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Networking of Multi-Robot Systems: Issues and Requirements

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Abstract: The advancement of Multi-Robot Systems (MRS), Wireless Sensor Networks (WSNs), and Unmanned Aerial Vehicles (UAVs) has led to their increasing use for large-scale monitoring. The research in this area has focused on developing advanced sensing and networking protocols, as well as specialized system topologies and embedded computer and communication platforms. This has resulted in a need for multidisciplinary projects to develop appropriate algorithms for data processing, communication, and control across diverse fields. The primary focus of this article is the collaborative features of MRS. It provides a brief overview of recent advancements in this vital domain, with a comparative focus on numerous recent theoretical and practical contributions. The article also identifies and discusses focus areas, such as a classification of MRS systems and the issues and requirements of MRS networking protocols. Additionally, references to applications in various domains, including the environment, agriculture, emergency scenarios, and border patrol, are highlighted. Finally, an integrated system model based on WSNs and UAVs is presented, along with an optimality study.

Keywords: multi-robot system, wireless sensor networks, unmanned aerial vehicles, path planning, trajectory optimization, swarm robotics, wireless sensor network

1 Introduction

Recent advancements in microprocessor-based systems have led to substantial improvements in almost all components and subsystems. The subsystems encompass a range of functionalities, such as memory and data storage, sensing artificial intelligence, processing capacity, actuation and control, communication capabilities, power consumption, and speed.

The advancements that occurred resulted in an increased use of robots. These machines became capable of performing intricate tasks in real-time and comprehending their surroundings through various means. As a result, robots became integrated into various aspects of society, including search and rescue, mining, construction, and laborious, repetitive jobs such as manufacturing, traffic control, and agriculture, in addition to enhancing human safety and comfort [1].

The implementation of robots in process standardization, quality control, and cost reduction has resulted in increased investment and advancements in associated technologies. This, in turn, has accelerated the integration of robots into various industries, leading to their increased usage in diverse applications. However, it became evident that a single robot, despite its intelligence and versatility, was inadequate for handling certain tasks due to the need for presence in multiple locations, high demand, avoiding a single point of failure, and ensuring system availability. This requirement led to the emergence of a field known as Multi-Robot Systems (MRS) that involves the collaborative use of multiple robots within a single environment working towards a common objective.

Multiple unmanned aerial vehicles (UAVs) together make up an MRS system, which is essentially a fleet of flying robots. In recent years, the scope of UAV applications has expanded greatly. These aerial machines are now capable of tackling complex problems, understanding their surroundings, and engaging with them in diverse ways. Moreover, UAVs are now utilized in a wide range of industries, such as agriculture, search and rescue, construction, and other industrial sectors. This integration has spurred increased investment in the UAV industry, leading to advancements in associated technology, and consequently accelerating their integration into various businesses.

The utilization of UAVs has various applications. One of these potential applications is to use UAVs as aerial access points, which can enhance the effectiveness of ground-based wireless networks [2-6]. Furthermore, equipped with advanced features like video recording, photography, or multi-spectral imaging, UAVs have the capability to conduct an extensive range of surveying tasks in a secure, economical, and efficient manner [7]. Additionally, UAVs can be utilized to collect data in wireless sensor networks (WSNs) in a faster and more efficient way, which can result in an extended lifespan of the network [8,9]. The paper presents a case study that concentrates on these types of UAV applications.

The rest of this paper is organized as follows: Section II outlines related work, while Section III provides a classification of MRS Systems. Section IV discusses the architecture, and Section V examines the limitations of MRS Networking Protocols and the specific application criteria. In Section VI, the proposed model is described, including the selected architecture, communication protocol, and underlying assumptions. Section VII presents the performance evaluation for the proposed algorithms. Finally, Section VIII presents a case study on optimality before concluding the paper in Section IX.

2 Related Work

In [36], the authors considered three key aspects when analyzing MRS: the design rationale, basic functionality and technology, as well as the tasks performed by the robot. Furthermore, they created a new classification system for MRS.

In [37], a review of MRS patrolling algorithms was conducted, which evaluated various techniques and examined their strengths, limitations, and challenges. The evaluation took into account a range of factors, starting with the robot's decision-making model, as well as the coordination and communication protocols utilized.

Additionally, [38] categorized distributed intelligence systems and investigated problems related to task allocation.

