MUM-T Formation Reconfiguration Analysis For a Defense Scenario

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Abstract— **Unmanned Aerial Vehicles (UAVs) operating in formation can leverage the capabilities and efficiency of UAV systems. This paper analyzes the impact in terms of time and distance demanded for UAV formation reconfiguration in a simulated manned-unmanned team defense scenario against threatening drone swarm attacks. With limited time for defense, it is necessary to optimize the allocation of the UAVs to each position of the target formation. The problem of optimizing multiple UAV formation reconfiguration is solved with the Hungarian algorithm, and the performance of transitioning between different formation shapes is evaluated in our scenario through 3D simulations. The results demonstrate the feasibility and effectiveness of the proposed formation reconfiguration solution integrated with our considered system architecture.**

Keywords— **Formation Reconfiguration, MUM-T Defense Formation, Simulation.**

I. Introduction

In recent years, unmanned aerial vehicles (UAVs) have been widely used in both military and civilian fields for a variety of applications. For instance, in the civilian field, UAVs are being used in public safety to support the monitoring of large-scale events such as stadiums, public concerts, and protests, in search and rescue in response to natural disasters, and have also been used to combat environmental crimes and drug trafficking. In the military field, UAVs have become required assets in modern warfare, revolutionizing attack and defense strategies, surveillance methods, reconnaissance, and logistics due to their capability to fly over dangerous environments without putting the lives of pilots at risk during the mission in addition to the ability to operate for long hours and provide data in real-time. In future operational scenarios with Cooperative Engagement Capability (CEC) [1], manned-unmanned teaming (MUM-T) allows unmanned platforms to cooperate with manned aircraft in missions with a shared objective. In this context, we have the concept of loyal wingman (LW) [2], where intelligent and connected UAVs can act as force and capability multipliers operating under the tactical guidance and control of the manned aircraft, as well as a higher-level remotely controlled UAV in the future.

Due to recent UAV attack episodes [3] [4] [5], the deployment of an efficient counter-UAV (C-UAV) system has become an essential requirement to protect high-value assets and areas against these threats. C-UAV systems have the ability to detect and identify hostile UAVs and produce specific responses to mitigate them. Several mitigation approaches [6] have already been considered to neutralize UAV threats, including non-physical responses such as laser weapons, radio wave jamming, signal spoofing, and cyberattacks, as well as physical responses such as projectiles, loitering munitions, drones with capture nets [7] as payloads, or even trained eagles [8]. Coordinated swarms of UAVs can overwhelm defensive systems, and being prepared to neutralize such a threat with low or equivalent cost solutions is vital to maintaining the balance between offense and defense in the coming decades. Research and new products using Multi-rotor Aerial Vehicles (MAVs) have increasingly gained focus in recent years due to their flexible capabilities and low cost, facilitating innovation and making them viable for various applications, including creating C-UAV systems with multiple MAVs.

This paper analyzes the performance of formation reconfiguration in tactical defensive formations for a future MUM-T air defense scenario against swarm attacks, extending the work of Ricardo et al. [2]. This provides a practical assessment of the proposed formation reconfiguration solution using a centralized optimization planning approach, and the results validate its ability to enable rapid and efficient adaptation of UAV formations in the considered system architecture.

The rest of this paper is organized as follows. Section II discusses the literature related to UAV formation control and defense approaches. We describe the scenario in Section III, the system architecture and our approach in Section IV, and the experiments and results in Section V. General conclusions and future work are discussed in Section VI.

II. Related Work

This section describes related work on UAV formation shape definition and reconfiguration in civilian and military fields.

Madridano et al. [9] presented a software architecture designed for the autonomous and coordinated navigation of UAV swarms applying the formations square, arrow, and line formation for specific cases in firefighting scenarios. The total distance traveled by the swarm was minimized by using the Hungarian algorithm.

The article by Bui et al. [10] allowed UAVs to form a V-shaped formation with the ability to navigate through narrow passages by dynamically adjusting their positions. The reconfiguration imitates pliers and scissors, altering their shape through the application of opposing forces on their handle arms, making the formation open or close its wings based on the Artificial Potential Forces.

