Geese Inspired Unmanned Aerial Vehicle Swarm Energy Aware and Harmonisation Scheme

by

Marang Mbaakanyi

Registration No: 16100167

Department of Computer Science and Information Systems,
Faculty of Science,
Botswana International University of Science and Technology

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Supervisor(s): Dr Dimane Mpoeleng

Department of Computer Science and Information Systems,
Faculty of Science, BIUST
mpoelengd@biust.ac.bw, +267 72972059

Signature ______________________ Date: 10/Aug/2021

August, 2021

Declaration of Authorship

Statement by Author

I, Marang Mbaakanyi, declare that this dissertation titled **“Geese Inspired Unmanned Aerial Vehicle Swarm Energy Aware & Harmonisation Scheme”** is my own original work and that it has not been presented and will not be presented to any other university for a similar or any other degree award.

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Marang Mbaakanyi

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The research in this dissertation was prepared in partial fulfilment of the Botswana International University of Science and Technology regulations and requirements for the award of a Master of Science Degree in Computer Science under my supervision and certify to the best of my knowledge that this is the solitary work of Marang Mbaakanyi.

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Dr. Dimane Mpoeleng

(Supervisor)

Date: 15/March/2021

Signature: ____________________

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Dedication

This work is dedicated to my family. Being a wife, a first time mother and a student was not really easy but because of the support I received from my loving husband, my daughters, my parents and siblings I became even stronger, better and more fulfilled than I could have ever imagined. I dedicate this dissertation to them.

Marang Mbaakanyi

Abstract

Over the past years the use of unmanned aerial vehicle (UAVs) swarms has increased drastically. Multiple cooperative unmanned aerial vehicles have introduced numerous possibilities of performing several tasks, saving time, money and impediments. However, even though they are making life easier unequal responsibility propagation amongst unmanned aerial vehicles in a swarm is the biggest detriment that has resulted in inconsistent battery consumption. Missions have failed as a result of unequal propagation of responsibilities as some unmanned aerial vehicles in a swarm work more than the others hence consuming more battery and in turn leaving the swarm before the completion of the designated mission, which then compels the remaining unmanned aerial vehicle to abort the mission. In response to the aforementioned disadvantage, this dissertation presents an energy aware and harmonization algorithm which will ensure equal responsibility propagation safeguarding that battery is drained evenly amongst the unmanned aerial vehicles.

This algorithm sets its foundation on bio-inspiration, specifically adapting the same biological makeup of geese because they share responsibility when they fly as a flock. In this algorithm, the leader-follower reciprocation mechanism is integrated with the energy-aware computational movement to facilitate the rotation of the leadership role based on the real-time update of the available battery in each unmanned aerial vehicle in the swarm. These features ensure an accurate definition of the rotation sequence with knowledge of when and how to rotate. This novel proposed algorithm was tested for feasibility and validity by field experiments. The equal propagation of responsibilities allocated to each unmanned aerial vehicle proved to enhance the battery consumption consistency of unmanned aerial vehicles in a swarm by 98% resulting in an increase in formation flight range as they were able to reach lap 4 and lap 6 as a swarm compared to lap 2 without the algorithm. Our Energy harmonization algorithm is adaptable to any similar swarm or group based systems that hinge their integrity and correctness on the consistent consumption of energy.

Keywords

Unmanned Aerial Vehicles (UAV), Swarm, Battery consumption, equal responsibility propagation, energy-aware, harmonization

Table of Contents

List of Figures

List of Tables

List of Equations

Glossary

Terms	Definition
Equal Responsibility Propagation:	refers to sharing roles evenly
Virtually rotating:	refers to changing leadership roles in the swarm
Battery drained evenly:	refers to an equal battery consumption
All or nothing missions:	engaging the entire swarm formation in a mission (all UAVs in use) and if any Unmanned Aerial Vehicle is lost then the whole mission is aborted
Energy-aware:	being cautious about the energy available. In terms of this research this is having knowledge about the existing or available battery.
Energy Harmonization:	is when the energy is balanced amongst the UAVs in a Swarm