Several articles have analyzed the collaboration and coordination of mobile robotic systems (MRS). In one study [39], researchers conducted a survey on the coordination of mobile MRS, outlining the communication system, scenario planning process, and decision-making mechanism. Another article [40] provided an overview of MRS cooperation methods in space applications. In addition, a third study [41] investigated ad-hoc wireless communication features among MRS robots using the Zigbee protocol and proposed a strategy for estimating inter-robot distance based on communication signal intensity. This technique has potential applications in search and rescue and multi-robot patrols. Despite the benefits of using multiple robots over single-robot systems, there has been limited research in the area of multi-robot systems, and only a few of these techniques have been put into practice.

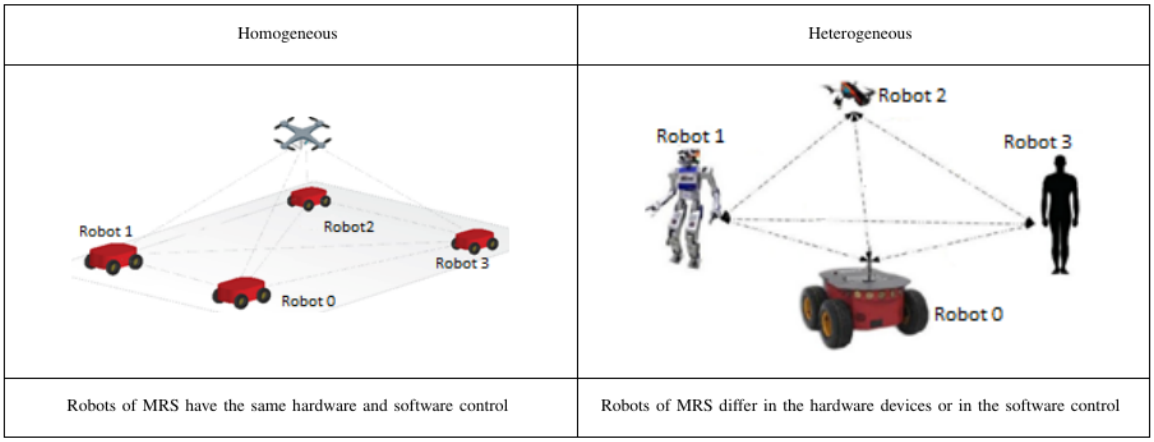
Multi-robot systems come in several types, including wheeled, legged, underwater, and aerial formats. Among these, the aerial format represented by unmanned aerial vehicles (UAVs) has gained popularity due to its ability to adapt to complex scenarios. UAVs have advantages over other types of robots, such as increased mobility with additional degrees of freedom and the ability to reach inaccessible locations through unorthodox trajectories in shorter durations. These characteristics have spurred further research into UAVs and their use in addressing various modern challenges. However, this mobility also brings forth challenges such as energy requirements, unstable connections due to increased movement, and privacy and security concerns. Despite these challenges, researchers are actively investigating ways to leverage the benefits offered by UAVs.

UAVs have found application in several areas, such as monitoring fuel supply pipelines [42], border patrol and surveillance [43], wilderness firefighting pre, during, and post-incident [44], and river search and tracking [45]. Researchers involved in projects in this field have analyzed the challenges associated with the use of UAV systems and aimed to address them.

According to Moreno et al.'s 2018 study, small-scale data collection by wireless sensor networks (WSNs) can aid farmers in enhancing their control over crucial processes, such as crop irrigation, fertilizer application, and determining optimal phases for sowing and harvesting. Additionally, WSNs generate a substantial amount of data, which makes them valuable for collecting information that contributes significantly to the development of farm management information systems (FMIS), as emphasized in reference [46].

In recent years, academics have displayed a keen interest in the integration of WSN and UAV technologies. To meet the evolving demands of monitoring and data collection across vast geographic areas, collaborative hybrid systems utilizing both air-ground and mobile-fixed UAV-WSN technologies have been developed [14,23]. Nevertheless, the successful implementation of UAV-WSN collaborative systems across a diverse range of applications requires the adoption of advanced approaches for data acquisition, transmission, processing, and mission control.

There are many commercially available UAVs that use different propulsion systems, but a significant proportion of them use electric propulsion due to



Homogeneous	Heterogeneous
Robots of MRS have the same hardware and software control	Robots of MRS differ in the hardware devices or in the software control

Figure 1: WSN Classification via Team Composition

their small size and lower maintenance and operational costs. Electric-powered UAVs are frequently used for surveillance purposes. However, their limited flying range means that using multi-UAV systems is a common approach to expanding coverage. In addition, satellites have become indispensable for global navigation and other applications, and they can also be used as an additional support infrastructure for providing data or instructions to UAV-WSN systems.

