From Air to Ground: Coordinating UAVs and UGVs in SAR missions

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***Abstract*—When dealing with large-scale natural disasters such as floods, landslides, hurricanes, or heavy snowfalls, there are often many victims who are trapped in hard-to-reach places, making the time to locate and rescue them critical. In this context, deploying unmanned aerial vehicles (UAVs) alongside a swarm of unmanned ground vehicles (UGVs) has the potential to speed up the Search and Rescue (SAR) missions, as the collaboration between these agents can combine advantages from both of them. The idea is that any simple UAV equipped GPS and communication capabilities can locate besieged and isolated individuals, referred to as Points of interest (POIs), and when it comes across (flies over) a GPS-limited UGV, it guides the UGVs toward the POIs. In this paper, we explore different approaches to Air-to-Ground (A2G) coordination in a number of distinct scenarios among unmanned vehicles, and through simulation compare their efficiency based of parameters and metrics.**

***Index Terms*—Mobility, Coordination Protocol, UAV, Swarms, Unmanned Ground Vehicles, Air-to-Ground communication**

I. Introduction

In disaster scenarios, time is a critical and limited resource. The urgency to locate and rescue survivors is increased by the rapidly changing conditions of the affected area and the speed of response by rescue teams can be greatly affected in a matter of seconds, making it critical to look for effective ways to carry out these missions. Therefore, Search And Rescue (SAR) missions are inherently complex and require seamless coordination between teams.

Two factors play an important role in the overall outcome of SAR missions.

Urgency: In most SAR missions, missing persons are isolated and trapped in a life-threatening situation, where the victim has little time for survival. So, it becomes important for the rescue entourage to locate and assist isolated or trapped people at the earliest possible time.

Isolated or inaccessible regions: many SAR missions happen in isolated or inaccessible regions, e.g., flooded areas, points of landslides, snowy mountains, forests, etc., or where the transportation and communication infrastructure is broken, making it much more difficult, time- and energy-consuming to run the entire rescue operation.

In flood disasters, such as the flood in Rio Grande do Sul, Brazil, in May 2024, the environment can completely change, as roads can be submerged and landslides can block access routes, and communication infrastructure may be damaged, making it more difficult to locate survivors.

With the popularization of Unmanned Aerial Vehicles (UAVs) in areas such as surveillance and agriculture, due to their effective performance in monitoring large areas and operating challenging environments, they have also been used in SAR missions, significantly enhancing the efficiency and safety of rescue operations [1].

Other Unmanned Vehicles have also been used in SAR missions [2]. In particular, Unmanned Ground Vehicles (UGVs) are useful for SAR missions that navigate complex terrain, as they can maneuver through rough and hazardous environments and rescue victims.

Hence, SAR operations using both UAVs and UGVs offer multiple advantages that make them an invaluable asset in emergency situations [3]. Some prominent benefits are the following:

Speed of Response: Drones can reach a location much faster than ground vehicles, including UGV, thanks to their ability to fly over traffic and other obstructions. They are also capable of reaching inaccessible places, such as remote or hazardous areas.

Situational Awareness: By providing rapid, cheap access to aerial images/data of a large area, drones allow early responders to map the entire search zone and pinpoint possible places where persons might be trapped and waiting for help. UAVs can further provide real-time visual information and data, reducing the time that ground vehicles move to the locations of trapped people.

Detection and identification: UAVs can carry different sensors, including thermal cameras, which are widely used in search and rescue missions. These sensors can identify ground objects and humans by detecting their heat signatures, making them easy to spot, especially in the dark or dense areas.

Coordination of the ground team: And last but not least, UAVs can spot the current location of each agent of the ground team, be it a human or a UGV, and pass directions to it of the most urgent or immediate location that should be visited next for the early response.

In addition to locating individuals, UAV-UGV coordination can also help in the collection of information that can assist SAR teams at the base station by providing statistical data such as how much time it takes to locate individuals and how much time each individual assistance takes. This data fusion can improve the efficiency of the mission.

There are numerous challenges to be explored in UAV-UGV coordination. The number of agents involved, the selection of coordinating agents, the available context information, and the mission objectives all influence the complexity of the problem at hand.

Using UAVs as coordinators offers significant advantages due to their aerial perspective and faster mobility, allowing them to quickly oversee large areas and relay information to ground units. However, UGVs play a crucial role in close-range navigation, as they operate directly in the terrain, allowing them to easily assist individuals.

