values indicate an increase in defending drone spacing, while negative values denote an increase in attacking drone spacing. For instance, a value of 50 implies that the defending swarm's spacing is 7.5 meters, while the attacking swarm's spacing remains at 5 meters. Conversely, a score of -100 indicates that the defending swarm's spacing is 5 meters, whereas the attacking swarm's spacing has increased to 10 meters. On the y-axis, the defence success rate is depicted, representing the proportion of attacking drones destroyed before reaching the target divided by the total number of attacking drones. In both swarms, 512 drones were arranged in a cube shape.

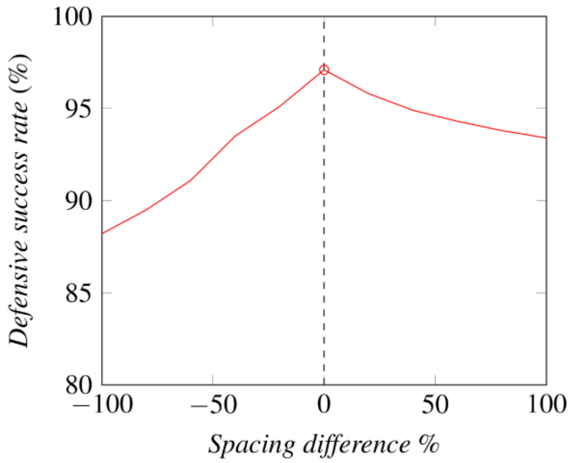

Figure 7. Effect of the changes in spacing on the defensive success rates.

This visualization provides insights into how alterations in drone spacing influence the effectiveness of the defensive strategy. It highlights the correlation between the relative spacing of attacking and defending swarms and the resulting defence success rates. Analyzing this relationship is crucial for optimizing defence strategies against drone swarms in varied scenarios.

The graphical results indicate that the optimal defence is achieved when the two swarms have the same spacing, as the defence success rate diminishes in both directions. This outcome is reasonable because when the drones share identical spacing, they can more effectively align with opponent drones, and the distance they need to cover is shorter. Another significant insight for the defence strategy is that "having more spacing is better than having less", as the latter incurs a heavier penalty on the defence success rate.

This finding underscores the importance of considering the relative spacing between attacking and defending swarms in optimizing defence strategies. Ensuring similar spacing allows for more efficient interception while maintaining a greater spacing on the defensive side proves advantageous. These insights contribute to refining and tailoring defence tactics, providing a nuanced understanding of how swarm characteristics, specifically their spatial arrangement, impact overall defensive success rates.

4.3.3. Effect of the Changes in Velocity on the Defensive Success Rates

Figure 8 illustrates the outcomes of speed adjustments in assessing defence strategies. The x-axis values represent the difference in velocities between the attacking and defending swarms. With the default velocity set at 4 meters per second, a value of 0 implies that both swarms move at this speed. Positive values signify an increase in the velocity of the defensive drones, while negative values indicate an increase in the velocity of the attacking drones. For instance, a value of 50 indicates that the defending swarm's velocity is 6 meters per second, while the attacking swarm's velocity remains at 4 meters per second. Conversely, a value of -100 implies that the defending swarm's velocity is 4 meters per second, whereas the attacking swarm's velocity is 8 meters per second.

According to the graph, having defensive drones that are 60% quicker is sufficient to neutralize the assaulting swarm. However, having an attacking swarm that is 25% faster doubles the offensive success.

Figure 9 illustrates the effects of changing the number of drones in the swarms. Positive values on the x-axis indicate an increase in the number of defending drones, while negative values represent an increase in the number of attacking drones. Given that the simulation's drone model typically allows a drone to destroy only one enemy drone, it is expected that the difference in numbers between the swarms equates to the number of drones reaching the target. In other words, if the attacking side has 100% more drones, 50% of those drones will reach the target unharmed. On the other hand, a mere 5% increase in the number of defensive drones is sufficient to completely thwart an equivalent attacking swarm. This insight emphasizes the significance of swarm size in determining the effectiveness of defence strategies.