List of Abbreviations

BIUST	**Botswana International University of Science and Technology**
UAV	**Unmanned Aerial Vehicle**
JS	**Java Script**

Introduction

1.1 Introduction

The use of Unmanned Aerial Vehicles (UAVs) – also referred to as drones have become not only of paramount importance to modern day warfare but a critical, substantial necessity. These sentiments have been echoed by Xueping *et al.* [1] and Wei *et al.* [2] who say, the aforementioned aircraft which does not require an on-board pilot has revolutionised from the execution of a solitary task to execute various missions like surveillance, monitoring, acquiring, tracking and destruction of targets with the use of advanced technologies.

Unmanned aerial vehicles have transformed from making use of a single entity to using multiple entities referred to as 'unmanned aerial vehicle swarm'. According to Mamta and colleagues [3] a swarm is a collection of interacting and cooperating individuals working in unison to achieve a common goal. Xueping and colleagues [1] state that an unmanned aerial vehicle swarm is a group of vehicles that work collectively, collaborating and communicating with each other to accomplish an objective. Research shows that having more than one unmanned aerial vehicle assigned to a mission dramatically increases the probability of success [4]. The advantages of a swarm of unmanned aerial vehicles is that: they can collect data from several vantage points concurrently [5], performance is improved as tasks are executed efficiently [3], there is task enablement and also the distributed sensing is much wider leading to successful flights. A swarm of unmanned aerial vehicles can be used for search and rescue as they can travel over a large area faster than a single unmanned aerial vehicle [1]. The other applications of unmanned aerial vehicle swarms are to help track and stop poachers, land survey, weather data collection, capturing huge image mosaic and many other mission based flights.

In spite of all the benefits associated with unmanned aerial vehicle swarm. There are limitations of unmanned aerial vehicle swarm, including erratic battery consumption which has limited their infiltration into everyday life [6]. The disparity has resulted in other unmanned aerial vehicles leaving the swarm earlier than the others because the battery had run out. This led to a disruption of data collection since a collection task is assigned to each unmanned aerial vehicle and thus resulting in unsuccessful swarm missions. According to Duan and colleagues [7], the primary cause of inconsistent battery consumption amongst unmanned aerial vehicles in a swarm is unequal role allocation [7]. In an unmanned aerial vehicle swarm, one unmanned aerial vehicle leads while one or more unmanned aerial vehicle(s) follows the leading aerial vehicle, this arrangement is referred to as a leader-follower formation [8], [9]. The leader unmanned aerial vehicle is allocated more tasks to do than the follower unmanned aerial vehicle(s) [10], leading to more battery being exhausted by the leader unmanned aerial vehicle as compared to the follower unmanned aerial vehicles [7], [11]. This means the leader unmanned aerial vehicle will leave the swarm sooner than the following unmanned aerial vehicle and will directly fly back to the deployment location and land resulting in the termination of the whole mission [12].

The reason for the termination of the mission is that in an unmanned aerial vehicle swarm the leader connects the follower unmanned aerial vehicles with the base station, it is allocated the role to direct and even convey commands from the base station with the other unmanned aerial vehicles. If it breaks out of the swarm, the whole mission is aborted because there will be no unmanned aerial vehicle relaying information on where they are going or what they are supposed to do. (The termination of the whole swarm applies to any unmanned each unmanned in the swarm as each unmanned aerial vehicle has a major role to play in the swarm for the mission to be successful [13]). This then limits the flight scope of the whole unmanned aerial vehicle swarm [7], [14]. Figure 1 displays a summary of limitations of an unmanned aerial vehicle swarm which are a result of lack of harmonization which is the major problem in unmanned aerial vehicle swarms.