In this work, we address key constraints that impact UAV-UGV coordination in SAR missions:

- **GPS-limited:** only the UAVs have GPS, while the UGVs use compass navigation and only have anti-collision systems like Light Detection and Ranging (LIDAR) sensors.
- **Distributed:** UAVs and UGVs communicate and coordinate through message exchange. As a result, the system operates without a central clock.
- **Unknown environment:** the area is unknown to both the UGV and the UAV and Points of Interest can be anywhere on the map.
- **Predefined Path planning for aerial coverage and mapping:** each UAV of the swarm has a predefined path planning.

The paper is organized as follows: The study of the most recent work is presented in Section II. The formulation of the problem at hand is described in Section III. The proposed approach, called A2G-Coord, is detailed in Section IV. The simulation of the approach is described in Section V. The illustrated results and discussion are shown in Section VI. Finally, the conclusions and next steps of this research are summarized in Section VII.

II. Related Work

According to Ding *et al.* [4], the coordination between UAVs and UGVs can be allocated into different categories based on the responsibilities of these agents. They can act as sensors, detecting events or changes in the environment and sending data to other components or vehicles, as actuators, performing actions or activities, as decision makers, making decisions for other components or vehicles, or as auxiliary facilities, providing agents with services such as energy and communication.

Munasinghe *et al.* [5] expand the survey and introduce new classifications of the collaboration between UAVs and UGVs. They explore the different applications of UAV-UGV when it comes to surveillance and monitoring, agriculture, and infrastructure inspection, as well as the limitations and challenges of Air-Ground collaboration towards complex coordination, communication latency and bandwidth constraints, energy and resource management, environment and terrain challenges, computational burden, communication network instability, and embedded hardware limitations.

Based on Ding *et al.*'s survey, our work extends the area of study by focusing on *UAVs Acting as Sensors as Well as Decision Makers and UGVs Acting as Actuators*, where UAVs provide UGVs with environmental information and guidance, being used as "eyes in the sky". When it comes to limitations and challenges, based on Munasinghe *et al.*'s survey, our work deals with *Complex Coordination*, as UAVs are much faster than UGV in our scenarios, and *Communication Latency and Bandwidth Constraints*, as all communication between agents is opportunistic.

More recent work has continued to contribute to this area of study, exploring advanced coordination strategies and improving communication frameworks.

Cladera *et al.* [6], based on the work of Miller *et al.* [7], show a collaboration method between UGVs and UAVs in scenarios lacking communication infrastructure within unexplored areas. Given the limited number of UGVs and time constraints, the UAV is tasked with searching the area, generating a semantic map, and disseminating the data to the UGVs. The UGVs then opportunistically communicate with each other and use the information to locate points of interest.

In Miller *et al.*, the UAVs build a semantic map in real time and opportunistically pass them to the UGVs, allowing them to choose and deconflict their targets without any external intervention. Communication between agents is distributed and opportunistic and UGVs do not have access to GPS.

In Castro *et al.* [8], two UAVs explore the area and update the environment map of a partially mapped area, while one UGV is responsible for updating the map at ground level and having the ability to transport a UAV to its top, changing the UAV battery during an aerial mission.

Table I gives a summary of the related work, comparing it with our approach, A2G-Coord. This comparison is regarding the number of UAVs and UGVs deployed, how each coverage path is planned, which UAV/UGV constraints are considered, how the UAVs interact, and which metrics were evaluated.

TABLE I: Related Work Comparison

Paper	Algorithm	Num of UAVs - UGVs	Coverage Path Planning	UAV Constraints	UGV Constraints	Communication	Evaluated Metrics
Cladera *et al.* [6]	Heuristic	1 - N	Predefined waypoints	Energy consumption	No GPS	P2P opportunistic	Number of visited targets Average time to visit targets
Miller *et al.* [7]	Heuristic	1 - 2	Global semantic planner	-	No GPS	P2P opportunistic	Time to visit all targets
de Castro *et al.* [8]	Neural Networks	2 - 1	Wave front algorithm	Battery scarcity	Limited visibility	P2P opportunistic	Obstacle avoidance success rate Path efficiency
A2G-Coord	Heuristic	N - N	Wave front algorithm	Fixed coverage path planning	No GPS Limited visibility	P2P opportunistic	Time to visit all targets

III. Problem Formulation

This work finds its motivation in the problem of time-critical Search and Rescue (SAR) missions using swarms of autonomous agents, where the main goal of these missions is to locate targets, usually individuals, in danger in hazardous environments, and there is a limited time frame to find and serve these targets.