3 Classification of MRS Systems

There are various perspectives from which multiple mobile robot systems can be categorized, and two general categories are collective swarm systems and intentionally cooperative systems. Another perspective focuses on coordination, which is influenced by the interaction between the robots in the system. Collective swarm systems are characterized by the assumption of many homogeneous robots, where each robot performs its own tasks with minimal knowledge about other team members. These systems utilize local control laws to generate team behaviors that are globally coherent, with minimal communication among the robots.

Conversely, robots that operate within intentionally cooperative systems possess knowledge about the presence of other robots within the surroundings, and work collaboratively by taking into account the state, actions, or abilities of their fellow robots to achieve a shared objective. The level of collaboration within intentionally cooperative systems varies, ranging from strongly cooperative to weakly cooperative solutions [3]. Strongly cooperative solutions necessitate robots to work in unison to accomplish tasks that cannot be performed independently. Typically, such approaches require some form of communication and synchronization among the robots. In contrast, weakly cooperative solutions enable robots to have periods of operational independence while coordinating their task or role selection.

Multi-robot systems that are designed to cooperate intentionally can effectively handle heterogeneity among team members, where the robots may differ in their sensor and effector capabilities. Such systems require a different kind of coordination compared to collective swarm approaches, where the robots are interchangeable. Another approach to classification involves a hierarchical structure illustrated in Figure 2, which presents a taxonomy of coordination dimensions. The first level of this structure is based on the system's ability to collaborate with the objective of achieving a particular task [5].

In [4], a cooperative system composition is defined as ”Robots that work together to achieve a common goal”. Moving on to the ”knowledge” level, Cooperative MRS can be classified into two categories, namely aware and unaware. Aware MRS are generally more intricate systems, with each robot possessing information about its fellow team members. In contrast, unaware MRS are simpler systems, and each robot operates without any knowledge of its teammates. The third level is centered around robot ”coordination”. Aware MRS can be strongly coordinated, weakly coordinated, or not coordinated. Lastly, the fourth level describes the ”organization” of strongly coordinated MRS, which is classified into three types: Strongly centralized, weakly centralized, and distributed.

At this point, the main difference is deciding between centralized and distributed decision-making. Centralized systems involve a leading robot that dictates the actions of all other team members, while distributed systems offer more autonomy to each robot for independent decision-making.

Alternatively, we can categorize MRS based on their attributes, such as communication, team makeup, and team magnitude.

According to their communication capabilities, MRS system can be divided into two groups: direct and indirect communication. This is shown in Table I.

Intentional communication through physical means, such as radio, is known as direct explicit communication.

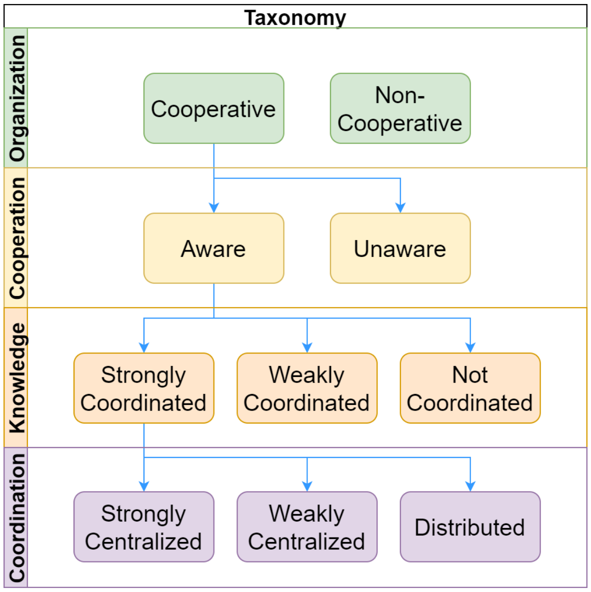


Figure 2: Taxonomy of Coordination Dimensions

However, this method can be costly, drain battery life, and cause radio frequency congestion. Furthermore, as the number of robots in the system increases, it can hinder the scalability of the system. Alternatively, direct passive communication involves robots using sensors to closely observe the actions of their teammates. Indirect implicit communication occurs when robots in an MRS detect the actions of their teammates through the effects they have on the environment.

Fig. 1 [6][7] illustrates the categorization of MRS systems based on team composition, which can be divided into two groups: homogeneous teams and heterogeneous teams.

One way to categorize MRS (Multi-Robot Systems) based on team size is by dividing them into two groups: those that are capable of handling a large number of robots and those that are not. Maintaining a communication network between the robot team members and the human operator poses a significant challenge in creating a scalable MRS.