In Brust et al. [11], a UAV defense system against malicious UAVs that utilizes a self-organized swarm of defense UAVs

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to intercept, capture, and escort the intruder was analyzed. Similarly, the *StringNet* herding approach, proposed by Chipade et al. [12], confines adversarial swarms by dynamically reallocating defenders based on the spatial distribution of attackers, ensuring effective engagement and control over the threat. In both works, an adaptive formation encirclement is created considering dynamic threats.

Wubben et al. [13] proposed a phased solution for collision avoidance during swarm reconfiguration. The method allocates each UAV to a sector based on its direction, initially adjusts the altitude before proceeding with horizontal movements to reach the target position in the formation. This strategy aims to reduce the flight path crossing. The simulated experiments demonstrated that the chances of facing collisions during the formation reconfiguration were significantly reduced.

Various algorithms with optimization techniques have been applied to address the challenges in formation reconfiguration, including metaheuristic algorithms such as Particle Swarm Optimization (PSO) [14] [15], Genetic Algorithm (GA) [16], Artificial Bee Colony (ABC) [17], and Pigeon-Inspired Optimization (PIO) [18], which find near-optimal solutions. For small-scale problems, a simpler deterministic control method is usually faster and more reliable than the computationally intensive metaheuristic approaches.

Peiyan Gao [19] proposed a fault tolerance algorithm for Autonomous Underwater Vehicles(AUV) formation based on reconfiguration using the Hungarian algorithm for fault condition target position assignment, which pursues a similar objective as our work, though in a distinct application context. Similarly to our hierarchical formation control approach, Skantzikas et al. [20] proposed a cooperative formation control strategy for multi-UAV systems to create and maintain regular formation shapes. Real-world experiments with four rotary-wing drones demonstrated the feasibility of the formation control when transitioning between circular, sector, and line formations. However, no reconfiguration optimization technique was applied in their work.

Our work focuses on enhancing the reconfiguration process by incorporating an optimization phase, while also analyzing the effort and additional computational overhead introduced by this step.

III. Scenario of Interest

This section defines the conceptual scenario of interest, based on the previous research by [2], and describes the definitions and assumptions used throughout this paper. Our scenario assumes that a swarm of hostile MAVs has been detected approaching a protected area with a high-value unit (HVU), as seen in Fig. 1. In response, a fleet of defense MAVs has been deployed to initiate a defense mission. This fleet uses the Manned-Unmanned Teaming (MUM-T) concept, and it is formed by a remote-controlled MAV, identified as the leader, and other autonomous MAVs as loyal wingmen (LW) under the tactical command of the leader. A human remotely controls the Leader MAV and is in charge of authorizing or overriding the behaviors of each LW MAV.

The objective is to intercept and neutralize all incoming threats and protect the HVU and the leader. The goal of the threats is to destroy the HVU using a technique known as a kamikaze attack, where each threat self-destructs by colliding with the target. The defense team positions itself in formation in front of the HVU and is able to reconfigure its formation shape upon Leader MAV request or according to the distribution of the attackers as a defensive strategy. The HVU has a high-quality MAV monitoring system in place that is capable of detecting and identifying malicious MAVs and the LW MAVs access distances and relative positioning of all MAVs of the scenario, considering perfect transmission capability.

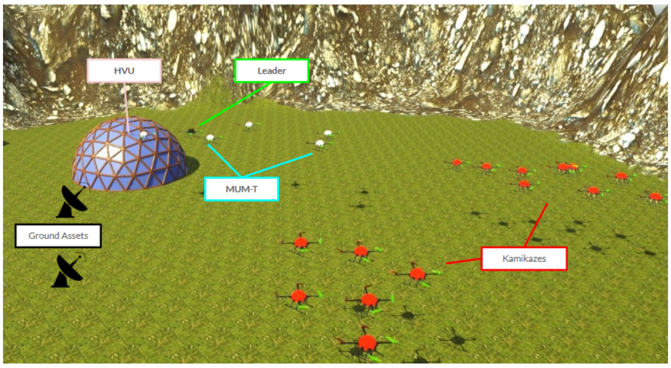

Fig. 1. Scenario of interest where MUM-T of MAVs are supported by ground assets to engage kamikaze threats to defend the HVU.