An aerial agent is represented by an Unmanned Aerial Vehicle (UAV), and a ground agent is represented by an Unmanned Ground Vehicle (UGV). All agents have means of wireless communication with fixed range with other UAV/UGV agents. They communicate to share their partial knowledge of the mission so far, as well as pass directions or positions to other agents.

The environment is represented as a bounded three-dimensional map. Points of Interest (POI) represent individuals in danger, and these targets remain stationary throughout the entire mission.

Agents are used to locate targets in challenging environments. Aerial agents can scan regions quickly, providing a broad overview of the area and identifying possible target locations using cameras, thermal imaging, and other sensors. Ground agents can navigate through difficult terrain to perform close-up searches and assist in the extraction of individuals.

During the mission, GPS signals can be compromised for teams on the ground while remaining accessible on the air. In such environments, UGVs cannot rely on GPS for accurate localization and instead depend on UAVs for directional guidance to reach POIs. Therefore, in this work, UAVs are the only agents with GPS capability.

All communication between UAVs, UGVs and POIs happens opportunistically, as the distributed algorithm operates only through message exchange between these agents. When they come into proximity, they exchange information that will help the mission goal.

The problem at hand is to design, implement, and evaluate heuristics and distributed algorithms for coordination among all UAV/UGV agents to minimize the time it takes for all POIs to be visited by at least one UGV. Or else, given a specific time frame (e.g. until the next rainfall), maximize the number of visited POI.

IV. Proposed Approaches

A2G-Coord approaches the problem using a base algorithm and tries to solve the issues and improve performance by applying various techniques and optimizations to subsequent algorithms.

A. Base Algorithm (BA)

The Base Algorithm involves a simpler solution, in which the UAVs do not distribute the information to the UGVs based on specific criteria. They simply pass all information in the order it was discovered, without prioritizing which data should be transmitted first. This means that UGVs may receive information that is not immediately relevant or optimal for their current state, potentially leading to suboptimal routes or outdated or redundant information.

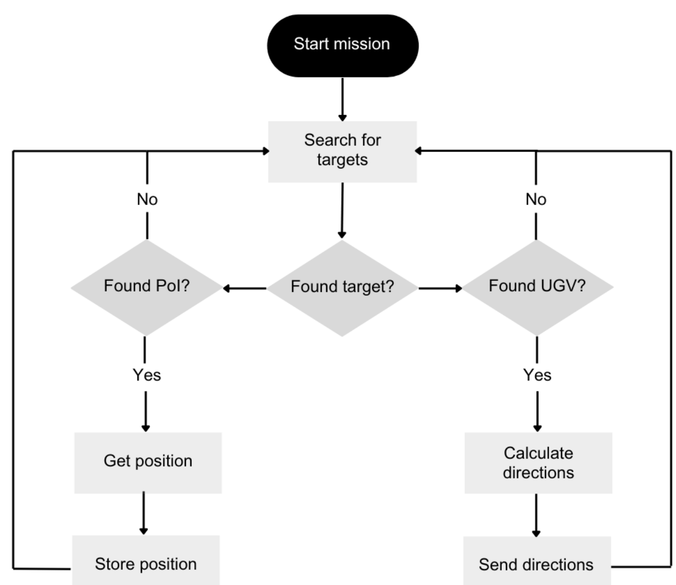


Fig. 1: UAV mission flow chart

1) UAV's mission: The UAV is initially positioned in a corner of the map. The Coverage Path Planning (CPP) used is based on a wave front algorithm [9]. The map is segmented into sections and the algorithm is applied individually to each section. After completing the navigation of a section, the UAV returns to its starting position to recharge before proceeding to the next section. As CPP falls outside the scope of this project, no additional path planning algorithms were implemented.

Furthermore, when more UAVs are added, the sections are distributed among them. For instance, if there are two UAVs, each one covers half of the map; with three, each one is responsible for a third of the map, and so on.

