A Novel Approach to Quantify Counter-Drone System Effectiveness Against UAS Swarms

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Abstract Swarm attacks composed of *Unmanned Aerial System* (UAS) have rapidly evolved into a sophisticated and constantly evolving threat to modern air defense strategies. By exploiting overwhelming numbers, high agility, and a coordinated behavior, drone swarms are able to penetrate and overwhelm traditional, multi-layered, defense architectures. Recent conflicts have highlighted critical vulnerabilities and challenges in maintaining robust defense and deterrence postures against drone swarms. As counter-UAS technologies, systems, and *Concepts of Operations* (CONOPS) continue to evolve, a method to evaluate their effectiveness and to quantify their relative performance becomes crucial. This paper details the adaptation of an agent-based modeling and simulation environment, developed by the German Aerospace Centre (DLR), to assess the operational performance of counter-UAS architectures from a holistic *System of Systems* (SoS) perspective. To address the computational challenges of large-scale swarm engagements, the approach integrates surrogate models informed by *high-fidelity* (hi-fi) simulations, into *low-fidelity* (lo-fi) models to approximate the behavior of counter-UAS systems, thereby enabling scalability and simulation on the theater scale. Combined with well-defined *Measures of Effectiveness* (MoEs), this methodology provides a novel approach for comparing counter-UAS solutions. It provides stakeholders and decision-makers with the information needed to evaluate system performance and make informed decisions in shaping future air defense strategies and architectures.

Introduction

UAS swarms pose a rapidly escalating threat to military forces worldwide, both in increasing technological sophistication and operational scale [1]. For example, in 2019 the Houthi militant group used a swarm of 18 drones and 7 missiles in a coordinated strike on Saudi oil facilities. The incident demonstrated the challenges that traditional air defense systems can face when encountering swarm tactics [2, 3]. More recently, during the Russian invasion of Ukraine, Russian forces repeatedly launched attacks involving hundreds of drones interlaced with cruise and ballistic missiles to overwhelm Ukrainian air defenses.

Traditional countermeasures - electronic warfare, *Anti-Aircraft Artillery* (AAA), and missiles - are effective against individual drones but are often costly or logistically unsustainable when facing large swarms [4]. As a result, research and development is increasingly focused on scalable, cost-effective counter-swarm strategies and systems.

To support informed decision-making on fleet composition and system procurement for counter-UAS missions, it is essential to evaluate how different air-defense architectures perform against swarms with varying compositions and tactics. This paper proposes a novel framework that combines hi- and lo-fi simulation models to compare system performance against large-scale UAS swarm threats. The method provides a scalable and quantitative means to assess performance and interactions within the complex drone-warfare SoS.

Methodology

The proposed approach integrates hi- and lo-fi *Agent-Based Modeling and Simulation* (ABMS) environments into a unified framework to evaluate the effectiveness of counter-UAS architectures. It is designed to balance fidelity and scalability, enabling engagements involving thousands of agents. This framework is demonstrated in Figure 1.

The implementation uses the off-the-shelf hi-fi ABMS environment *Modern Air Combat Environment* (MACE), developed by BSI[1], together with the *AirShield Simulation Environment*, as the lo-fi ABMS environment. The latter was developed by DLR to enable the evaluation of counter-UAS systems within a broader SoS context and to translate those evaluations into optimized system requirements and is based on the work shown in [5].

The two complementary simulation layers are:

1. **Hi-fi layer:** Detailed digital models represent threat and defensive systems, including the complex modeling of communication networks, electronic warfare, and C2. Engagement dynamics, sensor performance, and effector lethality are modeled deterministically by simulating the physics that govern them. Thus, these simulations effectively represent the complex interactions between individual drones and countermeasures. Due to the high complexity and computational demand, this layer is limited to engagement-level scenarios.

[1] https://www.bssim.com/mace/

2. **Lo-fi layer:** This layer scales the analysis from engagement to theater level by using simplified digital surrogate models, allowing thousands of agents to interact. These surrogate models are generated to bridge the fidelity gap between the hi- and lo-fi layers. Engagement dynamics are modeled stochastically, informed by relationships derived from the hi-fi layer (e.g. rounds-to-kill as a function of target altitude, speed, and aspect) through one-on-one engagements.