IV. System Architecture

We added a Formation Design component into the High-Level Decision-Making layer of the system of the previous work of Ricardo et al. [2], as presented in Fig. 2. This new decision-making component in the current system creates the formation shape for the MUM-T defense agents to enhance the defensive strategy against potential threats.

This component contains algorithms to create regular shapes, like circular, semicircular, echelon, V-shape, using the current number of LW MAV in the MUM-T system. An adaptive formation shape approach, named MixAPF (see `https://youtu.be/D3SjKShk2Hc`), was developed in Ferreira et al. [21]. This approach was designed to create non-regular formation shapes for the defense team, discovering

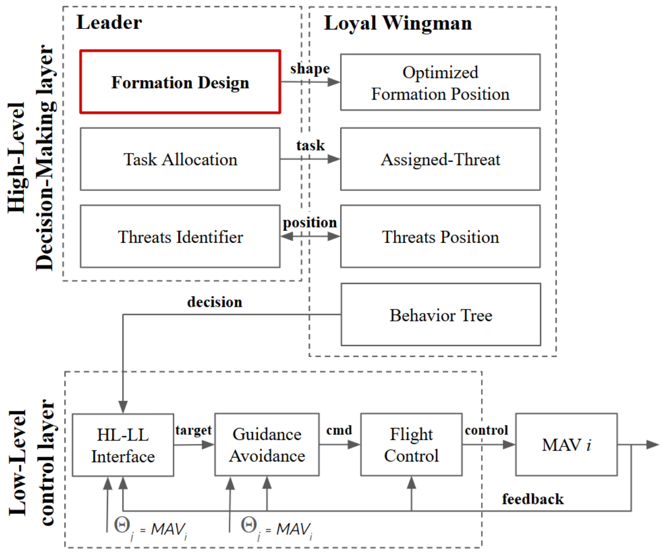

Fig. 2. System architecture with the Formation Design component highlighted, responsible for generating a Hierarchical Formation Control framework

each LW MAV's best strategic position and free collision formation position using dynamic Artificial Potential Fields to adapt the formation shape according to each kamikaze's cluster position.

The defense structure uses the Leader-Follower Approach (LFA), where the Leader MAV has the anchor role in controlling the overall formation, and the LW MAV are followers, intrinsic behavior of this kind of system. As we use a hierarchical decision-making approach where each LW MAV can act autonomously under the supervision and authorization of the leader, each LW MAV receives the positioning command from the leader and goes to the position in the formation upon entering the *GoToFormation* behavior. All positioning commands between the High-Level Decision-Making and Low-Level Control layers use relative positioning concerning the absolute leader position. The Low-Level Control Layer developed by Ricardo et al. [2] is responsible for the stability, robustness, vehicle dynamics, and the guidance based on the reciprocal collision avoidance using the adaptive velocity obstacle method (AVO) and the flight control of the current selected formation shape maintenance using a first-order sliding mode control (SMC) approach.

The formation reconfiguration process, as seen in Fig. 3, is mainly composed of three steps: determining whether the current formation needs reconfiguration, defining the new formation shape, and optimizing the target assignment position. The formation reconfiguration is required when the operator explicitly requests to change the formation, through the Leader MAV, or due to variations in the number of LW MAVs caused by malfunctions or combat losses. It is also required when the MixAPF adaptive formation shape is selected and detects the Leader MAV movement changed its relative position against the threat clusters. Upon detection of formation reconfiguration, the component computes the shape and its available target positions based on the number of LW MAV. All target positions in the formation are computed at the same altitude as the Leader MAV to respond uniformly to the threats, minimizing blind spots using a protective perimeter of the HVU and the Leader MAV. This approach also reduces the complexity of the coordination in multi-agent systems during movement and reconfiguration.