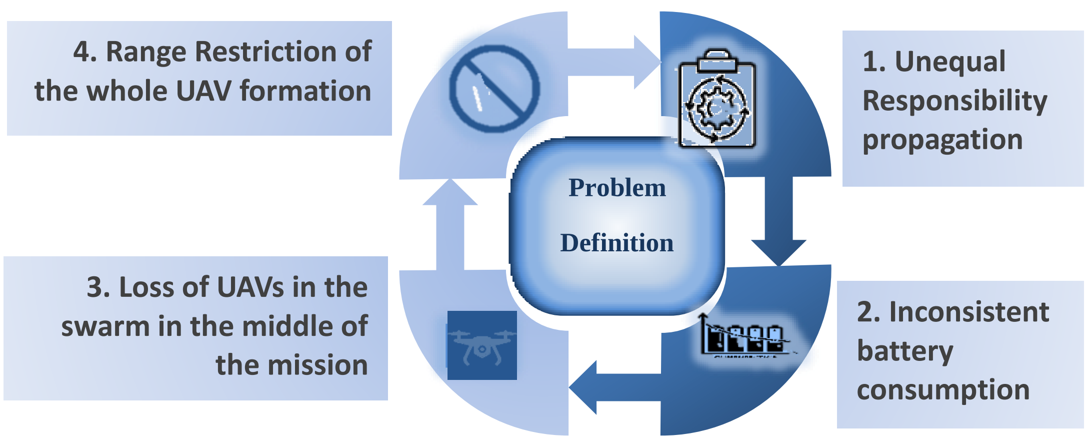


Figure 1: Diagram showing problem definition framework interpretation

In response to the above-mentioned predicaments, this study sets its foundation in the application of nature by adopting the same behavioural capacities of geese in unmanned aerial vehicles. Geese, which are also known as migrating birds fly in a rotational leader-follower formation in order to preserve energy so that they complete their mission together [14]–[16]. When the leader tires it rotates back into the formation and another goose becomes the leader [15]. This is because there is more effort needed at the front than at the back [15]. The same notion has been incorporated in this study by developing geese inspired unmanned aerial vehicle swarm energy-aware and harmonisation algorithm. The algorithm: 1. Adopts the leader-follower formation control where one unmanned aerial vehicle is assigned as a leader and the other unmanned aerial vehicles as followers, 2. Ensures equal responsibility propagation by virtually rotating unmanned aerial vehicles safeguarding that battery is drained evenly amongst the unmanned aerial vehicle s leading to the success of the designated mission, 3. Integrates the energy-aware computation with the leader-follower formation mechanism in order to get the real-time update of the available battery in order to know when to facilitate the rotation between the leader and follower.

The energy-aware and harmonisation algorithm certifies that the unmanned aerial vehicles in a swarm start the mission together and end the mission as a group. It focuses on an all-or-nothing mission, meaning either fully or not at all operative. This means it engages the entire swarm formation in a mission (all unmanned aerial vehicles in use) and if any unmanned aerial vehicle is lost, then the whole mission is aborted. When the mission commences a leader unmanned aerial vehicle is chosen and the remaining unmanned aerial vehicles become followers, both the leader and follower unmanned aerial vehicles are allocated tasks as per their role. As the mission continues the battery level of all the unmanned aerial vehicles is in constant check (at each threshold interval) and if there is a follower unmanned aerial vehicle with the highest battery level than that of the leader unmanned aerial vehicles they will then switch responsibilities (the preceding leader becomes the follower and the follower becomes the leader). The rotation continues in order to safeguard that there is equal responsibility propagation amongst the unmanned aerial vehicles, ensuring that the battery is drained evenly because the survival of each drone is critical and fundamental to the accurate performance of the mission [9]. The energy-aware and harmonization feature is what makes the algorithm distinctive. This feature ensures the workload is shared evenly in all the unmanned aerial vehicles in a swarm and also it alerts the base station to be aware of when to execute the rotation threshold sequence, allowing the unmanned aerial vehicle with more battery than the others to be the leader.