Table II presents a classification of multiple applications, considering factors such as bandwidth, mobility, delay tolerance, range, security, scalability, and reliability. This classification provides a comprehensive overview of the diverse range of applications for MRS Systems and the trade-offs required to adjust to various environments.

On the other hand, we can also classify MRS according to their features like communication, team composition, and team size. According to their communication capabilities, MRS system can be divided into two groups: direct and indirect communication. This is shown in Table 1.

Table 1 WSN classification via communication

Direct Communication		Indirect Communication
Explicit	Passive	Implicit
Via Communication Link	Via Sensing	Via Environment

Direct explicit communication is intentional communication using a physical mean of communication such as radio. This method is financially expensive, drains battery life, and clutters the radio frequency. In addition, considering the number of robots in the system also, it can limit system scalability. Direct passive communication is when robots use direct sensors to closely observe the action of their teammates. Indirect implicit communication is when the robots in the MRS sense the actions through the effects of their other teammates throughout the world.

To classify MRS systems by Team composition, we can group them into two groups: homogeneous and heterogeneous teams. This is shown in fig. 1 [6][7].

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To classify MRS systems by Team size [8], we can group them into two groups: systems who can handle large numbers of robots and those that cannot. The difficulty in a scalable system is the ability to ensure that the communications network is maintained between the robot team members and the human operator.

In table 2, we present a classification of a number of applications based on their bandwidth, mobility, delay tolerance, range, security, scalability, and reliability. This provides a high level view on the range of applications for MRS Systems and the trade-offs made to suit different environments.

4 Networking Architecture

The basic elements in single-robot systems make up the building blocks of multi-robot team architectures. The effectiveness and adaptability of the system largely depend on the design of its control architecture. Multiple approaches can be taken when designing architectures for multi-robot teams, such as centralized, hierarchical, decentralized, and hybrid, each with its own philosophy.

4.1 Centralized architectures

Theoretically, it's possible to have centralized architectures that can coordinate an entire team

Table 2 Networking requirements of Top-rated MRS Applications

Topic	Application	Bandwidth	Mobility	Delay tolerance	Range	Security	Scalability	Reliability	Reference
Box Pushing and Containers	Warehouse, Shipyard or airport management	L	M	H	L	L	M	H	[25]
Exploration	Search and rescue-disaster areas – cave and mines – map building	M	M to H	L	M	L	L	M	[26-28]
Satellite Formation	Starlink satellites	H	H	L	H	H	M to H	H	[35]
Military Use	parameter monitoring and patrolling – Landmine clearance	L	M	M	L	H	M	H	[31]
Environment Sensing	Forest fire detection	L	L	H	M	L	H	H	[29-31]
Mechanized Agriculture	Vineyard – lawn mowing – Seed drilling, planting , Weeding, crop spraying and Harvesting	L	M	H	M	L	L	M	[33,34]
Infrastructure	Airport runway snow removal, autonomous cars	L	M	H	L to M	M	L	H	[25]
Gaming	Soccer	M	M	L	L	L	L	L	[32]

Notes: L= Low M=Medium H= High

from a single point of control. However, in practice, such systems are often impractical because they are vulnerable to a single point of failure. Additionally, it's difficult to transmit the system's complete state back to the central location in real-time, which further complicates the issue. These types of approaches are best suited for situations where the centralized controller has a clear line of sight to the robots and can easily send group messages for all robots to follow.

4.2 Hierarchical architectures

For certain applications, hierarchical architectures are feasible. This control strategy involves each robot supervising a relatively small group of other robots, who, in turn, oversee another group of robots, and so on, until the lowest robot performs its assigned task. This approach to architecture is more scalable than centralized approaches and bears a resemblance to military command and control. However, a potential drawback of the hierarchical control architecture is its ability to bounce back from malfunctions in robots located high up in the control tree.

4.3 Decentralized control architectures

Multi-robot teams commonly use decentralized control architectures, where each robot relies solely on its local knowledge to take actions. This approach is preferred because it enhances resilience to failure, as no robot is dependent on another for control. However, achieving overall cohesiveness in such systems can pose a challenge since the local control of each robot must account for the higher-level objectives. Modifying the behavior of individual robots can be complicated if the objectives change.

4.4 Hybrid control architectures

Hybrid control architectures integrate local and higher-level control methods, providing a balance between robustness and the capacity to direct the entire team's actions using global goals, plans, or control. Hybrid architectures are widely used in various multi-robot control approaches.