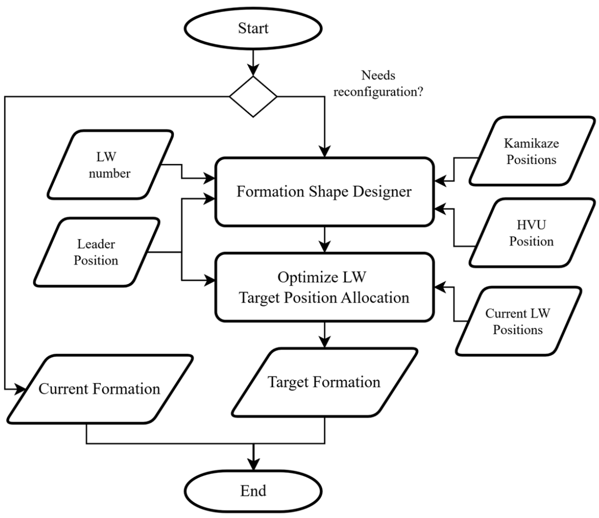

Fig. 3. Formation reconfiguration steps

The formation designer outputs the available positions sequentially based on geographic angle rotation to construct the predefined shape. Each LW MAV target formation position must be determined using the current available positions defined in the shape, which is equivalent to a task assignment problem. An optimized assignment can reduce the total distance and time cost of movement during formation reconfiguration, this can be achieved using the Hungarian algorithm [22], which finds the optimal assignment between the available target positions T_j in the formation and the current LW MAV position P_i, with minimum overall distance for the reconfiguration transition. The objective function is represented in (1).

$$\text{Minimize} \quad \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x(P_i, T_j) \tag{1}$$

The cost matrix c_{ij}, the only required input for the algorithm, is created using the Euclidean distance $||P_i - T_j||^2$, considering the direct flight path from the current position to the target formation position. Taking this into account, the Leader MAV represents the unique obstacle that must be considered in the reconfiguration planning. Since LW MAVs cannot follow the straight-line trajectory when approaching the Leader MAV, their actual trajectories diverge significantly from the planned direct paths, increasing the distances travelled by the LW MAV when deviating from the Leader MAV. This situation occurs mainly in reconfiguration from or to circular formations. Direct path intersections among LW MAVs are ignored, since the reciprocal collision avoidance embedded in their guidance results in only minor deviations from the planned paths. To prevent straight-line trajectory crossings near the Leader MAV, which makes the LW MAV change its altitude, we applied a penalty equal to twice the cost whenever the computed path intersects the Leader MAV's position within a radius of 1.5 meters. This value corresponds to the safety parameter value for the collision avoidance implemented in the Low-Level control layer in our scenario.

The output of the algorithm is a $x(P_i, T_j)$ matrix flagged with the optimized solution, where the sum of each row element and the sum of each column element of x is 1, defining unique pairs of assignments. Each flagged column and row defines which LW MAV should move to which target formation position, as illustrated in Fig. 4.

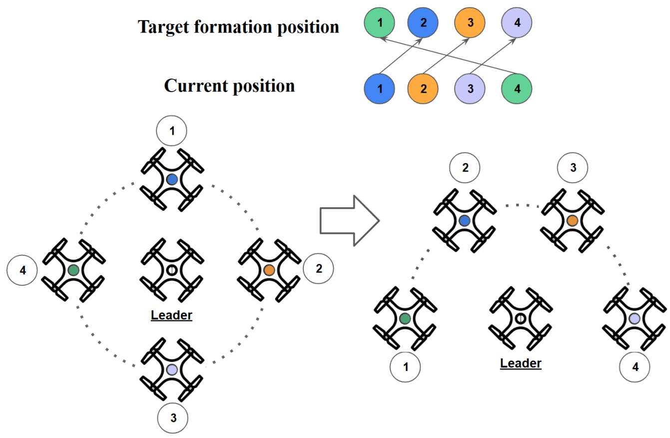

Fig. 4. Target formation position allocation optimization using Hungarian algorithm

V. Experiments and Results

The process of formation reconfiguration needs to consider collision avoidance, computational overhead, and energy consumption. In this section, the results of the experiments performed to evaluate the formation reconfiguration performance are presented and discussed. The focus is on the analysis of the reconfiguration time and the approximate effort, measured as the sum of the distances traveled by each LW during the formation transition, considering that energy consumption is proportional to the distance traveled by the MAV. Such metrics are considered determining factors for the success of a mission in dynamic defense scenarios, where fast and efficient decisions can be decisive.