Figure 2 shows a summary of how this research was conducted. It explains how the necessary data and information to address the research objectives were collected, presented and analyzed. The first segment shows the algorithm development phases which were used labelled as: 1. Problem Identification and Analysis 2. Design and development 3. Implementation and Evaluation. The second segment shows the objectives that were being addressed. The third segment shows the approaches that were followed in addressing the set objectives. The last segments show the tools that were used to fulfil the sets methods. This methodological approach was used to produce a generalizable understanding of responsibility propagation in order to make available an archetypal sample that can be replicated by other researchers. The other reason for using this methodology was because the research questions needed to be resolved and fulfilled by carrying out experiments, making this a suitable approach to use.

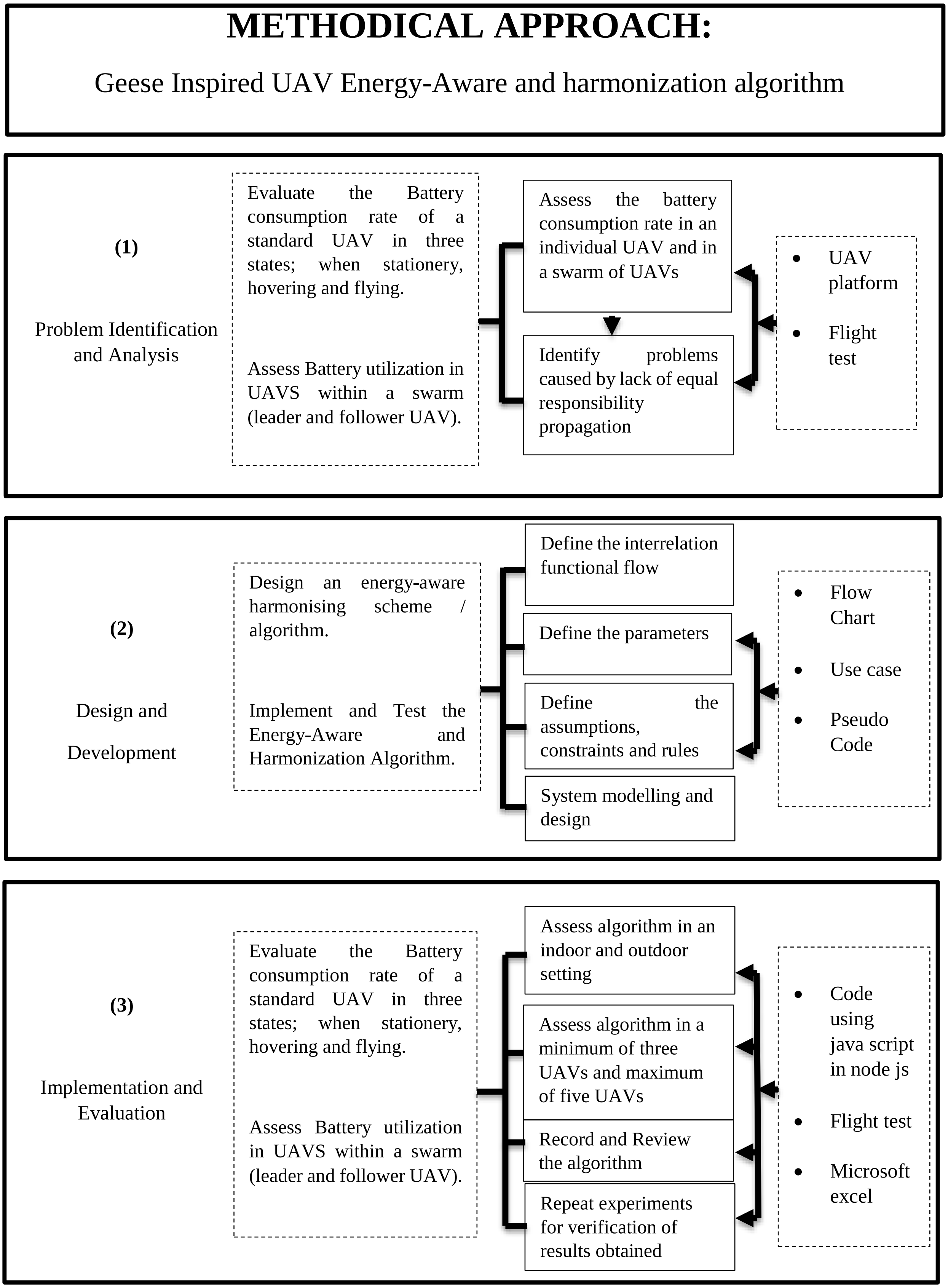


Figure 2: Summary of the methodological approach

1.1.1 Motivation

This segment discusses the three factors that motivate the research undertaken. First, there is a dearth of research on unmanned aerial vehicle swarm energy-aware and harmonization algorithms [17]. Second, there is a need to explore methods that can increase the success rate of unmanned aerial swarm missions. Third, there need to improve the battery inconsistency in unmanned aerial vehicle swarms. This research provides numerous benefits that address the problem area. It enables the valuation of the rate at which battery is consumed in a single unmanned aerial vehicle and also numerous unmanned aerial vehicles in a leader-follower formation. This allowed us to verify if unequal sharing of responsibilities was indeed the primary cause of battery consumption inconsistency as stated by Duan and colleagues [7]. It also enabled us to come up with ways on what can be done to solve the confirmed problem of unequal responsibility propagation and how the solution can be incorporated which in our case is the development of the Geese Inspired UAV Swarm Energy-Aware and Harmonisation Algorithm. Furthermore, we evaluated if indeed the algorithm has solved the problem of unequal responsibility propagation by the experiments carried out.

