ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DRONE WARS 3D: AN INTERACTIVE SIMULATOR FOR DRONE SWARMS

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

DRONE SAVAŞLARI 3D: İNTERAKTİF DRONE SÜRÜSÜ SİMÜLATÖRÜ

YÜKSEK LİSANS TEZİ

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Oyun ve Etkileşim Teknolojileri Ana Bilim Dalı

Oyun ve Etkileşim Teknolojileri Yüksek Lisans Programı

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OCAK 2023

Gökhan KARADENİZ, a M.Sc. student of ITU Graduate School student ID 529191007 successfully defended the thesis entitled “DRONE WARS 3D: AN INTERACTIVE SIMULATOR FOR DRONE SWARMS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 30 DECEMBER 2022
Date of Defense : 24 JANUARY 2023

to whom I owe all, my mother,
her şeyimi borçlu olduğum anneme,

FOREWORD

I would like to extend my sincerest gratitude to my thesis advisor, Assoc. Prof. Dr. Gökhan İNCE, for his invaluable assistance and support throughout the preparation of this thesis. I would also like to thank Lieutenant Colonel André HAIDER and Asst. Prof. Dr. Mehmet BAYRAM for their invaluable guidance and contribution to the creation of a more realistic simulation environment and the resulting valuable outcomes. I am also grateful to Luben Nikolaev POPOV for generously granting me early access to his thesis, which greatly aided in the development of my own research. I would also like to express my appreciation to my family for their love, support, and encouragement throughout this journey. Their unwavering belief in me has been a constant source of motivation and strength.

November 2022

Gökhan KARADENİZ
(Technical Game Designer)

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ABBREVIATIONS

AAG : Anti-Aircraft Gun
AAM : Anti-Air Missile
DSR : Defense Success Rate
DARPA : U.S. Defense Advanced Research Projects Agency
EDA : European Defense Agency
GPS : Global Positioning System
İHA : İnsansız Hava Aracı
LOCUST : Low-Cost Unmanned aerial vehicle Swarming Technology
MG : Machine Gun
OFFSET : Offensive Swarm Enabled Tactics
RTS : Real-Time Strategy
SWADAR : Swarm Advanced Detection and Tracking
UAV : Unmanned Air Vehicle

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DRONE WARS 3D: AN INTERACTIVE SIMULATOR FOR DRONE SWARMS

SUMMARY

The utilization of drone swarms, characterized by their formidable destructive capabilities and broad range of potential applications, has led to the pressing need for effective countermeasures to mitigate their potential threats. Additionally, the relatively low cost of drones has further amplified the need for robust defense strategies.

Although consumer-type drones can be neutralized by electronic countermeasures or microwave weapons, military-grade drones are produced to be protected against such attacks, leaving the physical destruction as the best choice.

Within the scope of this study, a simulation environment was developed in the Unity3D game engine in order to measure the effectiveness of defense systems against drone swarms and to find effective defense tactics and swarm formations. Unless otherwise stated, swarms with the same default values were used in the tests.

The actor types in the simulation were 1) drone, 2) drone swarm, 3) machine gun, 4) laser weapon, 5) anti-aircraft gun, 6) air defense missile launcher.

In the tests of defensive drone swarms against offensive drone swarms, two enemy swarms (identical in everything but their formations) were created. Then attack drones destroyed were inspected by applying all possible formation combinations. Results show that, the drone swarms have an average success rate of over 90% in destroying enemy drone swarms. Though, in order to achieve this success rate, the defending swarm must be located on the attacking swarm's target approach path.

Another noteworthy finding was that each formation was most effective in defending against the enemy swarm having the same formation of attacking party. A strategy to copycat the offensive swarm's shape when possible seems to be viable given the fact that identical swarms are more effective against each other.

This finding was also supported by the results of drone spacing tests. When two swarms of the same number and formation were used against each other with different drone spacing, the most effective defense was obtained when the drone spacing of the two swarms were equal.

According to the results of the speed tests, the defending swarm can destroy all enemy drones when it is 60% faster. When the attacking swarm is faster, the number of drones that can reach the target increases by 100% at 25% speed difference and by 200% at 70% speed difference.

In the test with changes in the drone counts, the defending swarm was able to destroy all enemy drones when it had 5% more drones. When the attacking side has more drones, slightly more drones have reached the target than the difference. This can be explained by the fact that our simulation model is structured as allowing one drone to destroy only one enemy drone in most cases.

When changes in speed and drone count are tested at the same time, it's observed that an attacking swarm moving 50% faster can be completely defended by a swarm with 40% more drones. This result shows that when the defender has weaker drones, it may be a good strategy to try to achieve superiority in mass.

It has also been observed that drone swarms can be used more flexibly and effectively than other actors in large area defense.

According to the test results, machine guns and laser weapons are not effective against drone swarms. Because they can only take out one drone at a time, these weapons can always take out the number of drones they can aim at in the time it takes the attacking drone to get to the target, given that each shot is accurate and potent enough to take out the target.

Modern anti-aircraft guns, on the other hand, were more effective against drone swarms due to the ability of their shells to explode on target. When the number of fragments scattered by the projectiles exploding on the target was set at 24, and the range set at 20 meters, 124 drones were destroyed by the fragments in addition to the 50 drones that were directly hit.

Anti-aircraft missiles also provided highly effective defense when their blast radius was larger than the swarm's drone spacing. As the blast radius increases, the effectiveness rate increases exponentially as the missiles are able to destroy neighboring drones of the one that directly hit. Since the swarms in the tests have a default spacing of 5 meters, when 18 missiles were launched towards the swarms, only 18 drones were destroyed when the blast radius was less than 5 meters. Destroyed drones increased to 190 when the blast radius was 10 meters, and all 512 drones were destroyed when the blast radius was 17 meters.

Since the defending drone swarms and the modern anti-aircraft gun happened to be the most effective actors in the tests, some scenarios to measure their synergy were also applied. When a defensive swarm of 256 drones was supported by 2 anti-aircraft guns against an offensive swarm with 25% faster and 25% more drones, only 8 drones could reach the target. This result was 102 without anti-aircraft guns support and 108 without drone swarms.

In conclusion, test results show that counter drone swarms and the weapons that can destroy multiple targets in an area are more effective against drone swarms than conventional weapons that provide "one shot, one kill". However, considering the flexible use of drone swarms, it would be useful for the defense to test other possible scenarios in a simulation environment.

DRONE SAVAŞLARI 3D: İNTERAKTİF DRONE SÜRÜSÜ SİMÜLATÖRÜ

ÖZET

Yapay zeka alanındaki gelişmeler muharebe sahasının giderek insansızlaşmasına yol açmakta, bu insansızlaşmanın başını nispeten ucuz ve 3 boyutlu yazıcılarla bile yapılabilecek kadar kolay üretim özellikleriyle İnsansız Hava Araçları (İHA) çekmektedir. Aynı özellikler İHA'ların sürü halinde kullanım fikrinin de gündeme gelmesini sağlamış, bu konuda girişimler hayata geçmeye başlamıştır. İHA sürülerinin bu derece ulaşılabilir olması, sağladığı avantajlardan sadece devletlerin değil terörist örgütlerin de yararlanmaya çalışmasına yol açmaktadır.

İHA sürülerinin esnek kullanım alanları ve ucuz maliyetleriyle yarattıkları büyük tahrip gücü, onlara karşı savunmayı da bir o kadar önemli kılmıştır. Ne var ki bu savunma yöntemleri halen tam bilinmemekte ve konvansiyonel silahların İHA sürülerine karşı ne derece etkili olacağı tartışılmaktadır. Avrupa Savunma Ajansı'nın (European Defence Agency) 2020 yılı "Savunma İnovasyon Ödülü" temasını "İHA sürülerine karşı savunmada inovatif çözümler/teknolojiler" olarak belirlemesi, konuya verilen önem kadar bu konuda bilgiye ne kadar acil ihtiyaç duyulduğunu da göstermektedir.

Tüketici tipi İHA'lar elektronik karşı koyma tedbirleri ya da mikrodalga silahları gibi araçlarla etkisiz hale getirilebiliyor olsalar da, askeri tip İHA'lar bu tip saldırılara karşı korunaklı olarak üretildiğinden en kesin savunma yöntemi fiziksel tahriptir.

Bu çalışma kapsamında, İHA sürülerine karşı savunma sistemlerinin etkinliğini ölçmek, etkili savunma taktik ve formasyonlarının bulunabilmesi sağlamak adına Unity3D oyun motorunda bir simülasyon ortamı geliştirilmiştir. İHA'ların elektronik harp vb. yollarla etkisiz hale getirilemediği, sadece fiziksel tahrip ile yok edilebildiği varsayılmıştır. Her bir aktörün menzili içindeki düşman unsurlarını tam doğrulukla tespit edebildiği, havanın berrak, rüzgarsız ve sürtünmesiz olduğu, patlamalar sonucu oluşan sisin tespit unsurlarını etkilemediği, tüm aktörlerin tamamen imha olmadıkları sürece kusursuz çalışmaya devam ettikleri kabul edilmiştir. Her bir aktör imha edildiğinde olayla ilgili zaman, konum, imha eden ve edilen aktör bilgilerinin bir dosyaya yazılarak sonradan analiz edilebilmesi sağlanmıştır. Görev çeşitleri; bölge ya da nokta hedeflerine taarruz, başka bir aktör tipine taarruz ve düşman İHA sürüsünü imha etmek olarak belirlenmiştir. Sürü yönetimi ya da hedef paylaşımı gibi sürü için iletişim gerektiren algoritmalar kapsam dışı tutulmuş ve sürü içinde olsalar da her İHA'nın bireysel davranış sergilediği bir sistem oluşturulmuştur.

Simülasyonda yer alan aktör türleri 1) İHA, 2) İHA sürüsü, 3) makineli tüfek, 4) lazer silahı, 5) uçaksavar topu, 6) hava savunma füzesidir.

İHA'ların fiziksel ölçü, taraf (savunma/taarruz), hız, patlama alanı özellikleri kullanıcı tarafından ayarlanabilmektedir. Taarruz eden İHA'lar sadece verilen hedefe ilerlemekte, düşman İHA'larından kaçınmaya çalışmamaktadır. Savunan İHA'lar ise kendilerine en yakın düşman İHA'nına doğru ilerlemekte ve minimum patlama mesafesine ulaştığında kendisini imha ederek patlama alanı içinde kalan dost ya da düşman unsurlarını, o alana ait tahrip olasılığına göre imha etmektedir.