A. Experiments

For the experiments, the following defensive formations were selected: the Circular formation, previously used in the work of Ricardo et al. [2]; the Semicircular formation, which generates a distributed line defense against directional threats; and the MixAPF adaptive formation shape, which generates a dynamic layered defense relative to the threat configuration.

For each configuration, transitions (see `https://youtu.be/m0nK_oEj5HY`) between selected formation shapes, seen in Fig. 5, variations in the number of LWs, and the presence or absence of the target position allocation optimization step in the formation were tested. One attack characterized by a concentrated threat as a single cluster, as show in Fig. 6, was used as a basis to stimulate the adaptive formation shape algorithm in a static manner, where the threats remained in formation at a fixed position in the scenario to ensure that the metrics were measured with the same environmental conditions of threat and leader positioning. The following metrics were evaluated:

- **Reconfiguration time**: Time required for all LWs to reach their positions in the new formation, as defined in (2).

$$Reconfig_{\text{time}} = t_{end} - t_{start} \tag{2}$$

- **Reconfiguration effort**: Sum of the real distances traveled by all LWs during the transition between the current formation and the new formation, according to (3).

$$Reconfig_{\text{effort}} = \sum_{i=0}^{LW} \sum_{t=1}^{N} ||(p_i(t) - p_i(t-1)||^2 \tag{3}$$

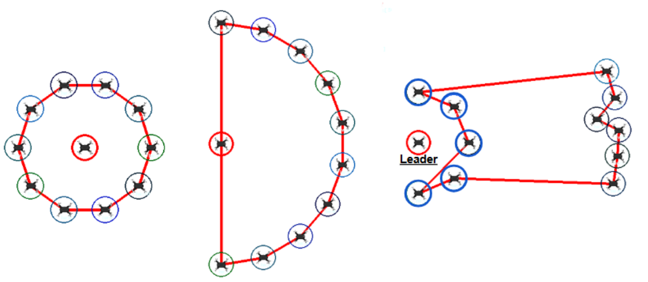

Fig. 5. Selected formation shapes: Circular, Semicircular, and the MixAPF

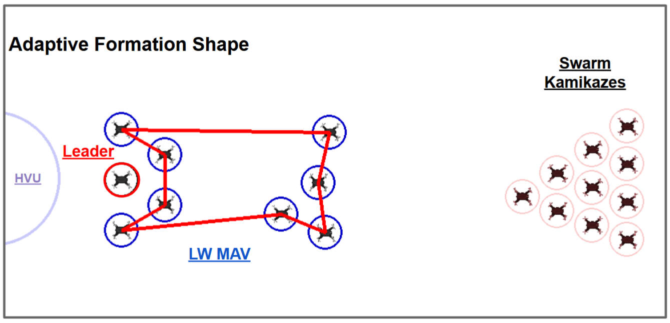

Fig. 6. Basic scenario with concentrated attack used to stimulate the adaptive formation shape MixAPF

The results were collected after running 100 test instances for each variation set of configurations (size, current formation, desired formation, and target position allocation optimization). The reconfiguration process is considered complete when all LWs have reached their allocated target positions within the formation, with a maximum positional error of 0.5 meters.

B. Results

In Fig. 7, an interesting observation arises in the range of 6 to 10 LWs, where most transitions, excluding the transition from Circular to MixAPF, demonstrate similar average reconfiguration times, which suggests a scalability in these cases due to fewer spatial conflicts during the transition. However, with 12 LWs, a significant increase in reconfiguration time is observed. This increase likely results from the intensive use of collision avoidance in the Low-Level control layer, as multiple LWs must hover close to each other at their target positions, affecting the time to reach and stabilize. This requires a balance of the number of LWs near the threats in