1.1.2 Contribution

This segment focuses on the contributions of this dissertation.

1. The geese inspired UAV energy aware and harmonization algorithm is validated in a practical outdoor experiments, unlike the previous studies which only proposed theoretical solutions, all the proposed methods will be tested in a practical setup not simulators.
2. The proposed algorithm ensures battery is balanced in all the unmanned aerial vehicles by rotating responsibilities of leading and following. This attribute ensures that no UAV is lost due to low battery during mission undertaking. If in case the battery becomes low then it will reflect in all the UAVs and they will all land for recharging then continue where they left of as a swarm.
3. The algorithm has an attribute referred to as a threshold, this feature is what makes the proposed algorithm distinctive. The threshold alerts when each rotation should be triggered. After calculating the threshold the resulting figure is subtracted from the

battery percentage of the leader, then rotation point is established and when the leader reaches the threshold the rotation sequence is executed.

4. The other contribution is that within the proposed algorithm there is an energy-aware feature which provides real-time update of the available battery in order to know when to facilitate the rotation between the leader and follower. This feature is what will influence the continuation of the swarm or discontinuation looking at the battery-level of each UAV in swarm without blindly flying the UAVs.

This Chapter is subsequently organized as follows. In Section 1.2, we define the problem account. In Section 1.3, we present the research objectives so as to have a well-defined picture of what was achieved in this research. In Section 1.4, we present the research questions. In Section 1.5, we present the significance of the research. In Section 1.6, we present the dissertation structure. These Sections are then followed by the summary of Chapter 1 in Section 1.7.