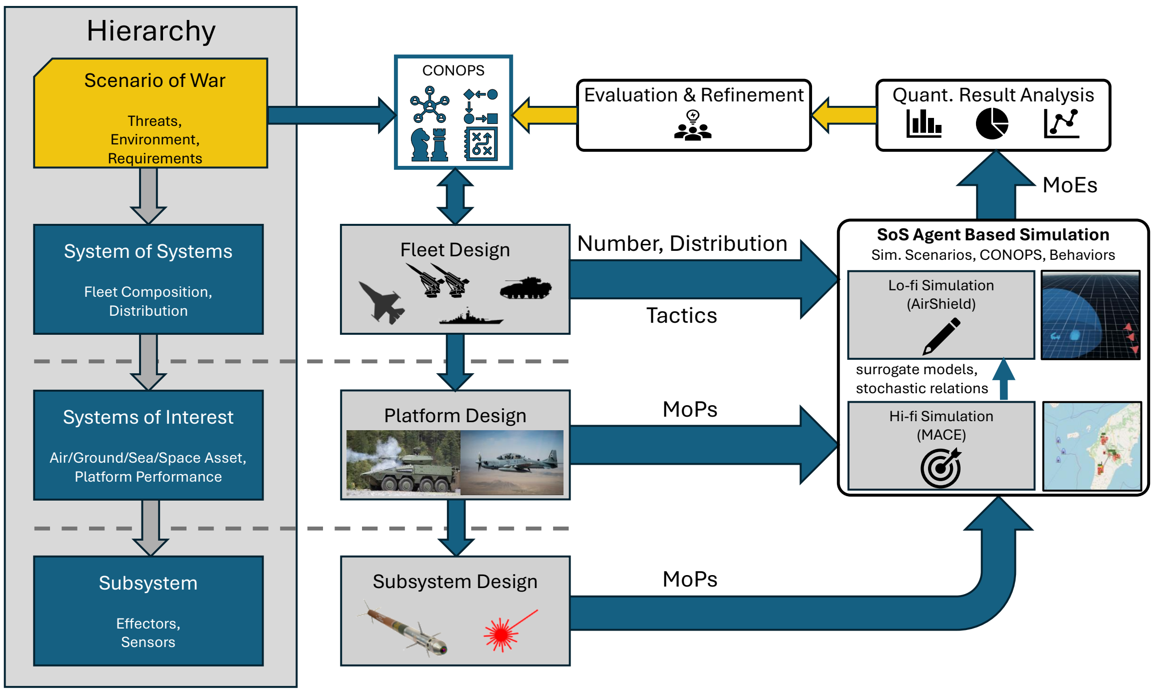

Figure 1: *System-of-Systems framework to quantify counter-UAS system effectiveness*

To demonstrate the framework, a notional baseline scenario is created in the AirShield environment, as illustrated in Figure 2. In this scenario, 200 Shahed-like adversary drones conduct an attack at an altitude of 200 m—a noteworthy detail since both simulation layers operate in three dimensions and therefore account for line-of-sight effects, including Earth's curvature. The attack targets a layered air defense architecture consisting of a long-range air defense element protected by five short-range gun-based AAA units. This study evaluates variations in *Measures of Performance* (MoPs) of the AAA and translates the effects of these MoPs to SoS-wide MoEs. The influence of the altered MoPs on the kill dynamics of the AAA typically are based on running one-on-one engagement studies within the hi-fi environment. In the following analysis, this is not done, and instead the AAA's kill dynamics are modeled as a normal distribution around a mean *rounds-to-kill* (RTK) and its standard deviation. The values for the mean and standard deviation originate from preliminary analyses in the Hi-fi environment. However, they are also evaluated as sensitivities in this paper to illustrate the modularity of the design variables and the underlying models.