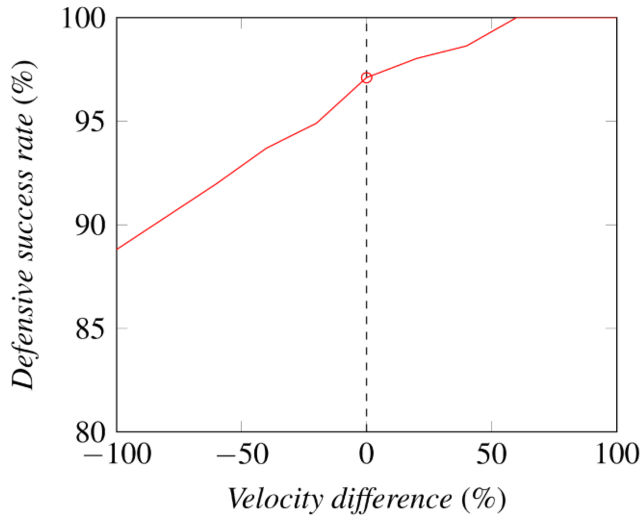

Figure 8. Effect of the changes in velocity on the defensive success rates.

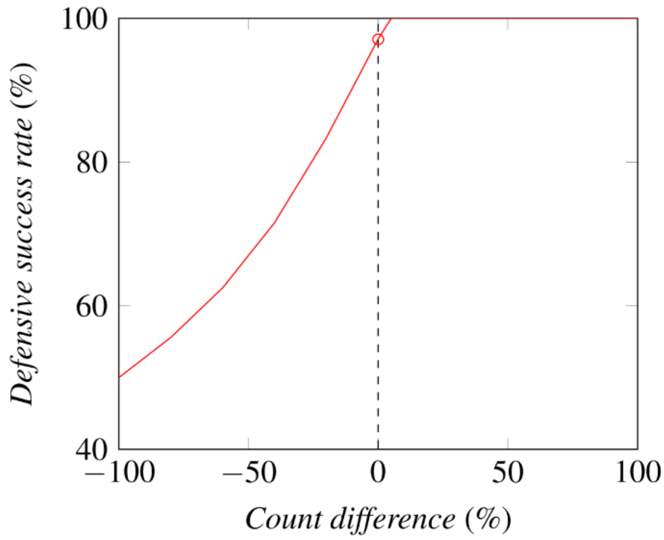

Figure 9. Effect of the changes in in drone count on the defensive success rates.

4.3.4. Effect of the Speed with respect to the Drone Counts on the Defensive Success Rate

Changes in drone speed and quantity can indeed have a significant impact, prompting a crucial comparison. Let's consider a scenario where the attacking side possesses superior technology, enabling them to manufacture drones that are 50% faster. Could the defensive side compensate for this technological disadvantage by deploying more drones? This scenario is common in conflicts, where the attacking side often holds technological advantages, while the defending side leverages terrain control to outnumber the offensive side.

To explore this scenario, two drone swarms with 512 individuals each were created and arranged in a cube configuration. The defending swarm moved at a speed of 4 meters per second, while the assaulting swarm moved at a rate that was 50% faster. While the number of drones in the defending swarm was increased, the velocity values remained consistent across all testing. The defending swarm was able to completely defeat the assaulting swarm when it had 40% more drones. Figure 10 illustrates the outcomes of these examinations.

Additionally, drone swarms demonstrate considerable effectiveness in defending large areas. Consider a scenario where 100 high-voltage transmission line poles (pylons) are positioned in a line with a distance of 100 meters between each. Traditional weapons with limited effective ranges would struggle to secure and repair this 10-kilometer power line. However, a drone swarm acting as a reactive minefield could effortlessly safeguard the entire power line without requiring human involvement. In the simulation environment, this scenario was tested with 5 attacking and defending drones for each pylon. Even in edge scenarios, such as not attacking an adjacent pylon and redirecting rescued drones to the next one, the defending drones were able to completely thwart the attacking drones. This highlights the versatility and efficacy of drone swarms in defending extensive and critical infrastructure.