İHA sürüleri kullanıcı tarafından belirlenen sayıda aynı tip İHA'ya sahiptir. Kullanıcıya İHA tipi ve sayısını, sürü şeklini (küp, piramid, prizma, kama ve ters kama) ve her bir eksen için İHA'lar arasındaki mesafeyi belirterek hızlıca büyük sürüler oluşturma imkanı sağlanmıştır.

Diğer aktörlerin menzil, sonraki hedefe kitlenme için gerekli zaman, atım sıklığı, mermileri hedefte patlıyorsa patlama alanı özellikleri yine kullanıcı tarafından belirlenebilmektedir.

Aktör türü ve özelliklerinin çok sayıda olması ile aktörlerin değişik sayı ve konuşlandırmalarla kullanılabilecek olması, oluşturulabilecek senaryo sayısının sonsuza yakınmasına yol açmaktadır. Bu çalışmada, İHA sürülerine karşı savunmada her bir aktörün etkinlik seviyesini ölçme imkanı sağlayacak sonuçları üretecek bazı temel senaryolar test edilmiştir. Testlerde aksi belirtilmedikçe varsayılan olarak 4 m/s hızla, 200 m. uzaklıktaki bölge hedefine doğru hareket eden ve patladığında 1 m. içindeki unsurları %100, 2m. içindeki unsurları %20 ve 4 m. içindeki unsurları %4 ihtimalle imha eden 512 adet İHA'ya sahip küp formasyonunda 5'er metre aralıklı dizilmiş sürüler kullanılmıştır.

"Her silah kendisinin doğal düşmanıdır" prensibinden hareketle, ilk testlerde taarruz eden İHA sürülerine karşı savunan İHA sürülerini kullanılmıştır. Varsayılan değerlerle birbirinin aynı iki düşman sürüsü oluşturulup mümkün olan tüm formasyon kombinasyonları test edilerek imha edilen taarruz İHA'yı sayısı ölçülmüştür. Sonuçlara göre İHA sürüleri, düşman İHA sürülerini durdurmada ortalama olarak %90 üzeri başarı sağlamaktadır. Dikkate değer olan bir bulgu ise, her formasyonun en etkili olarak kendi formasyonundaki düşman sürüsüne karşı savunma yaptığı olmuştur. İkiz sürülerin birbirlerine karşı daha etkili olduğu bilgisi, bir düşman İHA süresi tespit edildiğinde, imkan varsa savunan sürüye onun şeklini adırmak gibi bir strateji kullanımını yararlı olacağını göstermektedir.

Söz konusu bulgu, İHA'lar arası aralık testleri sonuçlarıyla da desteklemiştir. Aynı sayı ve formasyondaki iki sürü değişik İHA'lar arası aralıklar kullanılarak birbirleriyle çatıştırıldıklarında, en etkili savunma iki sürünün İHA aralıkları eşitken elde edilmiştir. Taarruz eden sürünün İHA aralık değeri daha büyük ise taarruz önemli ölçüde daha başarılı olurken, savunmadaki sürünün İHA'lar arası mesafesi daha büyük olduğunda ilk durum kadar olmasa da savunma başarısının azaldığı gözlenmiştir. Aralıklar eşitken İHA'ların hedef İHA ile eşleşmesinin daha kolay olması ve kat etmeleri gereken yolun en kısa mesafeye inmesi bu durumun sebepleri olarak gösterilebilir.

Kat edilen yolun uzunluğu kadar bu yolun ne kadar sürede alındığı da önemlidir ve bu süre hıza bağlıdır. Varsayılan sürüler kullanılarak diğer tüm değişkenler sabitken İHA hızları değiştirilerek yapılan testlerin sonuçlarına göre savunan sürü %60 daha hızlı olduğunda tüm düşman İHA'larını yok edebilmektedir. Taarruz eden sürünün daha hızlı olduğu durumda ise hedefe ulaşabilen İHA sayısı; %25 hız farkında %100, %70 hız farkında ise %200 artmaktadır.

Söz konusu sürüler olduğunda sürüdeki eleman sayısının büyük önemi vardır. Varsayılan sürüler İHA miktarları değiştirilerek birbirleriyle çatıştırıldıklarında elde edilen sonuçlara göre savunan sürü %5 daha fazla sayıda olduğunda tüm düşman İHA'larını yok edebilmektedir. Taarruz eden taraf daha fazla sayıda olduğunda ise, fazlalık İHA sayısından biraz daha yüksek bir miktar hedefe ulaşmaktadır. Bu, simülasyon modelimizin büyük çoğunlukla bir İHA'nın bir İHA'yı yok etmesi şeklinde yapılandırılmış olmasıyla açıklanabilir.

Hız ve sayı birlikte değiştirildiğinde görülmüştür ki %50 daha hızlı hareket eden bir taarruz sürüsü %40 daha fazla İHA'ya sahip bir sürü tarafından tamamen savunulabilir. Bu sonuç, savunanın teknolojik olarak taarruz edeni yakalayamadığı durumlarda sayı üstünlüğü sağlamaya çalışmasının iyi bir strateji olabileceğine işaret etmektedir.

İHA sürülerinin geniş alan savunmasında diğer aktörlere oranla daha esnek ve efektif kullanılabileceği de gözlenmiştir.

Makineli tüfek ve lazer silahı test sonuçlarına göre İHA sürülerine karşı pek etkili aktörler değillerdir. Bu silahlar her atımlarının isabetli ve hedefi imha etmeye yeter olduğu varsayıldığı durumda aynı anda en fazla 1 İHA'yı imha edebildiklerinden, her zaman için taarruz eden İHA'nın hedefe ulaştığı sürede nişan alabildikleri İHA sayısı İHA'yı yok edebilmektedirler. Varsayılan değerlerle yapılan testlerde hedefe varış süresi 50 saniye olduğundan bu silahlar saniyede 1 hedefi yok etseler dahi 50'den fazla İHA'ya sahip her sürüdeki fazlalık İHA'lar hedefe ulaşmayı başaracaktır.

Modern uçaksavarlar ise mermilerinin hedefte patlama özelliğiyle İHA sürülerine karşı daha etkili olmuşlardır. Hedefte patlayan mermilerin şarapnel sayısı 24, şarapnellerin dağılım menzili 20 m. olarak belirlendiğinde doğrudan vurulan 50 İHA'ya ek olarak 124 İHA'nın şarapnel etkisiyle imha olduğu görülmüştür. 24'ten sonra şarapnel sayısındaki artış çok etkili olmamıştır. Şarapnellerin menzilleri içindeki bir İHA'ya isabet etme olasılıkları şarapnel sayısı ile doğru orantılı iken sürü aralıkları ile ters orantılıdır. Bu nedenle modern uçaksavar silahı dar aralıklı, yoğun sürülere karşı daha etkili olmuştur. Bir İHA sürüsüne noktasal hedef verildiğinde her bir İHA aynı noktaya ulaşmaya çalıştığından aralıkları giderek azalmaktadır. Modern uçaksavar için aynı testler noktasal hedef verilmiş sürülere karşı yapıldığında 20 m. menzil için; şarapnel sayısı 24 iken 138, 32 iken 184 İHA'nın şarapnel etkisiyle imha olduğu gözlenmiştir.

Uçaksavar füzeleri de patlama yarıçapları İHA aralıklarından daha büyük olduğunda oldukça etkili savunma sağlamışlardır. Patlama yarıçapı arttıkça füzeler vurulan İHA'ya komşu İHA'ları da imha etmeyi başardığından etkinlik oranı üstel olarak artmaktadır. Yapılan testlerde sürüler varsayılan olarak 5 m. aralığa sahip olduğundan, 18 adet füze sürüye doğru gönderildiğinde, patlama yarıçapı 5 m.'den küçükken sadece 18 İHA imha olurken, 10 m. olduğunda bu sayı 190'a çıkmış ve 17 m. olduğunda 512 İHA'nın tamamı imha edilmiştir.

Savunan İHA sürüleri ile modern uçaksavar silahı testlerde en etkili aktörler olarak öne çıktıklarından ve farklı karakteristiklere sahip olduklarından bu iki aktör arasındaki sinerjiyi ölçmek amaçlı testler de yapılmıştır. %25 daha hızlı ve %25 daha fazla İHA'ya sahip bir taarruz sürüsüne karşı 256 İHA'ya sahip bir savunma sürüsüne 2 adet uçaksavar desteği verildiğinde sadece 8 İHA hedefe ulaşabilmiştir. Bu rakam uçaksavarlar olmadığında 102, İHA sürüsü olmadığında ise 108 olarak gerçekleşmiştir.

Sonuç olarak; İHA sürülerine karşı “bir atım, bir ölüm” sağlayan konvansiyonel silahlar yerine bir alan içindeki birden fazla hedefi imha edebilen silahların ve karşıt İHA sürülerinin daha etkili olduğu gözlenmiş, bununla birlikte sürülerin değişen özellikleri ve esnek kullanım imkanları göz önünde bulundurulduğunda, olası diğer senaryoların bir simülasyon ortamında önceden denenmesinin savunan taraf için faydalı olacağı sonucuna ulaşılmıştır.

1. INTRODUCTION

There has been a significant increase in the use of Unmanned Aerial Vehicles (UAVs), or drones, in recent years, particularly in military applications. This trend can be attributed to the decreasing cost and increasing reliability of drones, as well as the widespread availability of the technology. In fact, it is now possible to produce a drone with embedded electronics using only a 3-D printer in a relatively short amount of time [1]. These developments have contributed to the growing popularity and utility of drones in various fields.

Not only are military forces taking advantage of the capabilities of drones, but terrorist organizations have also been known to utilize them. For instance, ISIS has been known to expand its drone fleet [2], and in 2018, a drone attack targeted Venezuelan President Nicolas Maduro during a public speech [3]. These examples, along with a global list of drone incidents, demonstrate that drones can be used in a variety of conflicts [4]. Security experts have warned that drones pose a significant threat to national security [5].

The affordability of drones also allows for the expansion of their use, including the concept of drone swarms. By grouping drones together, it is possible to create a more formidable offensive unit that presents a greater challenge for current air defense systems. For example, a swarm of ten explosive-laden drones was used in a coordinated assault on Russia's Hmeimim airbase in western Syria in January 2018 [6].

In response to the growing threat of drones, Russian companies have developed anti-drone systems, such as in the wake of a swarm of drones attacking Saudi oil facilities and reducing global production by 5% [7].

The U.S. Defense Advanced Research Projects Agency (DARPA) has revealed a drone swarm program called Offensive Swarm Enabled Tactics (OFFSET), which envisions the cooperation of infantry forces and up to 250 unmanned aircraft systems to accomplish various missions in complex urban environments [8].