5 MRS Networking Protocol Issues and Requirements

In a multi-robot system, selecting the routing and networking protocol involves various criteria that can impact the network's overall performance. There is no universal solution for choosing the appropriate combination of variables since it depends on the application's specific needs. Hence, the recommended approach is to identify the essential performance indicators and optimize the relevant metrics to align with them. This ensures the network is tailored to meet the requirements of the application.

5.1 Modularity for Scalability

Scalability hinges on modularity. In distributed systems, it's essential to construct the network using relatively compact, self-contained modules to ensure its scalability. Additionally, we must specify how these modules' instances interact with each other to enable the network's horizontal scalability with minimal overhead and reconfiguration expenses. If we build the network around a sizable central unit, it will inevitably compromise connectivity and limit the range, curtailing the number of units (robots) that can join the network.

5.2 Computational Complexity

Routing is a significant networking component that can involve significant computational complexity. Various factors impact the computational complexity of the routing protocol, such as its synchronicity or asynchronicity, and whether processing information is single-threaded or multi-threaded. Consequently, some routing protocols demand greater computing power than others. A faster, multi-threaded CPU will increase data transfer speed, but also raise energy consumption and the cost per unit. Thus, there's always a cost-benefit tradeoff. Whenever possible, it's advisable to prioritize low-performance, simple routing protocols over high-performance, speed-optimized protocols, particularly for non-mission-critical applications. Doing so lowers unit costs, allowing for deploying redundancy and high availability at reduced costs.

5.3 Simultaneous Localization and Mapping (SLAM)

Real-time accurate localization is essential for multi-robot systems to avoid redundant operations and optimize data collection. However, as you would expect, it will add a cost overhead to the network, whether it is by adding GPS module to the UAVs for outdoor, unrestricted applications, or by deploying positioning routers across the field for indoor, restricted applications. The quality of the GPS module, or density of the router distribution can affect the precision of the localization, and thus it needs to be adjusted to the density of robots deployed per grid unit to optimize for collection and avoid collision.

5.4 Required Bandwidth

Building upon the previous criterion, if the traffic density was increased above a certain level, this can lead to congestion, collision, and interference. To avoid such a situation, the single-unit bandwidth can be adjusted to fit the suggested configuration.

5.5 Reliability

Network reliability and data integrity are key for a good number of MRS UAV applications, and in such cases, there is very low tolerance for network interruption, and transmission errors. This requires the MRS networks to have high availability through redundancy, as well as deploying active-passive or active-active disaster recovery depending on the application to secure failover in case of failure of primary nodes or sinks.

5.6 Connection to control center

Robots in an MRS system must communicate with their control center through the corresponding sinks. Proper Choice of QoS and other networking parameters is important for the R2R and R2I traffic. Smooth integration of the two types of systems must be ensured.

5.7 Mobility

Mobility is a very important factor that needs to be considered when working with MRS. Depending on the application, the degree of mobility can vary. From low mobility and high precision as in landmine detection systems, search and rescue missions, or oil pipeline fracture detection, or high mobility and low precision as in fire monitoring, spatial surveying, or anomaly detection. Therefore, the routing protocol used by the MRS needs to be chosen in line with the mobility specifications in order not to hinder the operation due to slower data transfer rates and localization problems.

5.8 Security

Regardless of the MRS, the application that is involved is a valuable target for attacks. These attacks can be passive or active. Examples of passive attacks can be eavesdropping, or traffic analysis, while ones of active attacks can be replay, masquerade, modification of message content, and denial of service (DoS). Regardless of the type of attack, at the least, it will incur extra costs of operation, and at most, it will jeopardize the whole mission and threaten the whole system. In all cases, the outcomes are undesirable. It is critical to make sure data is encrypted properly at rest and transmitted over secure protocols while in transit. Many tools are available to secure the data from locking the system behind a VPN, ensuring proper tunneling between connected units, taking a continuous signed heartbeat from each registered unit. Depending on the application, security should be prioritized according to the previously discussed criteria.

6 Case Study: Optimal Starting Position of an additional UAV

A number of research studies were carried out to investigate the potential uses, features, and issues associated with Wireless Sensor Networks (WSN) [15-19], as well as the utilization of robotics and UAVs [20-21]. With significant technological progress, sensors are now equipped with data processing capabilities, enabling on-board intelligence. Recent literature has focused on design considerations for WSN, which primarily include accessibility, scalability, reliability, production costs, networking protocols, energy consumption, data transmission, processing capabilities, communication range, and autonomy.