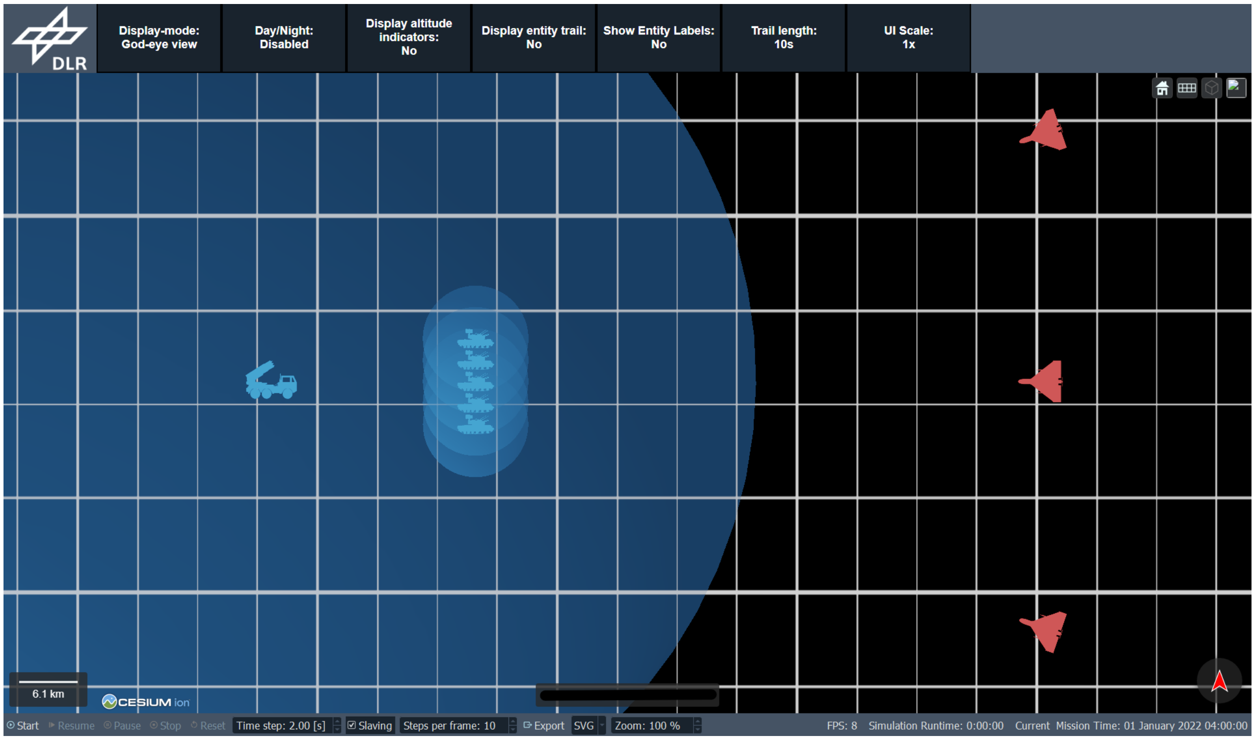

Figure 2: *Baseline scenario in the AirShield user interface. Each cell width represents 6.1km. Blue zones show the engagement areas of counter-UAS systems, limited by Earth's curvature (not detection zones).*

To evaluate the SoS effectiveness, a set of normalized MoEs is defined. Each MoE component - survivability (number of undamaged systems, $\hat{S}$), lethality (number of killed drones, $\hat{L}$), expended munition cost ($\hat{C}$), and infiltration rate (shortest distance to the drone's target, $\hat{I}$) - is normalized and averaged over multiple simulation runs for each data point. This weighted sum is shown in Equation 1. The weights of the MoE variables originate from subject matter experts' opinions, a method detailed in [6].

$$\text{MoE} = 0.42\,\hat{S} + 0.36\,\hat{L} + 0.16(1 - \hat{C}) + 0.06(1 - \hat{I}) \quad (1)$$

Results

For the demonstration, variations in the AAA's turret slew rate and effective engagement range are investigated to understand their influence on overall SoS effectiveness. As previously noted, the hi-fi study is not conducted for this simplified scenario and therefore these parameters are not linked to the lo-fi kill dynamics. Instead, the mean RTK value and its standard deviation are incorporated into the analysis. Furthermore, to illustrate potential future offensives, the adversary swarm size is also included. The design space shown in Figure 3 is created and represents the MoE values for each data point using a color. The standard deviation of the mean RTK was found to have a negligible impact, likely due to the high number of rounds being fired by the AAA units, and is therefore excluded from this analysis. Instead, the plot shows values for varying the mean RTK at three standard deviations of spread.