The United States' Low-Cost Unmanned Aerial Vehicle Swarming Technology (LOCUST) program, developed by the Office of Naval Research, acts as a multi-barrel missile launcher, but instead of missiles, it launches drones [9]. Once launched, the swarm operates autonomously as a group while being monitored by a human operator [10].

The European Defense Agency's (EDA) Defense Innovation Prize 2020 contest focused on identifying innovative ideas, technologies, and solutions for counteracting swarms of Unmanned Aerial Vehicles (UAVs). The first of the two winning projects, called Swarm Advanced Detection and Tracking (SWADAR), proposed a technological solution for tracking drone swarms to provide an operational picture of swarm attacks. SWADAR utilizes a team of defensive drones that track the hostile swarm from different perspectives. The second winning project, called "Full-Duplex Radio Technology for Enhanced Defense Capabilities Against Drone Swarms" aims to neutralize enemy swarms through jamming. EDA Deputy Chief Executive Olli Ruutu stated that these results reflect "the strategic importance of drones and the threat they pose to modern air defense systems, especially when used in large swarms coordinated by artificial intelligence-supported platforms." [11].

EDA also funded a project called "EuroSWARM: Developing technology for UAV swarms in defense applications" led by Cranfield University, with a grant of 434,000€. The goal of the project was to develop a UAV swarm architecture technology to demonstrate that unmanned swarms can have a significant impact on the battlefield if they are operated in an efficient and effective manner [12].

Drone swarms can be used for a variety of military objectives, including raiding, sabotage, ambushing, patrolling, serving as an air shield against missiles, creating dynamic minefields, surveillance, and logistics. There are also numerous risks to civilians, such as the potential for explosive or chemical-laden swarms to be flown into crowded places like stadiums, or for a large swarm to be flown into passenger plane engines during takeoff or landing. Helicopters are also at risk of encountering a drone swarm as they share similar flying altitudes [13]. Therefore, defense against drones should be a priority component of any national strategy.

However, the effectiveness of drone swarms depends on the use of effective tactics. Swarm tactics are considered to be at a very early stage [14], and the goal of this study is to propose, create, modify, and test tactics with a lower cost using an interactive simulation platform created on a game engine. This real-time strategy (RTS) game-like simulation uses drone swarms, as well as some co-actors, against attacking swarm drones and missiles.

2. RELATED WORK

The fact that the drone swarms have a big offensive potential, it is essential to develop effective countermeasures. There are researches about defense systems against them. In Table 2.1 [15], Guitton categorizes the countermeasures against drone swarms and indicates their limitations.

Table 2.1 : Countermeasures against drones and their limitations.

Countermeasure	***Effect on target***	***Limitations/vulnerability***
Direct fire	Destruction	Size of targets Number of targets Visibility
Hunting drones	Destruction	Number of targets Visibility Inherent drone weaknesses Deployment time
Missiles	Destruction	Costs
Laser weapons	Destruction	Atmospheric conditions Smokescreens Target's coating
Microwave weapons	Disabling	Sealing of electronics
Electronic jamming	Disabling Control taking	Sealing of electronics
Defending drone swarm	Individual destruction Swarm disruption	Lack of accurate response Deployment time

Conventional weapons that open direct fire will be less effective as the number of targets increases and the size of drones get smaller. The latter also makes them cheaper. Hunting drones are also ineffective against large swarms and deployment arises as a secondary problem. Counter-Unmanned Aircraft Systems Mobile Integrated Capability (CMIC) developed by U.S. Army is an example [16]. This system uses its sensors to search for the hostile UAV and its pilot, then neutralizes them.

Jamming methods can be effective against consumer-type drones as most of them rely on Global Positioning System (GPS) signals to navigate and unencrypted protocols to communicate, but military-grade drones will have precautions against electronic combat and may have the intelligence to act autonomously enough to follow a pre-programmed route or perform any pre-loaded scenario. So, these methods can be used as auxiliary measures but cannot be relied on as a single solution. Missiles cost way too much and laser weapons can be neutralized with some coating and/or even with smokescreens. In this table, there is a point that differentiates "Defending Drone Swarm" from other countermeasures. Other solutions' limitations and vulnerabilities can be exploited by the attacking side, but the limitations of the defending drone swarm cannot be exploited, rather, they can be minimized with appropriate tactical implementations. All homogeneous systems are native rivals/enemies of each other. An infantry division, a tank battalion, a helicopter squadron, are all natural enemies to another unit of the same type, and so are drone swarms.

The "Drone Swarm Simulation" project which is made in a Unity game engine, introduces a real-time simulation of one or more drone swarms comprised of independently behaving drones attacking a group of naval turrets [17]. This simulation is then used to gather and analyze mission outcome data for different drone and swarm configurations with the purpose of both using and defending against drone swarms in naval warfare.

Another study that uses the Unity game engine examines the survivability of drone swarms in a virtual reality environment [18]. In this game-like study, swarms fly along various paths and the player aims at shooting them. This simulation also examines the effects of direct fire only.

Zhang et al. address the concept of a defensive UAV swarm launched from a sea-based platform [19]. Defense success rate (DSR) is proposed as a metric of effectiveness. It analyzes the impacts of different design factors by using three types of agents: a blue High-Value Unit (HVU) to protect, a patrolling blue UAV in defense and a red UAV on offense. Agents' behaviors are relatively constrained and they are initialized on air. Blue UAV agents are also subject to constraints such as limited endurance.

Additionally, a blue UAV is considered to operate as a small missile, and the targeting of a red UAV is assumed to be both fully accurate and self-destructive, that is, a successful kill of a red UAV also results in a loss of the targeting blue UAV. The blue HVU operates in a given patrol area, and its objective is to remain in that area and to accurately detect and immediately assign each incoming red UAV to blue UAVs [19].

Szarka et al. offer a method to neutralize missiles with drone swarms [20]. These incoming missiles have different orbits and velocity and to stop dynamic particles are used. The simulation environment is 2D and missiles and drones have no dimensions, they are represented as points. Another restriction for the sake of simplicity is that the drones do not collide with each other, which does not reflect real-life conditions.

The study of D'Urso et al. consists of a 3D visualization engine, a physics simulator, a flight control stack, and a network simulator to handle communications between unmanned aerial vehicles [21]. It is a middleware that coordinates some other simulation tools. The work of Xiao et al. XTDrone is a customizable multi-rotor UAVs simulation platform based on ROS, Gazebo, and PX4 [22]. The platform integrates dynamic models, sensor models, control algorithms, state estimation algorithms, and 3D scenes and supports multi-UAVs and other robots. Soria et al. have written the software SwarmLab in MATLAB, that aims at the creation of standardized processes and metrics to quantify the performance and robustness of swarm algorithms [23]. These simulations focus on flight and control algorithms.

Some of these related works are only theoretical studies and are not supported by experiments or simulation results. Some drone swarm simulations examine only flight and control mechanisms but are not interested in any combat tactics. Some simulations' environments are in 2D, others are artificial. So, they are not capable of measuring the effect of any real-world terrain. These simulations also have limited scenarios chosen by the researchers and do not allow other users to implement different cases created by them. Most simulations do not use the advantages of a game engine and have minimal user interaction. Drone Swarm Simulation does use a game engine and implements a combat scenario but the defense system is limited to conventional weapons, which opens direct fire [17]. The work of Zhang et al. also examines a combat scenario but this is limited and not customizable in any respect [19]. Current simulations also have a limited number of agent types.

Our simulation platform which is called “Drone Wars 3D" benefits from being developed on a game engine and being completely 3D. It allows users to select an artificial terrain from various pre-loaded ones, such as a mountainous or plain terrain and users are also able to load custom height-map data to create real world-based terrains simply by entering the geographical coordinates of the area. Scenarios to be tested are fully customizable. Drone attributes like physical dimensions, movement capabilities, and explosion effects, and swarm specifications like count, formation, and deployment places can be customized by the user. In Drone Wars 3D, there are more agent types to choose from and the user has full control over them, as they are modular. Users also have a chance to pause the simulation and make reasonable adjustments. A detailed report file that has information about every destruction event that occurred is produced, so users will have an opportunity to examine detailed results. In short, Drone Wars 3D combines the flexibility and ease of use of an RTS game and the reliability of a simulation in order to supply a research platform to develop drone swarm defense tactics against drone swarms.

3. SIMULATION PLATFORM

The simulation platform is an integral part of this study, as it provides a platform for the investigation and evaluation of different defense strategies against drone swarms. In this section, an overview of the simulation model and its components will be provided. Furthermore, the different mission types and terrain configurations used in the simulation will be discussed in detail. Lastly, the actors involved in the simulation, including drones, swarms, machine gun, anti-aircraft gun, anti-aircraft missile launcher, and laser weapon, will be described and their properties will be analyzed.

3.1 Overview

"Drone Wars 3D" is a drone swarm defense simulation platform developed using the Unity game engine that is designed to facilitate the creation and testing of various use cases involving different types of drone swarms and countermeasure actors. This platform is modeled after real-time strategy (RTS) games and allows for the exploration of tactics and formations that can be used to defend against enemy drone swarms. Figure 3.1 illustrates a general view of the simulation.

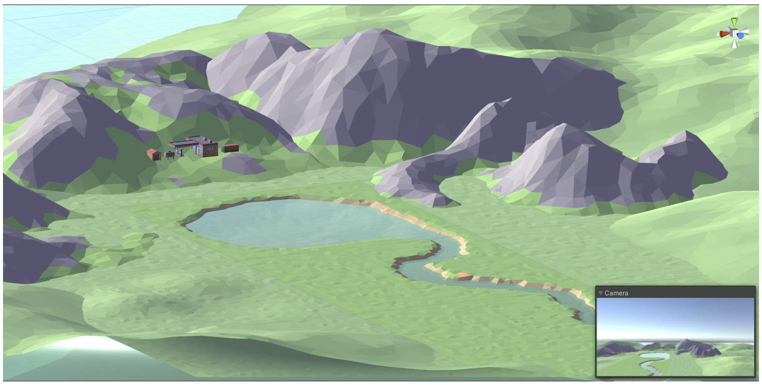

Figure 3.1 : Drone wars 3d has an rts game-like view and controls.

The drones in the simulation, illustrated in Figure 3.2, are equipped with passive sensors and are capable of being controlled by an operator to follow a specific route and take up a designated position in a new formation. Additionally, the drones are designed to be resistant to jamming as military-grade drones are jamming proof unlike consumer-type drones. [24] However, they do not have any armor and are completely destroyed upon being hit. All drones are considered to be fully operational until they are destroyed. The drones are assumed to be able to detect any hostile drones within their detection range. It should be noted that the simulation does not take into account factors such as wind, air drag, smoke, dust, or explosions.