One prevalent architecture for Wireless Sensor Networks (WSNs) utilizes a hierarchical tree structure where several sensing nodes (SN) are clustered around a central relay node (RN). The RN takes responsibility for collecting, summarizing, and sometimes processing the sensor data before delivering it to the end-user [14]. Meanwhile, more sophisticated WSN architectures aim to enhance transmission speed and dependability by incorporating mesh routing, multi-hop, and adaptable/dynamic topologies.

Several recent publications, research efforts, and commercial products have been dedicated to the deployment of Wireless Sensor Network (WSN) [16] and Unmanned Aerial Vehicle (UAV) [22] systems. Our case study contributes to this field by offering a focused analysis and emphasizing the essential collaborative aspects between these two elements, as well as the methods for intelligent data processing, computation, communication, and control. The primary objective of this case study is to investigate the optimal starting position for a supporting UAV named UAVS in a designated area that is already being serviced by two other UAVs (UAV1 and UAV2). We examine both the theoretical and experimental approaches, beginning with the latter, as it builds on the prior section's discussion and sets the stage for a more in-depth theoretical analysis.

6.1 Model Description

In our application, it is crucial to establish a cooperative relationship among the units in the Multi-Robot System (MRS). Specifically, individual robots (in this case, UAVs) should optimize their trajectory planning to minimize redundant work and interact with other robots in a collaborative, rather than competitive, manner.

Typically, the MRS communicates through a Wireless Sensor Network (WSN) with a multi-dimensional topology, which means that it is divided into levels, each with a distinct mode of operation and communication. Nodes can be deployed in a predetermined geometric pattern (such as linear, clustered, or geometric networks) or randomly scattered throughout the monitored area. Our research focuses on data collection using UAVs in a WSN and explores the use of one, two, and four robots.

The architecture we employ adheres to the formulation and assumptions outlined in the **referenced paper**. It comprises four components: **(1) Sensor Nodes (SNs)**, **(2) Relay Nodes (RNs)**, **(3) Unmanned Aerial Vehicles (UAVs)**, and **(4) Sinks**. To move data from the SNs to their corresponding RNs, we employ a Periodic Push Model, while we utilize a Pull Model to move data from the RNs to the UAVs.

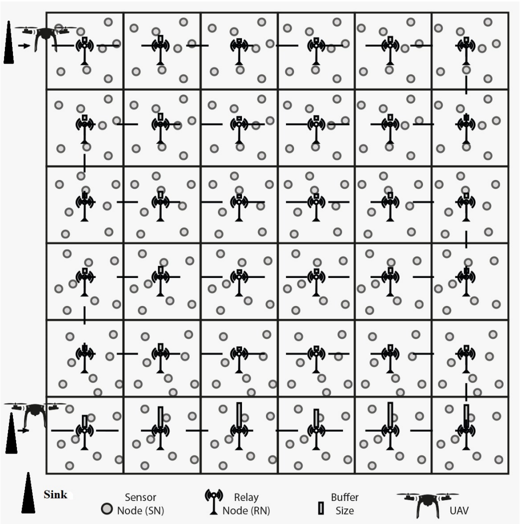

Figure 3: Model Visualization

6.2 Experimental Approach

The central idea is to enable UAVS to provide assistance to UAV1 and UAV2 in covering a designated zone if they fall behind in their data collection. Specifically, we employ a greedy algorithm and vary the starting position of UAVS across the entire range that extends between UAV1 and UAV2 upon its arrival.

Following our earlier discussion, we recommend adopting an asymmetric approach to data collection as it is most effective in dealing with non-uniform data distribution. We address this issue by considering a problem in which the non-uniformity of data distribution is defined by the occurrence of an event in a specific section of the field, and it is characterized as follows:

- Magnitude: Seven times the average of data distribution.
- Span: Second half of the serviced zone.
- Direction: UAVS is set to move towards UAV1.

To achieve statistical stability, the simulations' results related to the starting position are averaged over 200 runs.

In our discussion, we will be using the following notation:

- N: Time of dispatching of UAVS.
- M: Time at which UAVS starts collection in the targeted zone.
- P: M - N : Duration between M *and* N
- R: Ratio of D at the assigned starting relay for UAVS

- $R*$: Ratio of D at the optimal starting relay for UAVS
- D: Distance between UAV1 and UAV2
- $D1$: Distance between UAVS and UAV1
- $D2$: Distance between UAVS and UAV2
- Clearing Time: Flying Time + Collection Time