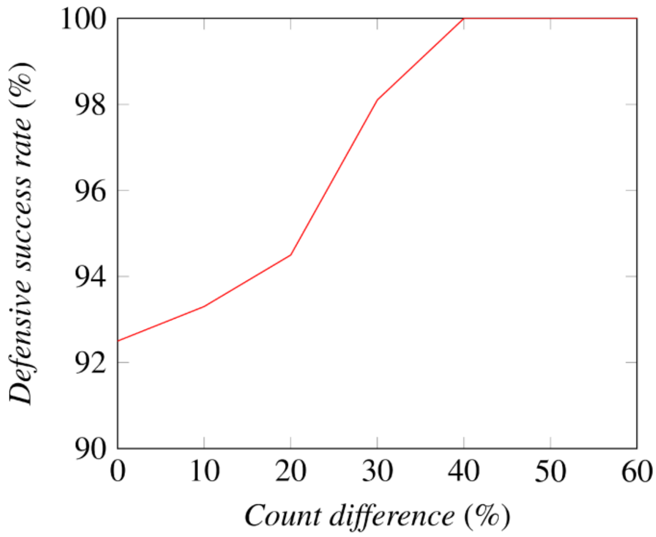

Figure 10. Effect of the speed with respect to the drone counts on the defensive success rates.

4.4. Results about Scenario 2: Machine Gun vs. Drone Swarms

Figure 11 illustrates the impact of the machine gun rate of fire on defence success rates. The curve follows a conventional constant/x pattern, where x represents the rate of fire. The constant in this context is the overall time required for the assaulting swarm to reach its target, approximately 50 seconds in test circumstances, calculated based on the swarm's velocity of 4 m/s and the distance to the target set at 200 meters. As the engagement time is reduced, allowing for more shots within the same time frame, the hit count of the machine gun increases. However, the findings suggest that the hit count is primarily governed by the time it takes for the drones to reach their target rather than the quantity, formation, or other attributes of the attacking drones. In the default scenarios, the swarm comprised 512 drones, ensuring that at least 400 drones reached the target.

In summary, conventional machine guns are not particularly effective against drone swarms, and if used for this purpose, they should be deployed in large numbers to have a meaningful impact.

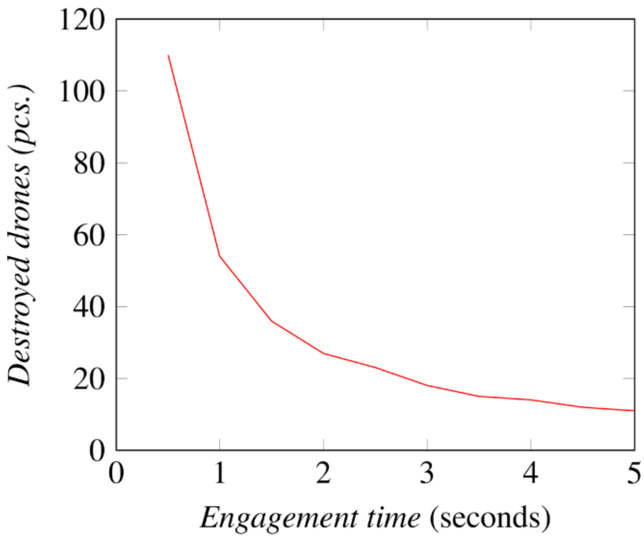

Figure 11. Effect of changes in machine gun engagement time on the number of drones destroyed.

4.5. Results about Scenario 3: Laser Weapon vs. Drone Swarms

Figure 12 illustrates the impact of laser weapon burn-up time on defence success rates. The effectiveness of laser weapons was evaluated across a spectrum of target destruction times, ranging from 15 seconds to 0.5 seconds in the experiments. The results are comparable to machine guns, suggesting that, like machine guns, laser weapons are a type of direct-fire weapon capable of destroying only one target at a time. The key distinction lies in the use of a laser beam instead of bullets. While this may be advantageous when targeting fast-moving, distant objects, it has no substantial impact on the effectiveness of laser weapons against drone swarms. Therefore, the same limitations and considerations that apply to machine guns also apply to laser weapons when used against drone swarms.

In conclusion, despite potential advancements in overcoming limitations such as the need for clean air and challenges in targeting surfaces covered in reflecting coatings, laser weapons appear to exhibit effectiveness comparable to machine guns against drone swarms. Considering that machine guns are significantly less expensive than laser weapons, the latter may not emerge as a practical and cost-effective alternative in the near future for countering drone swarms.