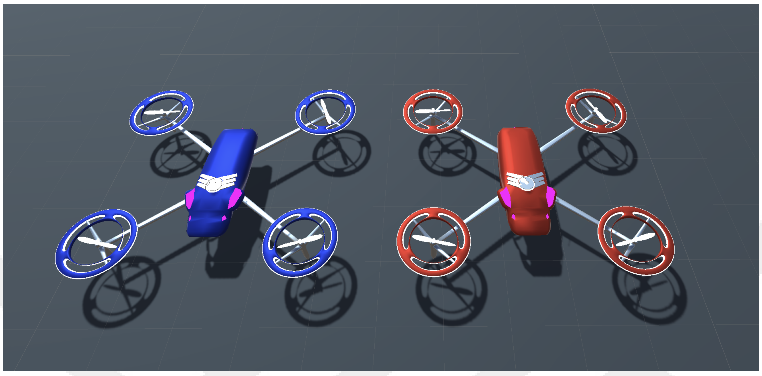

Figure 3.2 : Graphical models of blue and red drones.

Whenever an actor within the simulation is destroyed, this event is logged in a file for later analysis. The following information is recorded for each destroyed actor: 1) Type, 2) Name, 3) Side, 4) Parent actor, 5) Position, 6) Destroyer actor, 7) Destroyer actor position, 8) Destruction type (direct hit or secondary impact) and 9) Time.

3.2 Mission Types

Mission types in the Drone Wars 3D are determined by considering general swarm robotics tasks, as described in [25]. Drone Swarm agents in the simulation can be assigned to the tasks below.

1. Attacking to a point target: A point target refers to a fixed location or object, such as a given coordinate or weapon, towards which the drones within the swarm are directed. Upon being directed towards a specific point target, all drones within the swarm will converge at this precise location. This is a mathematically predictable outcome, given the nature of the point target and the collective behavior of the swarm, which is characterized by a shared goal of reaching a common destination.

2. Attacking to an area target: An area target refers to a specific region or zone, rather than a specific point, towards which the drones within the swarm are directed. It is expected that the drones will fly in a parallel formation, as each drone will independently aim to reach the closest point of the designated area target in relation to its own position.

3. Attacking to a detectable target: Attacking a detectable target refers to the scenario in which the drones within the swarm are directed to locate and engage a specific type of target. Upon detecting the target, each drone will independently aim to reach the closest detectable target of the specified type. This can lead to a distributed attack on multiple targets rather than a concentrated attack on a single target. One of the advantages of this mission type is that the location of the target is not required to be known in advance, as the drones are able to autonomously locate the target. An example of the utility of this mission type is when the operator lacks prior knowledge of the location of a specific target, such as Anti-aircraft guns. In this case, designating Anti-aircraft guns as the target type for detection would allow the drones within the swarm to autonomously locate and engage these targets.

4. Structuring an air shield with drones: Structuring an air shield with drones refers to the scenario in which the drones within the swarm are directed to form a protective barrier in the air.

5. Defending against incoming enemy swarms: Defending against incoming enemy swarms refers to the scenario in which the drones within the swarm are directed to engage and neutralize a hostile swarm of drones. Each drone will independently detect and track the incoming enemy drones, and engage the nearest one, acting as a kamikaze and destroying any incoming drones within its blast radius.

3.3 Terrain

The simulation includes a variety of pre-loaded artificial terrains to reduce processor usage. The user also has the option of creating location-based terrains by entering geographic coordinates, which will call an embedded map API to fetch height-map data for the specified area and create the terrain accordingly. However, in our experiments, we used pre-loaded flat terrains to eliminate the need for drone swarms to have obstacle avoidance capabilities and to reduce the impact of environmental factors for the sake of determinism.

3.4 Actors

Drone Wars 3D uses drones, swarms, machine guns, anti-aircraft guns, laser guns, and anti-aircraft missile launchers as actors to study their interactions. In this section, a comprehensive examination of each of these actors will be conducted, highlighting their functionalities, properties, constraints and behavior within the simulation.

Drones: The drones in the simulation are the base models for the swarms and act as individual agents with the properties given in the Table3.1.

Table 3.1 : Drone model properties.

Properties	Unit
Physical dimensions	m
Maximum elevation	m
Detection range	m
Top speed	m/s
Acceleration	m/s
Top speed-upward	m/s
Acceleration-upward	m/s
Explosion attributes	Explosion model array
Explosion attribute-Blast radius	m
Explosion attributes-Hit rate	m
Chance of explosion when destroyed	%
Minimum distance to detonate	m

Physical dimensions refer to length along the x, y, and z-axis. *maximum elevation* limits the maximum altitude the drone can reach. *Detection range* is the distance a drone can detect other drones from and will be locked on the nearest enemy drone if necessary. Defending drones always lock on attacking drones. Attacking drones lock on defending drones only if their goal is to destroy enemy drones. Given another objective, such as blowing up an arsenal or putting out of order some power lines they are interested in defending drones and reaching given target location instead. Drones always aim at reaching *top speed* when moving towards their target. *Acceleration* is the rate of velocity change over time. To create a more realistic movement, the user may want to set a specific top speed and acceleration value for upward movement. When set, y-component of the velocity vector will not exceed *Top speed-upward* and upward acceleration will be *Acceleration-upward*. If these values are not specified, the drone will utilize the general top speed and acceleration values.

Explosion attributes uses multiple *blast radius* and *hit rate* values to decide if a target will be destroyed. For instance, if a drone has 3 blast areas with a radius of 1, 3, and 7 meters and hit rate of 1, 0.7, and 0.2 respectively, 100% of any drones within a distance of 0 to 1 meter, 70% of any drones within a distance of 1 to 3 meters and 20% of any drones within a distance of 3 to 7 meters away from the exploded drone are destroyed by the game engine. The explosion model also has an attribute of *minimum distance to detonate*. This distance indicates how close a drone should get to an enemy drone before it self-destructs. If zero, physical contact is necessary.

Chance of Explosion when destroyed denotes the rate if destroyed drone will also detonate. If it does, its explosion effects will also be taken into account. This is more important if two collided drones have different explosion attributes. Figure 3.3 shows a pyramid-shaped (red drones attacking) and a v-shaped swarm (blue drones defending) colliding into each other.

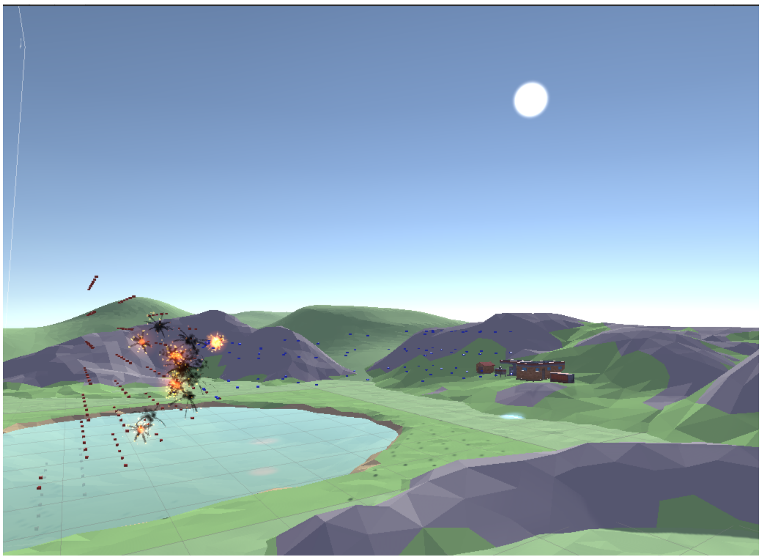

Figure 3.3 : Two swarms collided.

Attacking drones do not dodge defenders, their only goal is to reach the target area. When the distance between two enemy drones falls below *Minimum distance to detonate*, the defending drone explodes, destroying itself and the drones nearby, depending on its explosion attributes. For the sake of realism, drones in their own swarm are also affected by this explosion if they are nearby, but there is no chain reaction triggered.

Swarms: To create a scenario, the user can initialize and deploy swarms anywhere on the map, before the simulation begins. If the swarm will be initialized after the simulation starts, this must be done by a drone launcher agent according to its limitations. All swarms are homogeneous in themselves. Properties of the swarm model are given in Table 3.2.

Table 3.2 : Swarm model properties.

Properties	Unit
Side	blue / red
Drone type	drone model
Drone count	number
Spacing x, Spacing y, Spacing z	m
Count x, Count y, Count z	number
Mission type	-
Formation type	-
Angle	degrees
Direction	degrees

Side keeps information about which side the swarm belongs to (*Blue* for defending side and *Red* for attacking side). *Drone type* is the type of drone the swarm consists of. It is critical because swarms inherit all attributes of the drones they are composed of. *Drone count* is the number of drones. Side, drone type and drone count values cannot be changed by the user after a swarm is initialized. *Spacing x,y*, and *z* denote the distance between drones in each direction. The X-axis is considered as width, the y-axis as height, and the z-axis as depth. *Count x*, *y*, and *z* are the numbers of the drones in each dimension. Regular shapes like a cube and pyramid do not require any *count* values. *Formation* is the shape of a swarm. It can take values such as cube, prism, pyramid, wedge, and v-shaped (inverted wedge).

- **Cube:** According to the given drone count, the swarm shape will be a cube as close as possible, e.g. if the drone count is set to 64, a 4x4x4 cube will be created. If the given number's cubic root is not an integer, then it will be rounded up to the next number, and the end segment of the cube will have fewer drones. Figure 3.4 illustrates a cube shaped swarm of 27 drones.