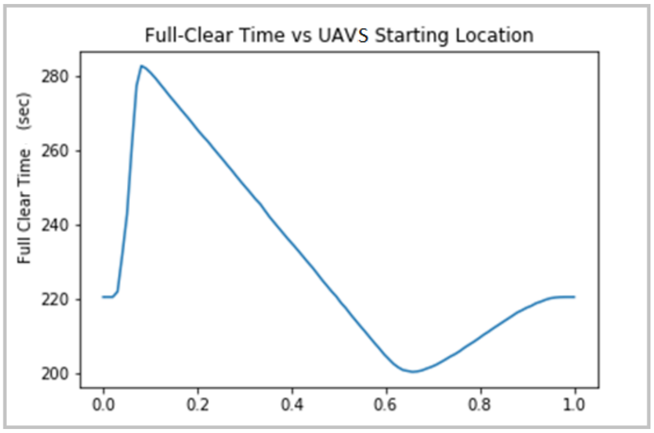

Figure 4: Starting Position of Supporting UAV

A simulation was performed to determine the optimal starting position for UAVs along the D axis. The distance between relays was used as the distance step, and the distance was normalized to a range between 0 and 1. A value of 0 indicated a position directly adjacent to UAV1, while a value of 1 indicated a position directly adjacent to UAV2. The simulation measured the duration (in seconds) required for the full clearance. The results of the simulation are presented in figure 4. Upon examining figure 4, it is observed that when UAVS starts very close to UAV1 (with a ratio of 0.0 or greater), completion time is one of two possible outcomes:

Examining fig.4, we see that when UAVS is set to start at a very close proximity to UAV1 (ratio 0.0+), the completion time is one of two cases:

- At worst equivalent to the symmetric case, where UAVS reaches the assigned relay before UAV1, and thus both sign off due to meeting up, or
- At best equivalent to the asymmetric case, where either:

  - UAVS reaches the assigned relay after UAV1 has started collecting data from it and thus signs off automatically, and UAV1 continues collection until it meets UAV2, or

  - UAVS reaches the assigned relay before UAV1 but continues collection in the opposite direction (out-of-scope scenario based on the assumptions above, but worth mentioning to justify why it was ruled out)

As the starting position shifts away from UAV1, the full clear time remains constant until duration P is strictly greater than the clear time of UAV1 from its location at time equal $N_t = N$ to relay $R - 1$, the relay just before the one UAVS is assigned to start collecting in the zone.

With the above stated condition, $D1$ is negligible. In other words, UAVS reaches the assigned relay near UAV1, and thus both sign off due to meeting up, leaving UAV2 to complete the collection of $D2$, which is approximately equal to D in this case by itself. This is similar to the symmetric case.

As $D1$ widens, the completion time starts dropping until the ratio R reaches the optimal value $R*$, where relays in $D1$ and $D2$ are cleared at approximately the same time.

As the ratio increases post $R*$, and $D2$ keeps on shrinking, the completion time starts an upward trend caused by having an amount of data in $D1$ more than double the amount of data in $D2$. This upward trend terminates at the same clear time of ratio = 0.0+ due to similar conditions, where UAVS and UAV2 meet, and only one of them continues the collection while the other signs off.

We observe a slope difference between the descent and the ascent; the slope of the descent is double the slope of the ascent. This is due to the fact that two UAVs are clearing $D1$ while one is clearing $D2$.

The purpose of this part of the case study is to find $R*$ and mininmize the full clear time.

We assume that all three UAVs (UAV1, UAV2 and UAVS) will be collecting data from the event zone from $time = M$ onwards, and thus have the same clearing speed.

In such a case, D should be split over three, where each UAV will clear a third of the range, and with UAVS starting at relay R and moving towards UAV1. The optimal starting relay $R*$ is located two-thirds of the way between UAV1 and UAV2, and that is what fig.4 illustrates graphically.

6.3 Theoretical Approach:

The experimental approach can satisfy the discussion of the considered case study with the assumptions stated above, but in order to generalize the analysis and monitor the effect of multiple variables over the optimal starting point, a more structured theoretical approach is needed, and is offered in this section.