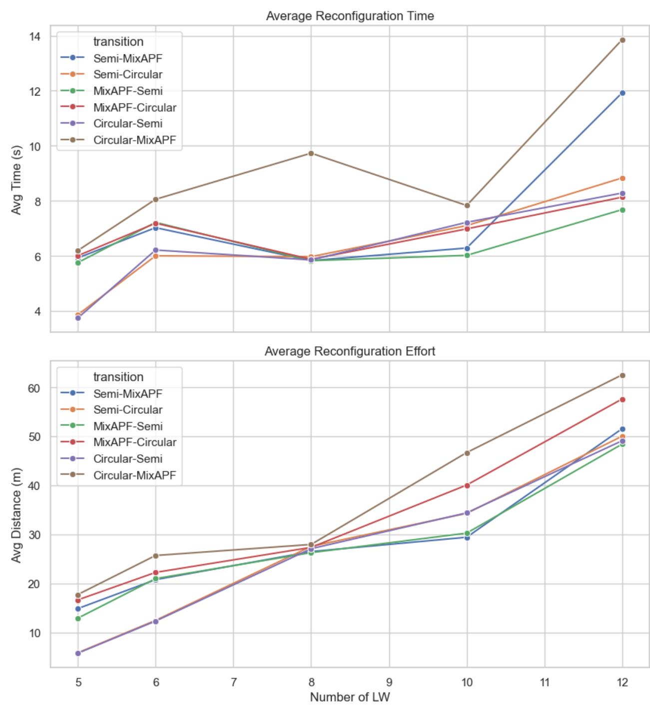

Fig. 7. Average reconfiguration time and distance for each transition

the formation shape designer.

Moreover, transitions between Semicircular and MixAPF, in both directions, exhibit significantly lower time and effort approximated costs than those involving the Circular and MixAPF formations. This bottleneck can be critical in scenarios that require a fast reconfiguration response. While adaptive formations like MixAPF can offer improved defensive coverage, particularly against concentrated attacks in previous experiments, they can incur longer reconfiguration times that must be weighed against the defense scenario time constraints. The decision-making layer should consider this limitation, especially when operating near the threat interception window.

Another important consideration is the time required to generate the MixAPF formation. Unlike regular formation shape algorithms, which exhibit nearly constant computation times for formation shape generation, the proposed adaptive formation algorithm must regenerate the artificial potential field either periodically or whenever the Leader MAV changes its position. This dynamic behaviour requires evaluating the algorithm's computational performance in our experiments. Additionally, using the Hungarian Algorithm for optimizing position assignment introduces a computational time complexity of $\mathcal{O}(n^3)$. While this is acceptable for our experimental setup involving up to 12 LWs, it is still worth evaluating the computational impact on the reconfiguration control.

As illustrated in Fig. 8, the computation time of the MixAPF increases approximately linearly with the number of LWs. In the experiments, the positioning optimization step had a negligible impact on overall performance for lower numbers of LWs. This suggests that the overhead introduced by the optimization process remains manageable for real-time use in small to medium-scale scenarios. In all experiments performed with different numbers of LWs, the importance of the optimization step for assigning positions in the Formation Design shows us a noticeable improvement in both reconfiguration time and overall effort in almost all transitions. The results of the experiment involving the most significant number of LWs (12 MAVs) are presented in Fig. 9 and 10.

The energy consumption is inherently decreased by reducing the distance traveled and flight time with low computational overhead during reconfiguration. Furthermore, it creates smoother reconfigurations by restricting routes that traverse the leader position area and prioritizing shorter direct flight routes during the target formation position allocation. The system reduces not only unnecessary energy expenditure but also alleviates the burden on the low-level control layer.