1.2 Problem Statement

Kai Li *et al.* [17] substantiates that the problem of balancing energy consumption amongst the unmanned aerial vehicles is there and verifiable and that there is a need to resolve it. Duan and colleagues [7] further state that the lack of balanced energy consumption is a result of unequal responsibility propagation amongst unmanned aerial vehicles in a swarm. Unmanned aerial vehicle swarm missions have failed as a result of losing some unmanned aerial vehicles in the process of execution because of inconsistent battery consumption as a result of unequal responsibility propagation because some unmanned aerial vehicles are allocated more tasks than others. In a leader-follower formation, the leading unmanned aerial vehicle uses more battery than the follower unmanned aerial vehicles because it acts as a gateway for the other unmanned aerial vehicles in a swarm to the ground station [7]. This means a leading unmanned aerial vehicle will use more battery and then leave the swarm before it completes its mission leading to a failed operation. This has been regarded as the biggest problem faced thus far in unmanned aerial vehicle swarm missions [8].

Therefore, the problem that has been addressed in this study is the lack of comparable responsibility propagation which leads to inconsistent battery consumption of unmanned aerial vehicles in a swarm. Duan *et al.* [7] state that this problem causes swarm missions to fail as some unmanned aerial vehicles(drones) run out of energy sooner than the others, hence, leaving the formation in the process of execution without completing the designated missions. Duan and colleagues further ague that this restricts the range of the whole Unmanned Aerial Vehicle formation leading to erroneous information collection [7].

1.3 Research Objectives

The overall research objectives that encompass the scope of this dissertation are summarized as follows:

1.3.1 Main Objective

1. Develop and evaluate a geese inspired unmanned aerial vehicle swarm energy-aware and harmonisation algorithm: The overall objective of this research is to build and assess an algorithm which addresses lack of comparable responsibility propagation which leads to inconsistent battery consumption of unmanned aerial vehicles in a swarm.

1.3.2 Specific Objectives

1. Evaluate the battery consumption rate of a standard UAV in three states; when stationery, hovering and flying.
2. Assess battery utilization in UAVs within a swarm in a leader and follower formation.
3. Design an energy-aware harmonising scheme / algorithm.
4. Implement and Test the Energy-Aware and Harmonisation Algorithm.
5. Evaluate the algorithm Energy-Aware and Harmonisation Algorithm.

1.4 Research Questions

1.4.1 Main Research Question

1. How is the development and evaluation of a geese inspired unmanned aerial vehicle swarm energy-aware and harmonisation algorithm going to be carried out in order to addresses the problem of lack of comparable responsibility propagation in UAV swarms.

1.4.2 Specific Research Questions

1. At what rate does a standard UAV consume battery when stationery, hovering and flying?
2. How much battery is utilized by UAVs within a swarm in a leader-follower formation?
3. What is the systematic plan of developing the Geese Inspired UAV Swarm Energy-Aware and Harmonisation Algorithm?
4. How is the Geese Inspired UAV Swarm Energy-Aware and Harmonisation Algorithm going to be implemented?
5. How is the Energy-Aware and Harmonisation Algorithm evaluated?

1.5 Significance of the research

This research presents a geese inspired unmanned aerial vehicle energy-aware and harmonization algorithm that will endure equal responsibility propagation by rotating unmanned aerial vehicles in a swarm safeguarding that battery is drained evenly amongst the unmanned aerial vehicles. In our algorithm development, we adopted the already existing leader-follower formation control where one unmanned aerial vehicle is assigned as a leader and the other unmanned aerial vehicles as followers and integrated it with the energy-aware and harmonization feature that we designed, making it a significant contribution to the body of knowledge of computer science. It has been called an energy-aware and harmonization algorithm because the aim is to equally share responsibilities among unmanned aerial vehicles in a swarm by rotating unmanned aerial vehicles based on the acquired real-time knowledge of the available battery in each unmanned aerial vehicle. This algorithm manages, disseminates and allows unmanned aerial vehicles to collaboratively share roles.

1.5.1 Practical Applications of the algorithm

This algorithm is not only of significance to the scientific body of Knowledge of computing but also to the nation as a whole. There are various applications of this algorithm such as: search and rescue missions, precision farming in agriculture missions, and many other applications. In this research we focus on the application of capturing mosaics.