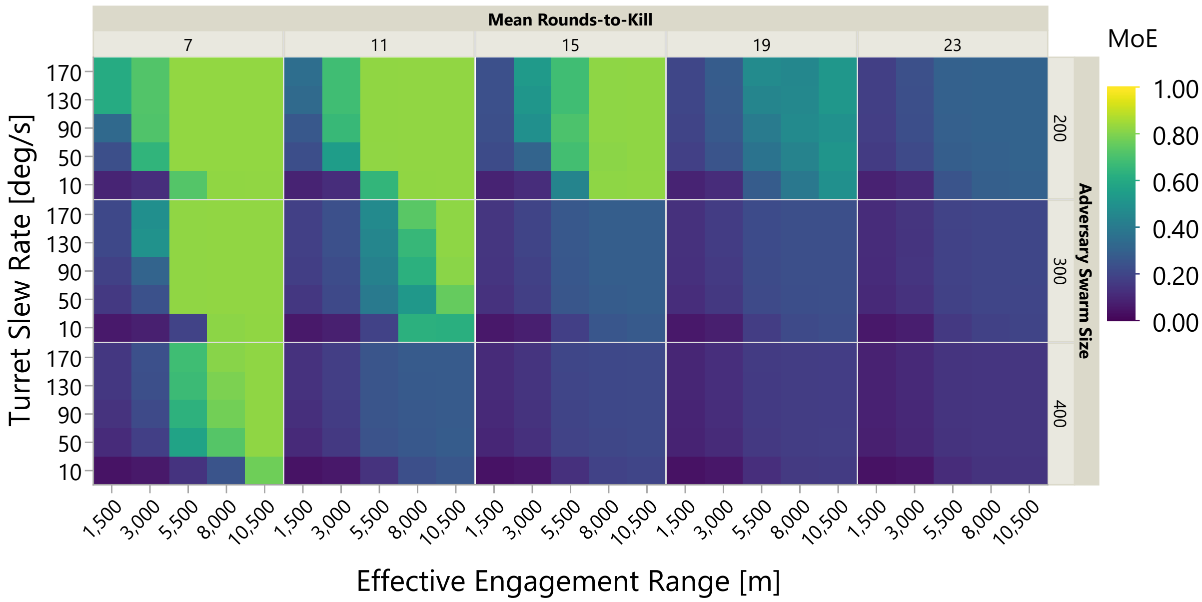

Figure 3: *Design space exploration of the AAA system*

Upon inspection of the results, three interesting patterns emerge:

Firstly, MoEs are highest when the AAA operates with large effective engagement ranges. This becomes apparent when the engagement range is increased beyond 5.5 km. However, it still requires that the mean RTK is low for the SoS to become effective. Thus, a combination of long engagement ranges with sufficient lethality (through low RTK) produces more desirable outcomes.

Secondly, for larger swarms, the system must possess a lower mean RTK for the SoS to remain effective. This dependency arises from a greater lethality, which logically increases the SoS effectiveness. Alongside this, reducing the mean RTK shortens required engagement lengths per target, and thereby reduces ammunition expenditure. This enables longer sustainment and lethality, which is particularly interesting considering that one AAA caries only 640 rounds.

Lastly, the increase of turret slew rate has a positive but small influence. Increasing the slew rate increases the MoE, especially at the extreme low end (10 deg/s). With reduced slew rates, the system can only maintain effectiveness if the effective engagement range is large enough to compensate. This seems logical, as an increased mean RTK increases the *engagement time per UAS*, which reduces the distance between the UAS and the AAA, increasing relative angular velocities of the UAS. However, this secondary effect of the slew rate should be investigated further as in the baseline scenario the swarm spread is relatively limited.

Conclusion

This paper presented a scalable agent-based simulation framework for assessing counter-UAS architectures within a system-of-systems context. By coupling high- and low-fidelity simulation environments, the framework enables quantitative evaluation of counter-swarm performance while maintaining computational feasibility for large-scale scenarios. The demonstrated case study of a layered air defense architecture illustrated how variations in subsystem Measures of Performance propagate to system-wide Measures of Effectiveness.

The results of the simplified demonstration indicate that effective engagement range and lethality, expressed as mean rounds-to-kill, are the primary drivers of the system-of-systems effectiveness, while the turret slew rate plays a secondary role. The influence of mean rounds-to-kill becomes particularly dominant as the adversary swarm size grows, increasing combat sustainment and lethality. Based on the mock scenario, the framework was able to identify the system's most influential design traits that provided the most favorable operational effectiveness within the system-of-systems. Importantly, the model demonstrates that assessing different configurations of the same resource can reveal solutions that are more scalable than focusing solely on technological enhancements.

Although not explored in this study, operational strategy, such as defense system positioning/ placement and fleet combinations could be evaluated, garnering further insights to the system-of-systems, exemplifying the framework's capabilities in supporting informed decision making for system designers. Lastly, AI methods, drone design, and their dynamics could be applied to the framework to expand its application potential and utility.

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