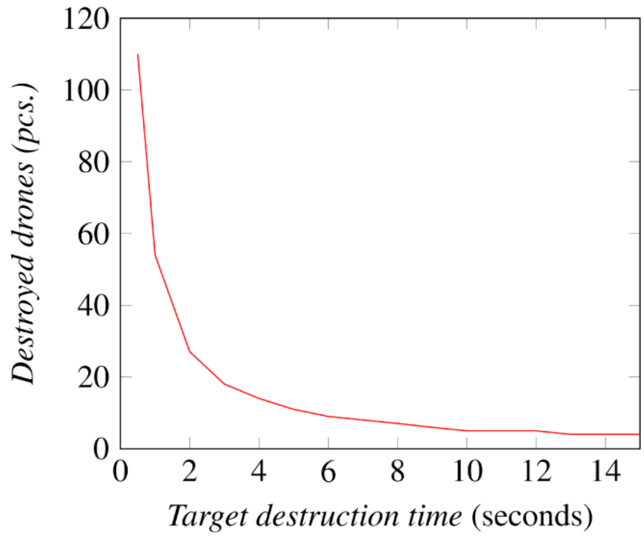

Figure 12. Effect of changes in laser weapon target destruction time on the number of drones destroyed.

4.6. Results about Scenario 4: Anti-Aircraft Gun vs. Drone Swarms

Figure 13 illustrates the impact of the Anti-Aircraft Gun (AAG) fragment count on defence success rates. The red solid line represents the number of drones destroyed solely by fragments as the swarm moves towards an area target. The line becomes nearly horizontal after 24 fragments, indicating an optimal value. The dashed line in the same color reflects the total number of drones destroyed, plus a constant value of 54 drones representing the number of drones damaged by direct fire.

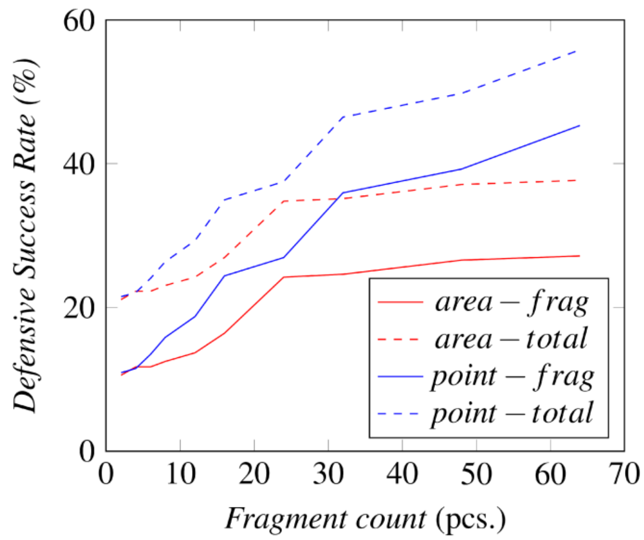

Figure 13. Effect of changes in anti-aircraft gun fragment count on the defensive success rates.

The results show that AAGs are significantly more effective against drone swarms compared to other conventional weapons. The spacing of the enemy swarm is a crucial factor in the AAG's effectiveness, as fragments disseminate from the target hit by the projectile and have a relatively short range. The blue solid line in the graph depicts the outcome of tests using a drone swarm and a point target, showing that the AAG's effectiveness increases when the drones converge over time.

However, the number of fragments and their range are crucial factors in determining the AAG's effectiveness. If the fragment range is less than the swarm spacing, no secondary impact occurs, and the AAG's effectiveness is comparable to that of a simple machine gun. Lower fragment counts also have a lower likelihood of colliding with neighboring drones.

4.7. Results about Scenario 5: Drone Swarms & Anti-aircraft Gun vs. Drone Swarms

The results seen in Table 6 highlight the substantial effectiveness of the combined use of drone swarms and anti-aircraft guns in countering an attacking drone swarm. In the scenario where both the defending swarm and anti-aircraft weapons were deployed, only 8 attacking drones successfully reached the target. This represents a notable reduction compared to scenarios where either the defending swarm or the anti-aircraft weapons were employed alone, resulting in 102 and 108 drones reaching the target, respectively.

The synergistic effects observed in combining these two defensive methods underscore the potential for enhancing overall effectiveness by integrating different defence strategies. This strategic combination capitalizes on the strengths of both drone swarms and anti-aircraft guns, resulting in a comprehensive defence against the attacking swarm. The findings emphasize the importance of thoughtful and strategic planning in countering drone swarm threats, suggesting that a multi-layered defence approach can contribute to a more robust and resilient system.