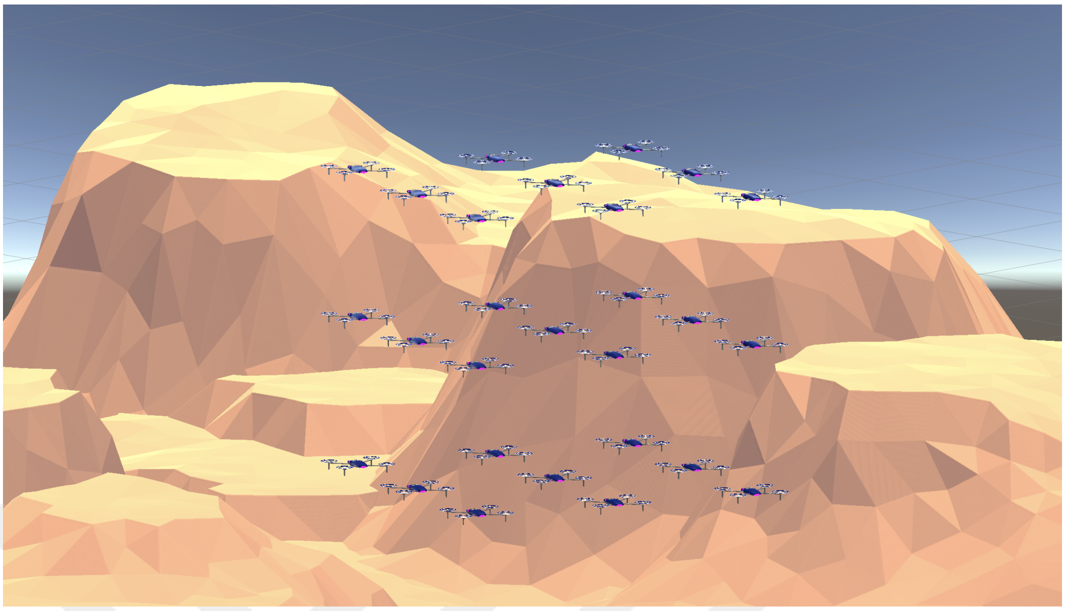

Figure 3.4 : Cube shaped swarm of 27 drones.

- **Prism:** In this shape, users can specify not only the drone count but also the counts on each axis. When two counts are given, SC_1 and SC_2, the last count SC_3 is automatically calculated using the drone count, DC, according to Equation (3.1).

  The formula is:

  $$SC_3 = Math.Ceiling(DC/(SC_1 \times SC_2)) \tag{3.1}$$

  If the total number of drones, *drone count*, is 100, the number of drones in width, *count x*, is 4 and the number of drones in height, *count y*, is 3, there will be 9 sets of drones in-depth, *count z*.

- **Pyramid:** In this layout, the tip of the pyramid looks at the target. When the tip is considered as the first segment, and the base is the last, the drone count in each segment equals the square of the segment order. Each segment centers the segment in front of it. If the drone count is not sufficient to shape a perfectly shaped pyramid the last segment will have fewer drones. e.g if the drone count is set as 120, segment counts will be 1, 4, 9, 16, 25, 36, and 29. In Figure 3.5, a pyramid swarm of 140 drones is depicted from both a side and top view. The base of the pyramid consists of 49 drones, as it is the seventh segment.

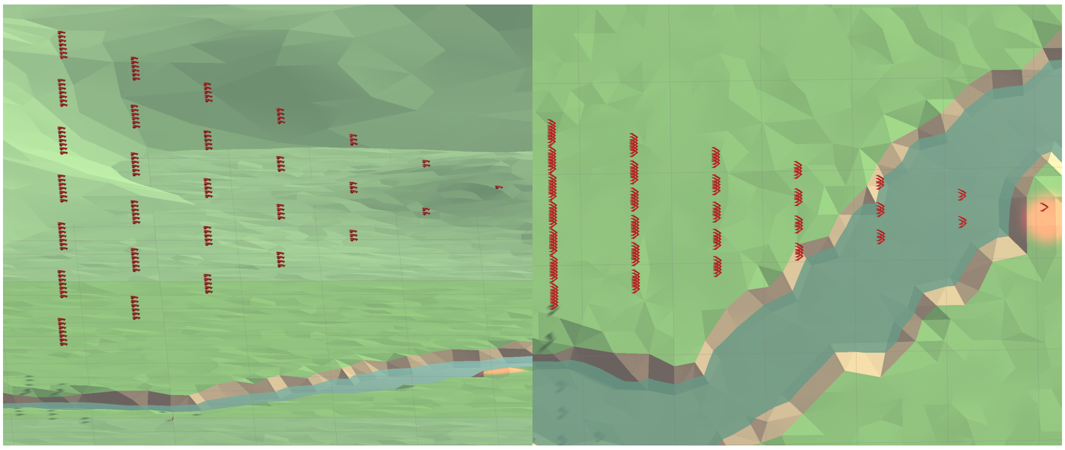

Figure 3.5 : Pyramid shaped drone swarm. (left) side view. (right) top view.

- **Wedge:** Drones are ordered in two identical prisms having an angle between them, forming an arrow-like shape. The user can specify the drone count, counts, and the angle by the *Angle* attribute. Wedge formation will be narrower if this value gets smaller, and will be wider if this value gets larger. In Figure 3.6, a swarm in a wedge formation with 150 drones is shown from a side angle. Distance x is 5, y is 10 and z is 15 meters. Count x is entered as 4, and count y is entered as 2 and angle is 30°.

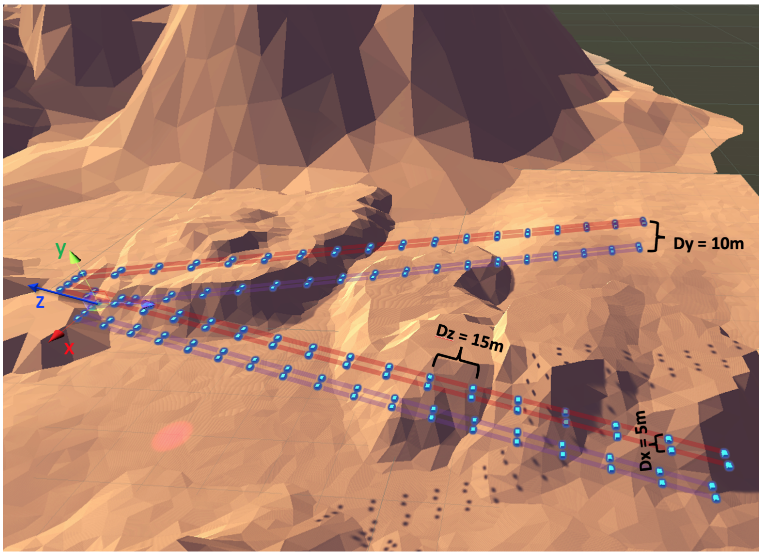

Figure 3.6 : Swarm in wedge formation, where the drone count is 150, count x is 4 and y is 2.

- **V-shaped:** Inverted version of the wedge formation. The tip of the arrow shows back instead of the target.

Direction attribute rotates swarms in any shape around y-axis, e.g. a swarm in the form of a wedge can be turned into a v-shaped swarm, or a pyramid-shaped swarm having its base at the front and its tip at back can be created when this value is given 180°.

Machine Gun: A machine gun (MG) is a conventional weapon that shoots rapid direct fire. Properties are stated in Table 3.3.

Table 3.3 : Machine gun model properties.

Properties	Unit
Fire rate (per minute)	number
Range	m
Hit points	$1 \leq N \leq 100$
Bullet destroy	boolean
Engagement time	seconds
Min-Max shooting angles	degrees

Fire rate is the number of bullets fired in a minute. *Range* refers to the distance that MG can detect and shoot the drones. *Hit points* are the number of drones that must reach MG to neutralize it if it's a target. *Bullet destroy* is set to true, by default, which means the bullet will not continue on its way after a hit. If this attribute is set to false, that means MG may hit more than one target at once as the bullet continues on its way. *Engagement time* is the time needed to have a successful aim at the next target. *Min-Max shooting angles* are unlimited by default. Bullet speed and count are infinite. Figure 3.7 shows graphic model of the MG in Drone Wars 3D.

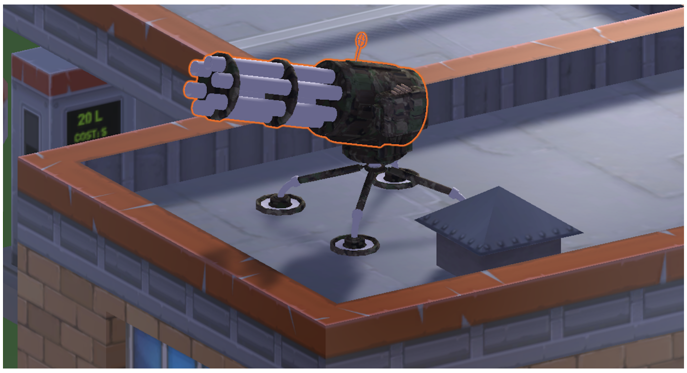

Figure 3.7 : Graphical model of machine gun.

Anti-Aircraft Gun: Anti-Aircraft Gun (AAG, turret) is a modern artillery weapon which shoots rapid direct fire. The main difference between a machine gun and AAG is that AAG's bullets explode and scatter destructive fragments around when they hit the target. Attributes are stated in Table 3.4.

Table 3.4 : Anti-aircraft gun model properties.

Properties	Unit
Fire rate (per minute)	number
Range	m
Hit points	$1 \leq N \leq 100$
Fragment count	number
Fragment range	m
Engagement time	seconds
Min-Max shooting angles	degrees

When an AAG bullet hits its target, it uniformly scatters *Fragment count* number of fragments which are effective in *Fragment range*. Other attributes work same with the machine gun. Figure 3.8 shows graphic model of the AAG in Drone Wars 3D.

Figure 3.8 : Graphical model of anti-aircraft gun.

Anti-Aircraft Missile Launcher: Anti-Aircraft Missile Launcher (AAML) launches missiles that explode at a given distance or when hit a target. Attributes are stated in Table 3.5.

Explosion distance cannot be changed after the simulation starts, as all missiles would be pre-loaded. *Explosion attributes* have the same model with drones. Other attributes work same with the machine gun.

Table 3.5 : Anti-aircraft missile launcher model properties.

Properties	Unit
Fire rate (per minute)	number
Range	m
Hit points	$1 \leq \mathrm{N} \leq 100$
Engagement time	seconds
Min-Max shooting angles	degrees
Explosion attributes	Explosion model array
Explosion distance	m

Laser Weapon: The laser weapon locks on to a target and burns it if it can remain locked for the required amount of time. Its attributes are given in Table 3.6. Figure 3.9 shows graphic model of the laser weapon in Drone Wars 3D.

Table 3.6 : Laser weapon model properties.

Properties	Unit
Range	m
Hit points	$1 \leq \mathrm{N} \leq 100$
Min-Max shooting angles	degrees
Target destruction time	seconds

Target destruction time is the lock on time required to completely destroy a drone. Other properties work same with the machine gun.

Figure 3.9 : Graphical model of laser weapon.

3.5 Simulation Environment

The Unity3D game engine was used to create the simulation. Aesthetically appropriate graphic representations of the actors were created. The game camera can be adjusted in 3D for easier visual observation by dragging the cursor toward the screen's edges, just like in real-time strategy games. The game engine interface was used to construct assignable variables, which made it simple to update all actor parameters. Drone swarms or any other actor can be swiftly formed in this manner with the desired properties. The simulation can be paused at any moment, actors can be added or removed, locations can be changed, and the simulation can be picked up from where it left off. On the screen, a score representing how many drones have reached the objective is continuously updated, and all other data is written to the log file.