During the mission, the UAV broadcasts messages at regular intervals to search for points of interest or UGVs. When a POI is detected, it responds with a message containing its unique ID, and the UAV gets its own coordinates on the map at that time. The UAV then records these coordinates in an arbitrary-sized buffer, known as *POI Buffer*. When an UGV is detected, the UAV calculates directions based on its own position towards the POI's positions, to guide the GPS-limited UGV toward the POI. It sends a copy of *POI Buffer* in a message to the UGV. This process is shown in figure 1.

2) UGV's mission: The UGVs begin their mission at the same location as the UAVs. They move towards the edge of the map in equally distributed directions.

During this mission, UGVs can communicate with both UAVs and POIs. When communicating with a UAV, they receive the *POI buffer* and begin a new mission, following each direction in the buffer sequentially until all POIs have been visited and the buffer is emptied. Even if a UGV has not received a specific direction to a POI, it will communicate with the POI if it happens to be along its path.

3) POI: POIs act as beacons, repeatedly broadcasting messages every few seconds with their unique ID.

B. Greedy Algorithm (GA)

Although the base algorithm solves the problem, its efficiency can be improved by optimizing the communication strategy between UAVs and UGVs. In particular, when UAVs pass directions to UGVs, they do not consider the current location on the map, meaning that all UGVs receive the collection of POIs in the same order.

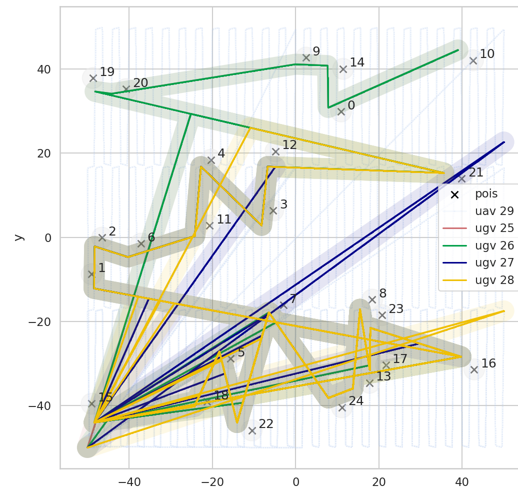
Hence, we use a greedy algorithm to rearrange the collected points of interest stored in the *POI buffer* based on the proximity of the UGV to the points.

The idea is that each UGV will receive directions tailored to its current location, and since all UGVs will receive a personalized ordered set of points, the total time to find all POIs is significantly reduced.

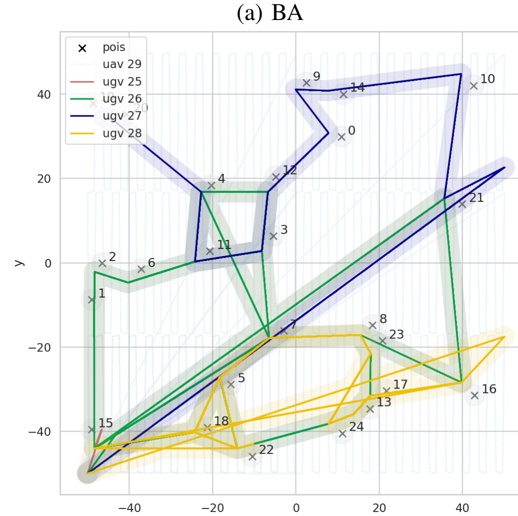
C. Load Balancing Algorithm (LBA)

Another issue outlined in the base algorithm is the lack of load distribution. To address this, the proposed optimization incorporates load balancing to distribute POIs among UGVs.

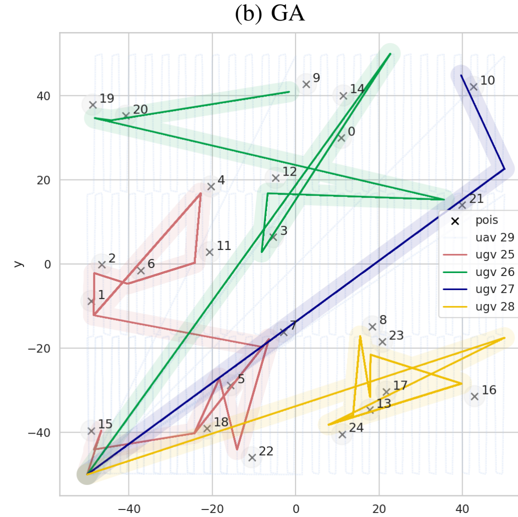
In this approach, every time an UAV sends directions to an UGV, it records in *POI Buffer* which UGV the direction was