Table 6. Defensive success rates in scenario 5: drone swarms & anti-aircraft gun vs. drone swarms.

Defence Units	Offence	Defence	Offence Speed	Defence Speed	Offence	Defence Success Rate (%)
Swarm&Turrets	320	256	5 m/s	4 m/s	24	96.87
Swarm	320	256	5 m/s	4 m/s	-	60.15
Turrets	320	-	5 m/s	-	24	57.81

4.8. Results about Scenario 6: Surface-to-Air Missiles vs. Drone Swarms

The test results seen in Figure 14 underscore the effectiveness of anti-air missiles against drone swarms, particularly under specific conditions. The exponential increase in the number of drones destroyed is attributed to the blast radius of the missiles. When the explosion radius exceeds certain limits, it can impact multiple drones within the swarm, resulting in a more significant destruction count.

The findings suggest that anti-air missiles can be particularly effective when drone swarms are assigned a point target and converge, exposing them to the blast impact. Additionally, the blast effect of these missiles makes them potent against dense swarms of micro drones. The results highlight the potential of anti-air missiles as a viable defence mechanism against drone swarms, especially when deployed strategically to exploit the swarm's characteristics.

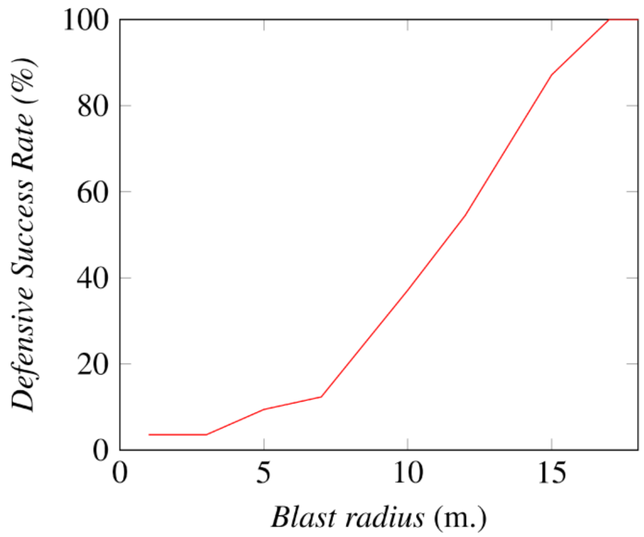

Figure 14. Effect of the changes in surface-to-air missile blast radius on the defensive success rates.

5. CONCLUSION

The widespread accessibility and affordability of unmanned aerial vehicles (UAVs), commonly known as drones, have generated apprehensions regarding their potential exploitation by both legal and illicit armed entities. Particularly, the emergence of drone swarms, capable of coordination through artificial intelligence-supported platforms, has heightened concerns about the likelihood of orchestrated large-scale attacks. Consequently, there is a growing demand for the formulation of effective countermeasures and strategies to mitigate these risks.

The utilization of a simulation platform for researching defence strategies against drone swarms holds paramount significance. Conducting real-world experiments with a substantial number of drones poses logistical challenges, financial burdens, and potential safety hazards. A simulation platform facilitates the creation of a controlled and reproducible environment for testing diverse defence strategies without the necessity for physical hardware. Moreover, simulations permit the manipulation of variables such as drone characteristics, swarm size, and defence strategy parameters, which may be impractical or unfeasible in actual testing scenarios. Furthermore, simulations provide a secure and ethical avenue for evaluating defence strategies, a task that may be deemed perilous during live demonstrations. Through the implementation of a simulation platform, a more profound understanding of the capabilities and limitations of various defence strategies can be achieved, enabling the development of novel and effective countermeasures against drone swarms.

In this study, a simulation platform was developed to assess the effectiveness of different countermeasures against drone swarms. The performance of each countermeasure was quantitatively evaluated by calculating its "Defensive Success Rate" within the simulated environment. Six distinct scenarios were meticulously chosen to encompass a broad range of countermeasure options, including traditional kinetic weapons, contemporary energy-based systems, explosive projectiles, and drone swarms themselves. The simulation results offer a comprehensive insight into the potential performance of these countermeasures against drone swarms, laying the groundwork for the formulation of effective defence strategies against this emerging threat.