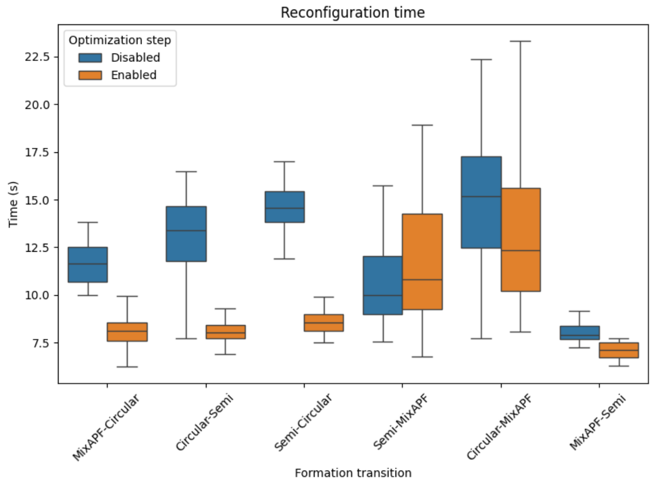

Fig. 9. Reconfiguration time for MUM-T with 12 LWs

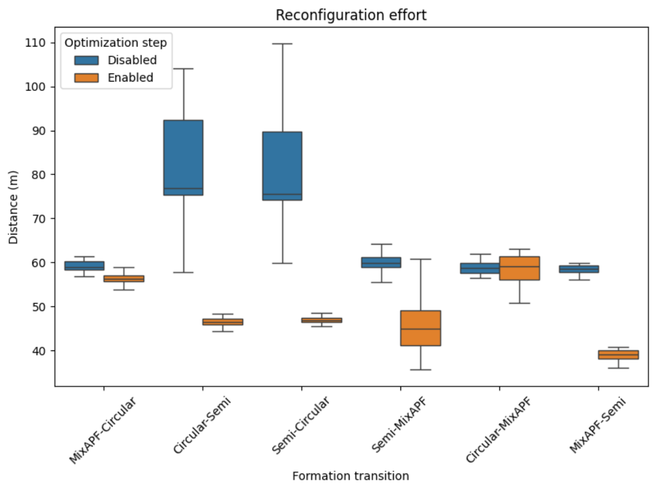

Fig. 10. Approximated reconfiguration effort for MUM-T with 12 LWs

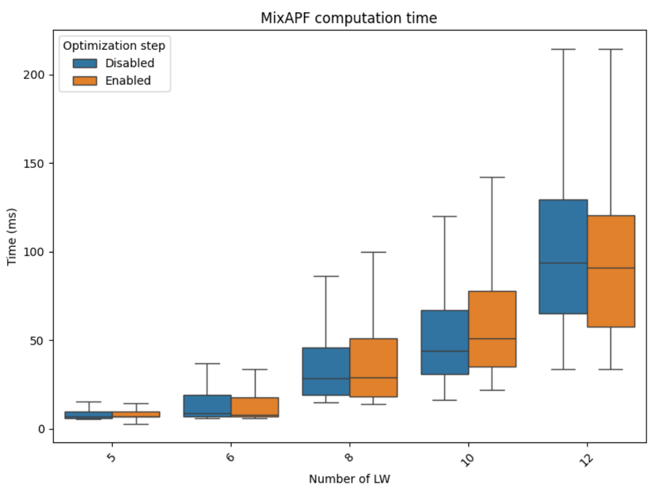

Fig. 8. Adaptive formation shape computation time

VI. Conclusion

This paper analyzes the effort of reconfiguring a UAV formation in a simulated defense scenario, focusing specifically on the formation shapes chosen to defend the HVU and the Leader MAV. We address the critical need to optimize the distance traveled by UAVs to minimize energy costs and, consequently, the associated time required to change the formation shape. Our proposed solution uses the Hungarian algorithm to efficiently solve the target allocation optimization problem of reconfiguring multiple UAVs. We obtained good results in reducing the overall movement of the UAVs during formation changes and the time to reach the new formation. As the number of LWs in the team increases, the average distance traveled by UAVs during reconfiguration increases linearly across all transition types. This is expected, as more UAVs generally require more movement. The transition from Circular to MixAPF often presents higher standard deviations for both time and distance, implying that this specific type of reconfiguration is less consistent due to more complex scenarios and intensive use of the collision avoidance. Several areas remain for future work, where we intend to extend the decision-making layer with the ability to autonomously determine the optimal defensive formation shapes, moving towards a more autonomous defensive system, where fast and efficient decisions can be decisive for the success of the defense mission. Another improvement on the autonomy level of the LWs involves adopting a decentralized consensus-based approach for target position allocation. Furthermore, using real drones in a controlled environment to evaluate the complexities of real-world conditions, such as sensor noise, communication delays, and environmental conditions, could be the subject of future work.

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