4. EXPERIMENTS AND RESULTS

The section on experiments and results presents a detailed analysis of the performance of the simulation in various scenarios. This includes an examination of the effectiveness of different countermeasures against incoming drone swarms, as well as an analysis of the performance of the different actors in the simulation. The results of these experiments are presented in the form of quantitative data, as well as graphical representation, to provide a comprehensive understanding of the simulation's performance and to draw conclusions about the scenarios simulated.

4.1 Experimental Conditions

Given that the parameters of the actors in the simulation can take a wide range of values, an endless number of scenario combinations can be generated for the experiments. While this demonstrates the necessity and importance of a simulation environment for drone swarms in order to test special cases, since the main objective of this study is to evaluate the efficacy of defenses against drone swarms, some of these vast number of scenarios are chosen in a way that allows deterministic results to be obtained and evaluated.

For testing purposes, the following default values are utilized unless otherwise specified. The attacking swarms are initiated at a distance of 200 meters from the target, which is a common range for an assault. To maintain consistency, the default swarm is defined as a cube-shaped group of 512 drones arranged in an 8x8x8 formation with 5 meter spacing 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 velocity of the drones is set at 4 meters per second, with the same acceleration value allowing the drones to reach their top speed in 1 second. The minimum distance for detonation is set at 0.5 meters. The default target type is an area target, indicating that the drones will move in parallel and maintain a constant spacing.

The probability of explosion upon destruction is set to zero in order to prevent chain reactions. All hit points are set to zero, meaning that any hit will result in the complete destruction of the actor. A summary of the default values can be found in Table 4.1.

Table 4.1 : Default values.

Parameter	Value	Unit
Target distance	200	m
Target type	Area	-
Swarm formation	Cube	-
Swarm count	512	pcs
Swarm spacing	5x5x5	m
Drone dimensions	0.5x0.4x0.3	m
Drone velocity	4	m/s
Drone acceleration	4	m/s
Minimum distance to detonate	0.5	m
Chance of explosion when destroyed	0	%
Hit Points	0	-
Explosion Area-I Blast Radius	1	m
Explosion Area-I Hit Rate	100	%
Explosion Area-II Blast Radius	2	m
Explosion Area-II Hit Rate	20	%
Explosion Area-III Blast Radius	4	m
Explosion Area-III Hit Rate	4	%

4.2 Test Scenarios

In this study, six different scenarios were examined in the simulation, each focused on a specific defense strategy against drone swarms. Each scenario was run multiple times to gather enough data and statistics. The selection of these six scenarios was based on the aim of examining a wide range of defense strategies against drone swarms. The scenarios include:

- Scenario 1: Drone swarms vs. drone swarms
- Scenario 2: Machine gun vs drone swarms
- Scenario 3: Laser weapon vs. drone swarms
- Scenario 4: Anti-aircraft gun vs. drone swarms
- Scenario 5: Drone swarms and anti-aircraft gun vs. drone swarms

- Scenario 6: Anti air missile launcher vs. drone swarms

The first scenario, drone swarms vs. drone swarms, was included to provide a baseline for comparison and to observe the behavior of the drone swarms in a pure swarm-versus-swarm scenario.

In accordance with the principle that "every weapon is a native enemy of its own kind", the first scenario utilized pure swarm versus swarm cases. Initially, the mutual variables of the swarms were established as equal, with the exception of the formation. Default values for the attacking swarm were employed, with the spacing of the defending swarm subsequently modified to correspond with the overall dimensions of the attacking swarm.

The second scenario, that of machine gun vs. drone swarms, and the third scenario, laser weapon vs. drone swarms, were designed to test the effectiveness of weapons that are capable of destroying one target at a time. The former scenario entails the examination of a traditional kinetic engagement method, while the latter scenario evaluates a modern, laser energy based strategy that utilizes concentrated beams to incinerate its target, despite its current nascent stage of development.

Classical machine guns have a long history and their technological specifications have remained relatively constant for a significant period of time. With a fire rate typically between 600-1200 rounds per minute, even the slowest machine gun can fire a 2-3 shot burst in a fraction of a second. Additionally, most machine guns have a muzzle velocity of more than 800 m/s, which allows them to reach their targets in a short amount of time. The constant values of machine guns have been incorporated into the "Engagement time" property of machine gun models, as they are fixed and not of particular interest. Alterations of "Engagement time" are made in order to measure its impact on the machine gun’s performance. A trained soldier can aim at a moving target in 5 seconds. An initial starting point is to reduce this number to half a second, as an unmanned machine gun with target detection capabilities can send a bullet to its target within that time frame.

Unlike machine guns, laser weapons are a relatively new development in the field of military technology. They are still in the process of development and improvement.

Laser weapons use a beam of lasers to burn through the target, which typically requires a sustained engagement of 15 seconds. However, as laser technology is rapidly advancing, some manufacturers have claimed to have reduced the burn-up time to 7 seconds.

Scenario 4, Anti-aircraft gun (AAG, turrets) vs. drone swarms, was chosen to test the effectiveness of stationary, traditional anti-aircraft systems against drone swarms. It should be noted that this scenario takes into account the additional capability of Anti-aircraft gun bullets to explode on impact and scatter fragments, which provides the possibility of destroying nearby drones. This feature of the Anti-aircraft gun adds a secondary impact zone, providing an extra layer of defense against drone swarms and an important aspect of this weapon that distinguishes it from single target weapons. The blast radius of these projectiles is not large, but the scattered fragments can be very destructive, making AAGs particularly effective against dense and crowded targets such as drone swarms. In addition, AAGs often have enemy detection and lock-on systems, as they are designed to engage fast-moving aerial objects including missiles.

The fifth scenario, drone swarms and anti-aircraft gun vs. drone swarms, aimed to test the cooperation between drone swarms and anti-aircraft gun in defense scenario. The two actors' distinctive qualities gave rise to the hypothesis that they may work better together, and experiments were done to explore this hypothesis.

Finally, the sixth scenario, anti air missile launcher vs. drone swarms, was included to evaluate the performance of anti-aircraft missile launchers in the defense scenario against a drone swarm. Anti air missiles have a huge blast radius while lacking fragments. A multi-barrel missile launcher can rapidly fire anti-air missiles, at a rate of one or two missiles per second. If the blast radius of the missile is smaller than the spacing of the drone swarm, the missiles will be wasted.

The goal of these experiments was to gather data on the effectiveness of different defense strategies against drone swarms and to provide insights into the behavior and performance of the different actors in the simulation. The simulation results will be used to measure the performance of the different defense strategies in terms of the number of drones neutralized.

The results will be analyzed and discussed in order to determine the effectiveness of each defense strategy against drone swarms.

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

4.3.1 Defensive Success Rates

Table 4.2 illustrates the neutralization rates of drone swarms -considerable as DSR- attacking an area target. Generally, the defending swarms are able to destroy the vast majority of attacking drones before they reach the target. It is important to note that the defending drones act as individuals and the swarm brain does not have any target-sharing algorithms, as swarm management and communication are outside the scope of this investigation. This can result in some friendly casualties as some defending drones may be caught in friendly fire or explosions. Consequently, it can be inferred that drone swarms would be even more effective in defense if they possessed intelligent swarm behaviors such as target sharing.

Table 4.2 : Defensive success rates in scenario 1: drone swarms vs. drone swarms.

Offense Defense	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

It is crucial to recognize that in order to attain a high defense success rate, the defending flock must be situated directly in the path of the approaching attacking flock. Given that the speeds of the swarms are similar or relatively close to each other, the greater the distance between the defending and attacking swarms, the lower the likelihood that the defending swarm will be able to catch up and destroy the attacking swarm. Therefore, it is essential to accurately predict the approach direction of the enemy and deploy the defending swarm to cover these directions, or, as an alternative, to utilize drone launchers to provide the defending swarm with an initial speed and create a barrage as needed. The significance of drone launchers has been acknowledged, and research and development efforts have already been initiated [26].

While the superiority of the formations over each other varies, it is noteworthy that the highest value in each column is located in the row corresponding to the same formation, forming a diagonal line. This implies that a defending swarm is more efficient when it is more similar to the attacking swarm.

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

Figure 4.1 demonstrates the effect of changes in the spacing between drones on defensive success rates. The values on the x-axis represent the difference between the spacing of the attacking and defending swarms. The default spacing is 5 meters, so a value of 0 indicates that both swarms have a 5 meter distance between their drones in all axes. Positive values represent an increase in the spacing of the defending drones, while negative values represent an increase in the spacing of the attacking drones. For example, a value of 50 indicates that the spacing of the defending swarm is 7.5 meters, while the spacing of the attacking swarm is 5 meters. Conversely, a value of -100 indicates that the spacing of the defending swarm is 5 meters, while the spacing of the attacking swarm is 10 meters. The y-axis represents the defense success rate, the proportion of drones destroyed before reaching the target to the total number of attacking drones. Both swarms consisted of 512 drones and were in the cube formation.

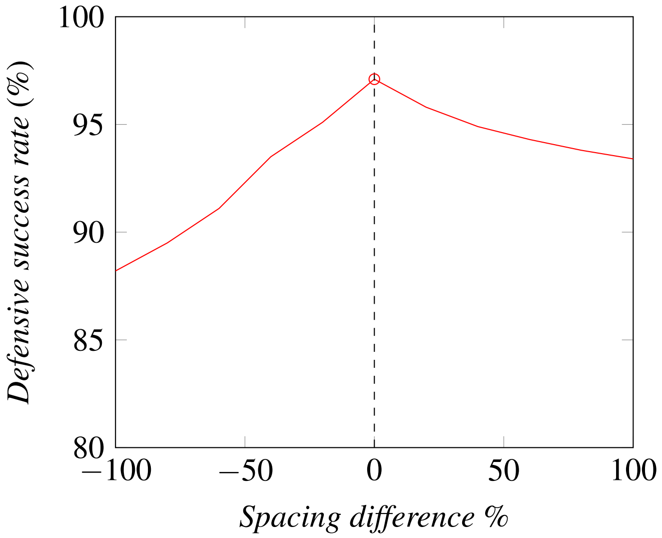

Figure 4.1 : Effect of the changes in spacing on the defensive success rates.

The results in the graph suggest that the best defense is achieved when the two swarms have the same spacing, as the defensive success rate decreases in both directions. This is reasonable because the drones will match up with enemy drones more effectively and the path they must take will be shorter. However, another significant finding for the defending side is that "having more spacing is better than having less spacing," as the latter leads to harsher punishment.