Utilization of a game engine as an alternative to a simulation software as the underlying framework in this study distinguishes it among the literature on swarm simulations. The study's capacity to generate and evaluate diverse scenarios with different entities establishes a testable infrastructure, thus surpassing the existing body of literature in the realm of game engine-based research. This elevates the prominence of the study, setting it apart from corresponding studies in the field.

The study yields valuable insights into potential countermeasures and defensive strategies against drone swarms. It establishes that while challenging, defending against drone swarms is not insurmountable. Counter swarms and anti-aircraft guns prove particularly effective in swiftly neutralizing large numbers of drones. Noteworthy is the importance of deploying counter-swarms strategically and considering swarm and individual drone properties such as count, spacing, and speed for an effective defence. In contrast, traditional single-target weapons, such as machine guns and laser weapons, demonstrate diminished effectiveness against the coordinated movements of drone swarms.

This study serves as a foundational point for further exploration in this domain, emphasizing the ongoing necessity to develop effective defence strategies against drone swarms. The findings can guide future research and development projects for drone defence systems. Subsequent investigations could enhance the intelligence of simulated drones by incorporating obstacle avoidance and target-sharing systems, offering a more realistic portrayal of modern drone capabilities and limitations for detailed strategy evaluations. Additionally, research on drone swarm control and coordination could enhance their effectiveness as a defence strategy.

Future endeavors may involve introducing ground or air-based drone launchers as new entities in the simulation, mirroring real-world swarm deployment scenarios more accurately. This approach aims to provide a more realistic context for the simulation, incorporating functionalities such as selective launch, reloading time, and assigned areas of operations. Integrating real-time targets and introducing a multiplayer feature could further enhance the simulation's realism, allowing for more accurate evaluations of defence strategies under dynamic conditions.

In summary, this study initiates a valuable exploration into defence strategies against drone swarms. Subsequent research endeavors intend to enhance the simulation's realism and complexity, aligning it more closely with real-world conditions and providing a deeper understanding of the effectiveness of diverse defence strategies.

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To Cite This Article: G. Karadeniz, A. Ozcan, M. Bayram, G. Ince, *Drone Wars 3D: A Game-Based Simulation Platform for Testing Aerial Defence Strategies Against Drone Swarms*, Journal of Aeronautics and Space Technologies **17**(Special Issue), 182-207 (2024).

VITAE

Gökhan Karadeniz received the B.S. degree in System Engineering from Turkish Military Academy after graduated Kuleli Military High School, Türkiye, in 2005, the M.S. degree in Game and Interaction Technologies in 2022 from Istanbul Technical University, Türkiye. His research interests include serious games and constructive simulation.

Ahmet Ozcan received the B.Sc. and M.Sc. degrees in computer engineering from Erciyes University, Kayseri, Türkiye, in 2011 and 2016, respectively. He received received the Ph.D. degree in computer engineering from National Defence University, Istanbul, Türkiye in 2023. His research interests include computer vision, machine learning, robotic systems and simulation.

Mehmet Bayram received his BSc in Industrial Engineering from the Turkish Air Force Academy in 2004, MSc degree in Industrial Engineering from Eskisehir Osmangazi University, Türkiye in 2010, and PhD degree in Industrial Engineering from Marmara University, Türkiye in 2019. Throughout his career, he worked in several positions of the Turkish Air Force and NATO as an officer. He started working as lecturer in the Turkish

National Defence University in 2021 where he currently works as an Assistant Professor of Industrial Engineering. His current research focus is on simulation, wargaming and AI.

Gökhan Ince received the B.S. degree in Electrical Engineering from Istanbul Technical University, Türkiye, in 2004, the M.S. degree in Information Engineering in 2007 from Darmstadt University of Technology, Germany and the Ph.D. degree in the Department of Mechanical and Environmental Informatics, Tokyo Institute of Technology, Japan in 2011. From 2006 to 2008, he was a researcher with Honda Research Institute Europe, Offenbach, Germany and from 2008 to 2012, he was with Honda Research Institute Japan, Co., Ltd., Saitama, Japan. Since 2012, he has been an Associate Professor with the Computer Engineering Department, Istanbul Technical University. His current research interests include human-computer interaction, robotics, artificial intelligence and signal processing.