We reduce the problem into a length D with an event occurring on one of its edges, scaling the average data per relay with a certain magnitude, which is to be discussed later. For our subsequent analysis, we use the following:

- NR_D: Number of Relays in D
- α: Ratio of D over which the event is spread
- β: Ratio of D at which UAV_{event} will sign off

- ETD_D: Estimated Total Data in D
- $\text{AD}_{/R_e}$: Average Data per Relay - Event
- $\text{AD}_{/R_{ne}}$: Average Data per Relay - Non-Event

Consequently, we have:

$$ETD_D = [\alpha * AD_{/R_e} + (1-\alpha) * AD_{/R_{ne}}] * NR_D \quad (1)$$

and the optimal data distribution between the UAVs is where each UAV collects an equal portion of the estimated total data in D (ETD_D). So,

$$DataLoad_{UAV_{e/ne}} = DataLoad_{UAV} = \frac{ETD_D}{3} \quad (2)$$

While solving for β, we assume:

$$AD_{/R_e} > AD_{/R_{ne}} \quad (3)$$

Solving for the optimal distribution requires that:

$$2 * DataLoad_\beta = DataLoad_{1-\beta} \quad (4)$$

$\text{AD}_{/R_{ne}}$ can be assumed as a unit value $AD_{/R_{ne}} = 1$, which in turn leads $AD_{/R_e}$ to be of a certain multiplier (m) of this unit value $AD_{/R_e} = m$, where:

$$1 < m < \infty \quad (5)$$

The following discussion considers three possibilities:

- $\beta = \alpha$
- $\beta < \alpha$
- $\beta > \alpha$

Subsequently, we investigate each one.

6.3.1 $\beta = \alpha$

$$DL_\beta = DL_\alpha = \beta * AD_{/R_e} * NR_D \quad (6)$$

and

$$DL_{1-\beta} = DL_{1-\alpha} = (1-\beta) * AD_{/R_{ne}} * NR_D \quad (7)$$

substituting (6) and (7) in (4), we have:

$$2 * \beta * m = 1 - \beta \quad (8)$$

solving for β:

$$\beta = \frac{1}{2 * m + 1} \quad (9)$$

examining the extremities of m in (9), we have:

- $m \to 1 \implies \beta \to 1/3$
- $m \to \infty \implies \beta \to 0$

6.3.2 $\beta < \alpha$

$$DL_\beta = \beta * AD_{/R_e} * NR_D \quad (10)$$

and

$$DL_{1-\beta} = [(\alpha - \beta) * AD_{/R_e} + (1-\alpha) * AD_{/R_{ne}}] * NR_D (11)$$

substituting (10) and (11) in (4):

$$2 * \beta * m = (\alpha - \beta) * m + (1 - \alpha) \quad (12)$$

solving for β, we get:

$$\beta = \frac{1}{3 * m} + \frac{m-1}{3 * m} * \alpha \quad (13)$$

examining the extremities of (13), we have:

- $\alpha \to \beta$
  $m \to 1 \implies \beta \to 1/3$
  $m \to \infty \implies \beta \to 0$
- $\alpha \to 1 \implies$ Event covering all of D
  $m \to 1 \implies \beta \to 1/3$
  $m \to \infty \implies \beta \to 1/3$

6.3.3 $\beta > \alpha$

$$DL_\beta = [\alpha * AD_{/R_e} + (\beta - \alpha) * AD_{/R_{ne}}] * NR_D \quad (14)$$

and

$$DL_{1-\beta} = (1-\beta) * AD_{/R_{ne}} * NR_D \quad (15)$$

substituting (14) and (15) in (4), we have:

$$2 * \alpha * m + (\beta - \alpha) = (1 - \beta) \quad (16)$$

solving for β, we get:

$$\beta = \frac{2}{3} * (1-m) * \alpha + \frac{1}{3} \quad (17)$$

examining the extremities of (17), we have:

- $\alpha \to 0 \implies \beta \to 1/3$
- $\alpha \to \beta$
  $m \to 1 \implies \beta \to 1/3$
  $m \to \infty \implies \beta \to 0$

7 Conclusion

To sum up, the core concept of this paper is to study the effect of allowing an additional UAV to support a lagging zone. It was noted that it is essential to take into consideration the starting position of the supporting UAV to achieve optimality.

With an experimental study of the starting position, we concluded that the remaining load of the zone should be split equally over the three UAVs. This split depends on the assumption of the data load spread across the zone, which is extrapolated from the trend surveyed thus far.

When conducting a theoretical study of the optimal starting position, we introduced a new variable which is the multiplier of the data load in the event area, along with the ratio of the event spread considered in the experimental part. We came to a similar conclusion when we fixed the multiplier at 1, which is that the optimal starting position is at one-third the distance from the UAV_{event} and converges to zero as we increase the multiplier towards infinity.

Future work can examine the number of extra needed supporting UAVs with respect to the currently deployed UAVs to achieve an optimal balance between the cost of idle supporting UAVs and idle UAVs post full clear.

Another area of improvement would be the modes of collaboration between zones, limitations imposed by the zone distribution, and the capacity to readjust zone allocation post deployment in a distributed approach.

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