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

The speed at which drones traverse the distance is also of significant importance. To evaluate the effect of changes in velocity, again identical cube-shaped swarms with 512 drones are employed, but this time with varying speeds. Figure 4.2 displays the results of these changes. In this graph, the values on the x-axis represent the difference between the velocities of the attacking and defending swarms. The default velocity is 4 meters per second, so a value of 0 indicates that both swarms have this speed. Positive values represent an increase in the velocity of the defending drones, while negative values represent an increase in the velocity of the attacking drones. For example, a value of 50 indicates that the velocity of the defending swarm is 6 meters per second, while the velocity of the attacking swarm is 4 meters per second. Conversely, a value of -100 indicates that the velocity of the defending swarm is 4 meters per second, while the velocity of the attacking swarm is 8 meters per second. The results in the graph reveal that having drones that are 60% faster on defense is sufficient to defeat the attacking swarm, while a 25% faster attacking swarm doubles the offensive success.

In the context of swarms, quantity is always a crucial factor. This makes comparisons of swarms with different drone counts inevitable. Figure 4.3 illustrates the results of changes in the number of drones in the swarms. The default number is 512. Positive values on the x-axis represent an increase in the number of drones in the defending swarm, while negative values represent an increase in the number of drones in the attacking swarm. Given that the drone model in the simulation typically allows a drone to destroy only one enemy drone, it is unsurprising that the difference in numbers between the swarms is equal to the number of drones reaching the target. To put this in numerical terms, when the attacking side has 100% more drones, 50% of those drones

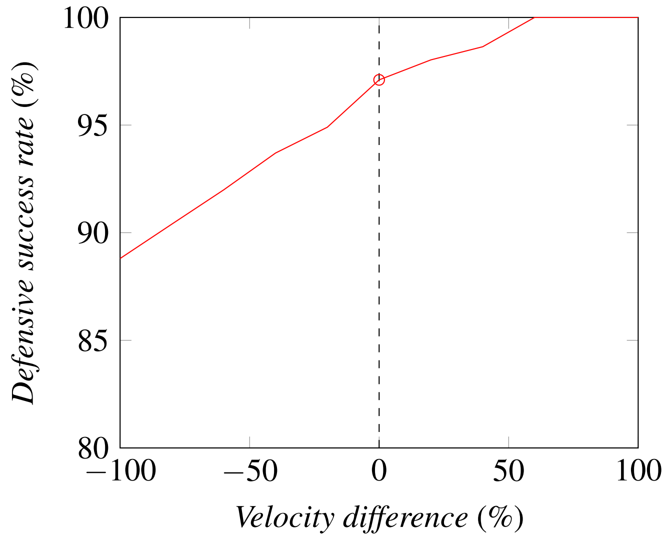

Figure 4.2 : Effect of the changes in velocity on the defensive success rates.

will reach the target unscathed. On the other hand, a 5% increase in the number of defensive drones is sufficient to completely defeat an identical attacking swarm.

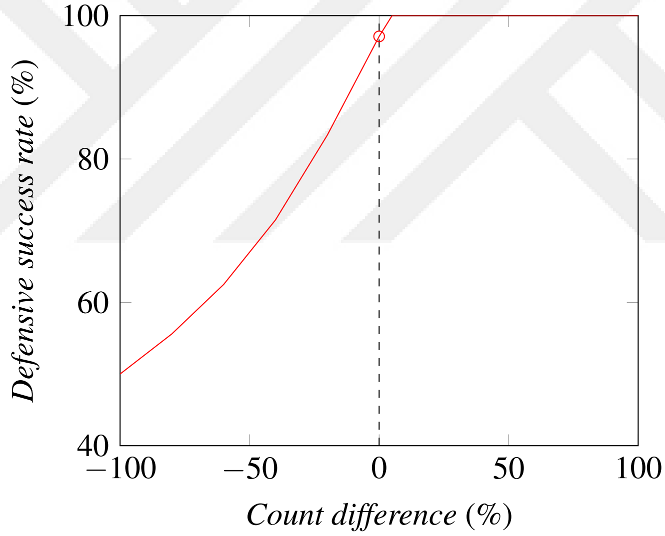

Figure 4.3 : Effect of the changes in drone count on the defensive success rates.

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

It is evident that differences in speed and number of drones can have a significant impact, prompting the comparison of the two. For example, suppose that the attacking side has superior technology and is therefore able to produce drones that are 50% faster. Could the defending side compensate for its technological disadvantage with an advantage in the number of drones? This is a typical scenario, as in combat the attacking side often has the technological advantage while the defending side has control of the terrain, enabling it to outnumber the offensive side.

To investigate this scenario, two drone swarms with a cube formation and 512 members was prepared. The defending swarm had a velocity of 4 meters per second, while the attacking side had a velocity that was 50% faster. These velocity values remained constant throughout all tests, while the number of drones in the defending swarm was increased. When the defending swarm had 40% more drones, it was able to completely defeat the attacking swarm. Figure 4.4 shows the results of these tests.

Drone swarms can also be highly effective in defending wide areas. For instance, consider a scenario in which 100 high-voltage transmission line poles (pylons) are arranged in a line with 100 meters of spacing between each. A mere 100 drones could fully destroy this 10-kilometer power line, which would be difficult to repair and protect with conventional weapons due to their limited effective range of a few hundred meters. However, a drone swarm acting as a reactive minefield could easily safeguard the entire power line without the need for human intervention. This scenario was run in the simulation environment with 5 attacking and defending drones for each pylon. The defending drones were able to fully counter the attacking drones, even in edge cases such as not attacking a neighboring pylon and redirecting saved drones to the next one.

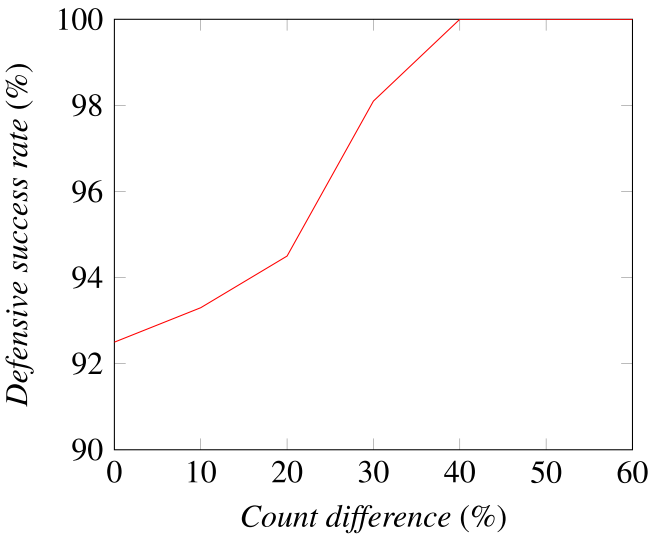

Figure 4.4 : Effect of the speed with respect to the drone counts on the defensive success rates.

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

As shown in Figure 4.5, the curve formed by the results is a typical constant/x curve. In this case, x represents the fire rate. The constant is the total time needed for the attacking swarm to reach its target. In test scenarios, this constant is approximately 50 seconds, as the swarm's velocity is 4 m/s and the distance to the target is 200m. It is not surprising that when the "engagement time" is set to 5 seconds, the machine gun will only be able to fire 10-11 times, while when it is set to 0.5 seconds, it will fire more than 100 times. Considering that each hit is a success, this will result in the destruction of a corresponding number of drones. These results indicate that a machine gun's hit count is not influenced by the number, formation, or other properties of the attacking drones, but rather is determined by the time required for the drones to reach their target. The default swarm used in the scenarios consisted of 512 drones, which results in at least 400 drones reaching the target.

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

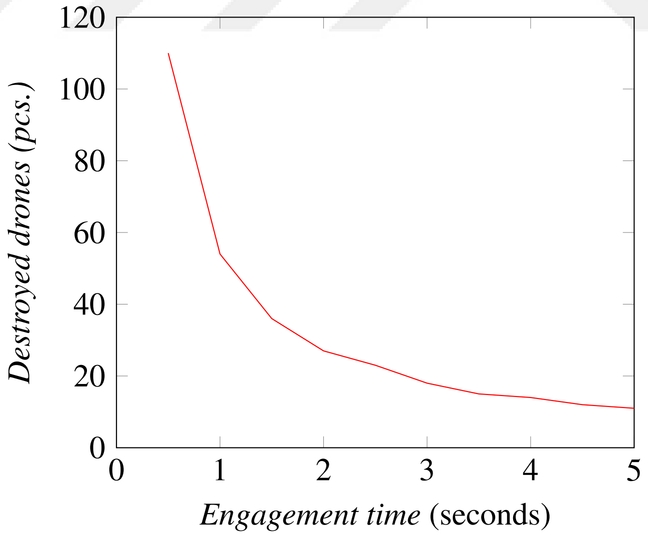

Figure 4.5 : Effect of changes in machine gun engagement time on the number of drones destroyed.

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

In the tests, the effectiveness of laser weapons across a range of target destruction times from 15 seconds to 0.5 seconds was measured, and as shown in Figure 4.6, the results are similar to those of machine guns. This is to be expected, as laser weapons, like machine guns, are a type of direct fire weapon that can only destroy a single target at a time. The main difference between the two is the use of a laser beam instead of bullets. While this may provide an advantage for targeting fast-moving, distant targets such as jet fighters, it does not significantly impact the effectiveness of laser weapons against drone swarms. Therefore, the same considerations that apply to machine guns also apply to laser weapons.

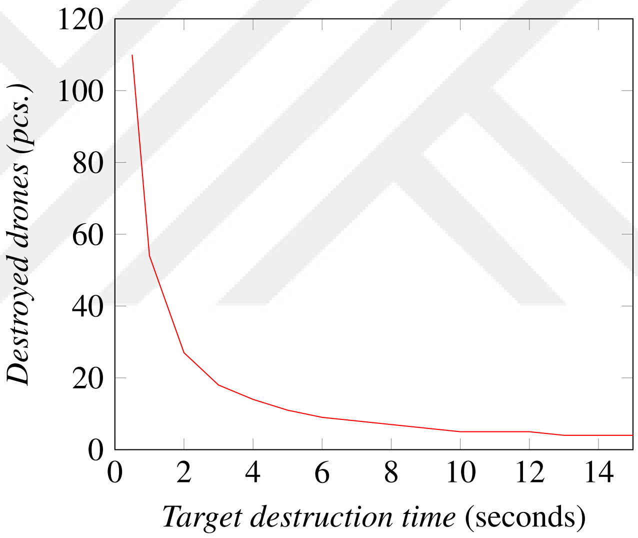

Figure 4.6 : Effect of changes in laser weapon target destruction time on the number of drones destroyed.