(a) BA

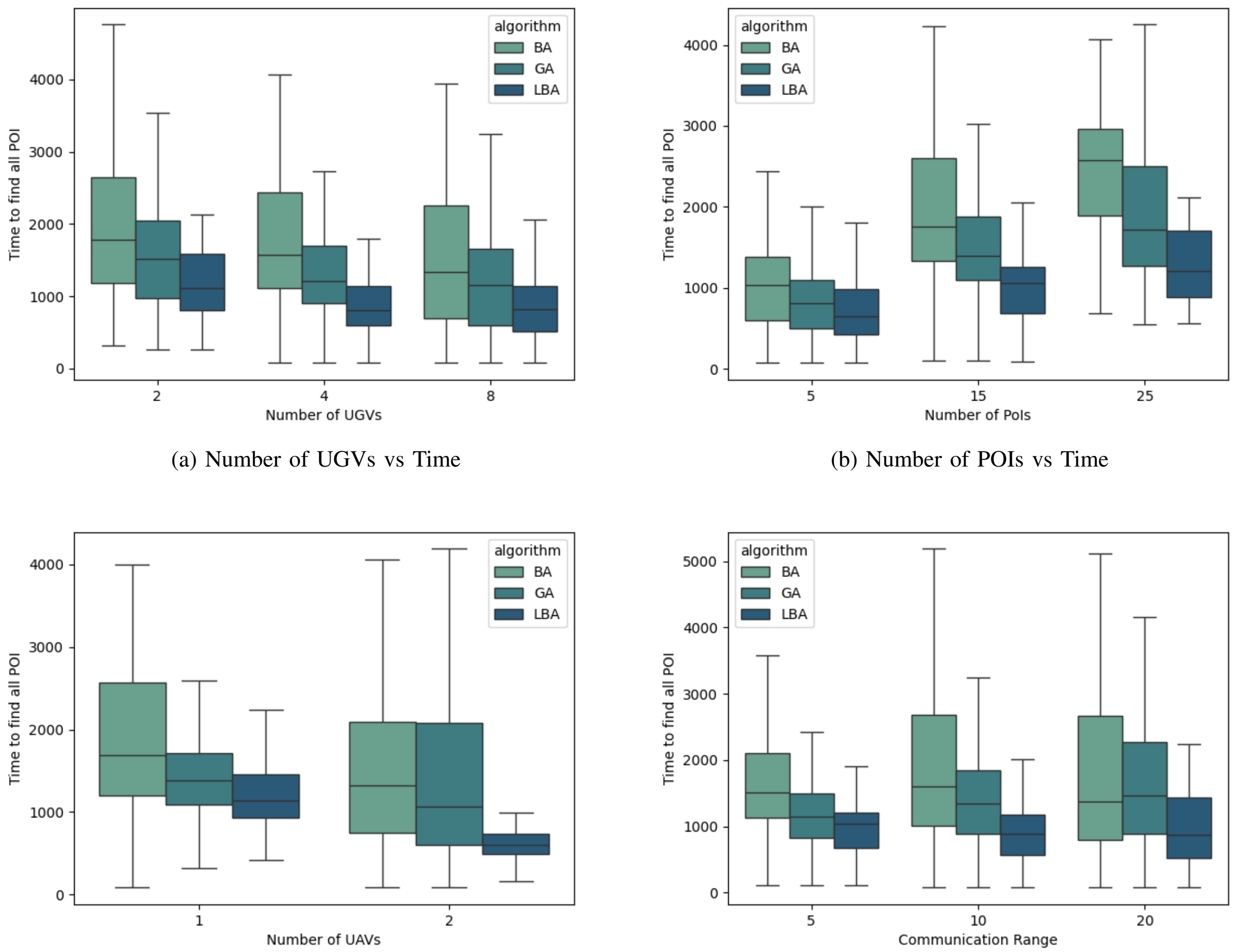


(b) GA



(c) LBA

Fig. 2: Selected simulation results exemplifying the different algorithms



(a) Number of UGVs vs Time

(b) Number of POIs vs Time

(c) Number of UAVs vs Time

(d) Communication Range vs Time

Fig. 3: Results of the simulated scenarios

sent to. A flag is added to *POI buffer* to indicate whether a POI's position has already been sent. An UAV will only send POI directions to a UGV if the flag is set to False.