Overall, even if the limitations of laser weapons such as the need for clear air and the inability to target surfaces covered in reflective coatings can be overcome, laser weapons appear to be at best as effective as machine guns against drone swarms. Given that machine guns are much cheaper than laser weapons, it is likely that laser weapons will not be a practical alternative for the foreseeable future.

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

In the tests, a constant value of 1 second was set for "engagement time" and a constant value of 20 meters for the "fragment range" in order to measure the impact of the secondary effect of the fragments on the target. A cube-shaped swarm of 512 drones was used, with a spacing of 5 m, to vary the "fragment count" while keeping all other properties of the swarm and the turret constant. The number of drones directly hit and the number of drones destroyed by fragments were separately measured.

Figure 4.7 presents the results of these tests. The red solid line in the graph shows the number of drones destroyed only by fragments as the swarm moves towards an area target. The line becomes almost horizontal after 24 fragments, which can be considered the optimum value. The dashed line in the same color shows the total number of drones destroyed, adding a constant value of 54 drones, which represents the number of drones hit by direct fire.

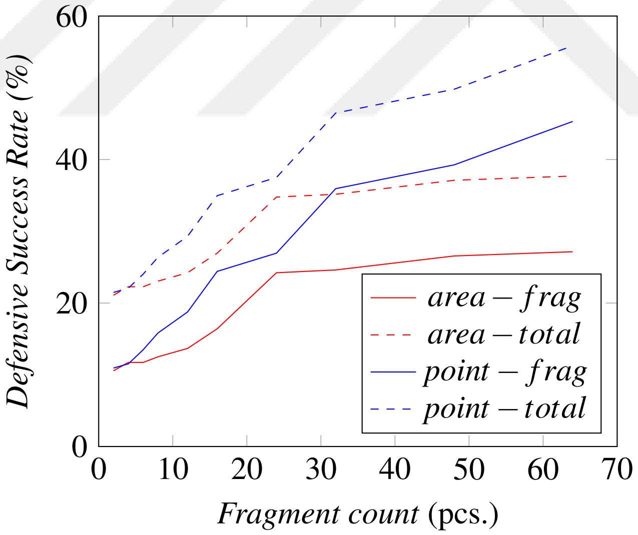

Figure 4.7 : Effect of changes in anti-aircraft gun fragment count on the defensive success rates.

As fragments disperse from the location of the target hit by the projectile and, although they are fast, have a relatively low range, it is expected that the spacing of the enemy swarm will have a significant impact on the effectiveness of the AAG. When moving towards an aerial target, drone swarms tend to maintain a constant spacing as they try to reach the closest point of the target. However, if given a point target, drones will converge over time as they all try to reach the exact same location. This can be an advantage for the AAG, as the fragments will have a higher chance of hitting a nearby drone. The blue solid line in Figure 4.7 shows the result of tests using a drone swarm with a point target. The blue line diverges directly from the red line and always stays above it, widening the gap until the end of the test. The blue dashed line shows the total number of drones destroyed in these point target tests.

Overall, AAGs are highly effective against drone swarms when compared to other conventional weapons. However, fragment count and range are critical factors in determining their effectiveness. If the fragment range is smaller than the spacing of the swarm, no secondary impact will occur and the AAG's effectiveness will be similar to that of a simple machine gun. Additionally, lower fragment counts will have a lower chance of hitting a nearby drone.

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

It appears that drone swarms and anti-aircraft guns are the most effective defensive measures. To examine the potential synergistic effects of these two measures, a special test were used involving a superior attacking swarm, a weaker defending swarm, and two anti-aircraft guns. The attacking swarm was 25% more crowded and 25% faster than the defending swarm, which was a cube-shaped group of 256 drones that could move at 4 m/s. The anti-aircraft guns had an engagement time of 1 second and a fragment count of 24. The results of this test showed that only 8 attacking drones reached the target when both the defending swarm and the anti-aircraft guns were present. When only the defending swarm was present, 102 drones reached the target, and when only the anti-aircraft guns were present, 108 drones reached the target. These results are summarized in Table 4.3.

Table 4.3 : Defensive success rates in scenario 5: drone swarms & anti-aircraft gun vs. drone swarms.

Defense Units	Offense	Defense	Offense Speed	Defense Speed	Fragments	Defensive 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: Anti Air Missiles vs. Drone Swarms

In the test, 18 of these expensive missiles was fired at a cube-shaped swarm of 512 drones with a spacing of 5 m in all axes. Figure 4.8 shows the number of drones destroyed by these missiles. The reason for the exponential increase in the number of drones destroyed is that as the blast radius increases, the blast can reach neighboring drones. For example, when the blast radius is smaller than 1x spacing (5 m in the test case), a missile can only take out one drone. However, when the blast radius exceeds the 1x spacing limit, it can also destroy neighboring drones, which can be between 2 and 5 for a cube-shaped swarm. When the blast radius reaches $\sqrt{3}$x spacing, it will also involve diagonal neighbors. And when it reaches 2x spacing (10 meters), second neighbors will be affected by the blast, increasing the number of drones that could be affected by the explosion to more than 20.

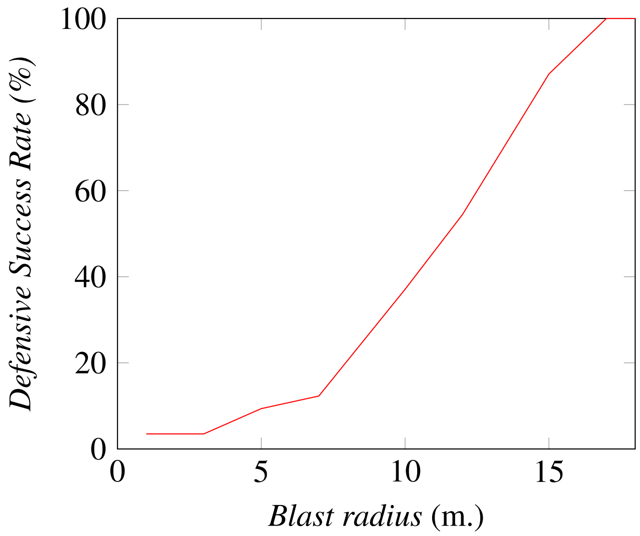

Figure 4.8 : Effect of the changes in anti air missile blast radius on the defensive success rates.

Overall, anti-air missiles can be substantially effective against drone swarms in the right conditions. In particular, when drone swarms are given a point target and converge, the reduced spacing makes them more vulnerable to the blast effect of anti-air missiles. Additionally, the blast effect of these missiles can also make them very efficient against dense swarms with large numbers of micro drones.

5. CONCLUSION

The widespread availability and affordability of drones has raised concerns over their potential destructive use by legal or illegal armed organizations. In particular, the development of drone swarms, which can be coordinated through artificial intelligence supported platforms, has raised concerns about the potential for coordinated large-scale attacks. This has led to a call for the development of effective countermeasures and strategies to mitigate these risks.

The use of a simulation platform for research on defense strategies against drone swarms is of paramount importance. Real-world experimentation with large numbers of drones can be logistically difficult, costly, and potentially dangerous. A simulation platform allows for the creation of a controlled and repeatable environment in which to test different defense strategies without the need for physical hardware. Additionally, a simulation allows for the manipulation of variables such as drone properties, number of drones in a swarm, and defense strategy parameters, which would be difficult or impossible to replicate in real-world testing. Furthermore, a simulation provides a safe and ethical way to test defense strategies that would not be possible in live demonstrations. Through the use of a simulation platform, it's possible to gain a deeper understanding of the capabilities and limitations of different defense strategies, and develop new and effective countermeasures against drone swarms.

For that reason, in this study, a simulation platform was developed in order to evaluate the effectiveness of various countermeasure actors against drone swarms. The performance of each countermeasure was quantitatively assessed by calculating its "Defensive Success Rate" within the simulated environment. A total of six distinct scenarios were examined in the simulation, which were carefully selected to encompass a broad range of countermeasure options, including traditional kinetic weapons, more contemporary concentrated energy-based systems, weapons that have explosive projectiles and drone swarms themselves. The results obtained from the simulation offer a comprehensive understanding of the potential performance of these countermeasures against drone swarms and furnish a basis for the development of effective defense strategies against this rising threat.

This study has provided valuable insights into the potential countermeasures and strategies for defending against drone swarms. It was found that while it is not an easy task, defending against drone swarms is not impossible. Counter swarms and anti-aircraft guns were found to be particularly effective in neutralizing large numbers of drones in a short period of time. It is worth noting that for an effective defense the deployment of counter-swarms should be at the correct location, and the properties of the swarm such as count, spacing, and the properties of the individual drones such as speed, should be carefully considered. On the other hand, traditional single-target weapons such as machine guns and laser weapons were found to be less effective against the large numbers and coordinated movements of drone swarms.

This study serves as a useful starting point for further research in this area and highlights the importance of continued efforts to develop effective defense strategies against drone swarms. The results of this study also can be used as a guideline for future research and development projects for drone defense systems.

Future work in this area could include further developing the intelligence of the drones in the simulation by incorporating obstacle avoidance and target sharing systems. This would provide a more realistic representation of the capabilities and limitations of modern drones, and allow for more detailed evaluations of defense strategies. Additionally, further research could be conducted on the control and coordination of drone swarms in order to improve their effectiveness as a defense strategy.

An additional area of future work could be the incorporation of ground or air-based drone launchers as a new actor in the simulation. Instead of initiating the swarms out of thin air, the use of ground or air-based launchers would provide a more realistic representation of how swarms are launched in real-world scenarios. This would provide a more realistic context for the simulation and would enable more accurate evaluations of defense strategies. Additionally, this new actor can have more functionality like selective launch, reloading time, and area of operations could be assigned to them, in order to mimic real-life scenarios more effectively. In this way, the study aims to provide more realistic and accurate representation of the defense strategies against drone swarms.

Another potential area of improvement would be the integration of real-time targets into the simulation. This would provide a more realistic scenario and allow for more accurate evaluations of defense strategies under dynamic conditions. Additionally, a multiplayer feature could be added to the simulation to model the use of multiple operators and the coordination of different defense strategies.

Overall, this study has provided a valuable starting point for the investigation of defense strategies against drone swarms. Future research in this area will aim to improve the realism and complexity of the simulation model to better reflect real-world conditions and to gain deeper insight into the behavior and performance of different defense strategies.

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