D. Comparison between algorithms

Using examples of UAV/UGV traces from our simulations, shown in Figure 2, it is possible to get a better idea of how the algorithms work. In the images, we can see an UAV, represented by the light blue lines across the map, four UGVs, represented by the blue, green, yellow, and red lines, and the 25 POIs, represented by "X"s.

It is possible to notice that in the first two algorithms the UGVs take unnecessary routes, as many of them pass through the same POIs, while the POIs in LBA have a better distribution between the UGVs.

V. Simulations and Experiments

In order to test and validate our approach, we used GrADyS-SIM NextGen[1] [10], a Python-based framework to simulate distributed algorithms operating on cooperating mobile nodes and swarms, developed in the Laboratory for Advanced Collaboration (LAC) at PUC-Rio.

The framework is easy to use and is suited to simulate all types of mobility, communication, and delay behavior of groups of nodes. A singular feature of GrADyS-SIM NextGen is that it allows the same simulation code to be translated into MAVLink/Ardupilot, and to be deployed in drones and rovers for experiments in real-world settings.

Our (simulation) experiments involved testing several configurations for the three algorithms, varying the number of UAVs and UGVs, as well as the wireless communication range among agents, and the POI density. In total, a variety of

[1] https://github.com/Project-GrADyS/gradys-sim-nextgen

54 configurations were evaluated, with each configuration of parameters, shown in Table II, executed 10 times. This number of configurations was chosen to represent a wide range of possible scenarios encountered by the algorithm [2].

The metric chosen to evaluate this work is the time it takes for all POIs to be visited.

TABLE II: Simulation Parameters

Parameter	Values	Unit
Number of UGVs	2, 4 and 8	-
Number of UAVs	1 and 2	-
Communication Range	5, 10 and 20	m
POI Density	0.05, 0.15 and 0.25	points/m^2

VI. Results

We compared the three algorithms (BA, GA and LBA) varying four parameters: wireless communication range, total number of UGVs, total number of UAVs, and number of POIs and evaluated how they influence the metric global time to visit all points of interest.

The *Base Algorithm (BA)* takes a naive approach to the problem, where during every opportunistic encounter of an UAV with an UGV, the UGV receives the entire set of PoIs to visit, known to the UAV. However, this approach has an obvious problem, as all UGVs will receive the same set of POIs, leading to redundant information and visits. We can observe in the four graphs, in Figure 3, that BA has by far the worst result for all parameters, as expected. It is possible to notice that the median in the four results is closer to the third quartile, although this is softened by increasing the number of UGVs and UAVs, and the range of communication, as shown in Figures 3a, 3c and 3d.The inverse is observed in Figure 3b, as the higher number of POIs increases the median.

With the *Greedy Algorithm (GA)*, after the UGVs receive all the points, they start to move to the closest PoI to visit (from the received set), then to the next closest point to the just visited PoI, and so on. This approach improves the metric, lowering the median and the third quartile, indicating that most of the results in GA are better than most of the results in BA.

As expected, the *Load Balance Algorithm (LBA)* gives the best result, as this approach has a better distribution of points to visit among the UGVs. The median in all graphs is much lower than in BA and GA, making it the most efficient algorithm, and the third quartile shows that it has the smallest spread, showing that the results are more consistent than the other algorithms.

[2]The source code for A2G-Coord is available on https://github.com/Project-GrADyS/A2G-Coord

VII. Conclusion and Future Work

The presented work focuses on an UAV-UGV coordination algorithm to find points of interest in an unknown area. This approach can be used on SAR missions, where POIs are individuals in danger and UAVs search the area to locate them.

Based on the results presented, the subsequent algorithms show a significant improvement in the Base Algorithm based on the chosen metric, with the Load Balancing Algorithm being the one with the lowest times. This potentially indicates that the use of load balancing is a promising direction for future work.

Furthermore, based on related work and simulation results, exploring effective collaboration between UAVs may be one of the next steps to improve algorithms.

Acknowledgments

This study was financed in part by AFOSR grant FA9550-23-1-0136.

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