In capturing huge mosaics unmanned aerial vehicles in a swarm cooperatively aerial image to create an overview picture. The capturing of huge mosaic pictures can be done when one needs to view the land from a high viewpoint when there were disasters. There is a need to see how much the area has been affected. It can be for capturing change or other important applications. Figure 3 shows the simulation of how 16 UAVs captured 104 images and then putting them together to make a huge mosaic. The first image a) shows initial state points, simulation of 16 UAVs with 104 captured images which are then combined and processed producing b) The topology captured by the UAVs [18].

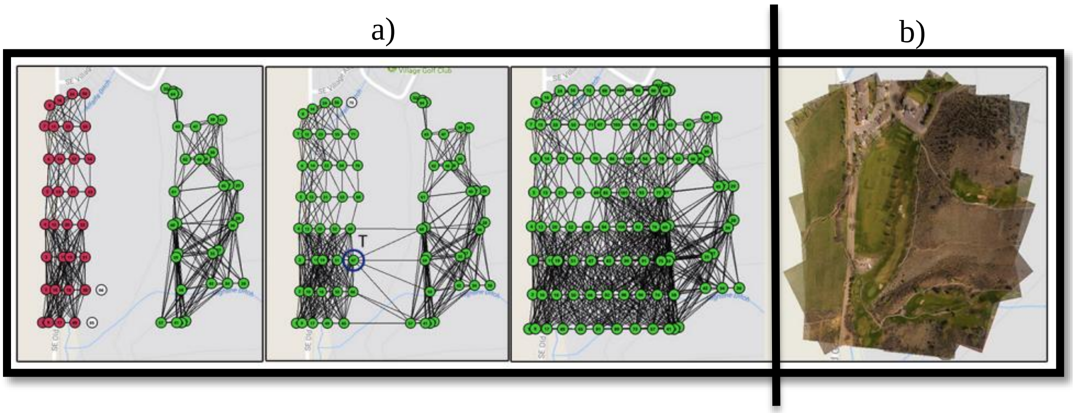


Figure 3: Shows the simulation of how 16 UAVs captured 104 images and then putting them together to make a huge mosaic

The geese inspired Unmanned Aerial Vehicle swarm energy-aware and harmonization algorithm ensures that during huge mosaic capturing no UAV is lost because of reasons that it has run out of battery before other UAVs. It ensures that the battery is exhausted equally to avoid losing one or more UAV(s) during the operation. This enables complete mosaic capturing to create an overview picture.

1.5.2 Expected Outcomes

Main outcome of the study: The developed geese birds inspired unmanned aerial vehicle swarm energy-aware & harmonisation scheme. The nature inspired patented control algorithm that synchronize battery consumption in a swarm of unmanned aerial vehicles. This algorithm can be applied in several applications that have an impact on society. These include search and rescue, crime prevention, anti-poaching, disaster management, construction and land surveys.

1.6 Structure of the Dissertation

The remainder of this dissertation is organized as follows. In Chapter 2, we present the literature review. In Chapter 3, we present the methodology. In Chapter 4, we present the results and analysis of the experiments conducted. In Chapter 5, we present the conclusion, which summarizes and outlines future research improvements and recommendation of the area of research. These Chapters are then followed by References and Appendices.

1.7 Summary

The problem of lack of inconsistent battery consumption of unmanned aerial vehicles has resulted in failed swarm missions as some unmanned aerial vehicles run out of batteries in the middle of missions. This is a result of the unequal role allocated to the drones as some are given more work than the others. The objective of this study is to develop geese inspired energy-aware and harmonization algorithm in order to ensure equal responsibility propagation by rotating roles so as to ensure synchronized battery consumption. The algorithm consists of three features, being: the leader-follower mechanism and the energy-aware and harmonization approach. This features enable alertness, real-time battery update, and synchronisation and a precise rotation sequence of unmanned aerial vehicle in a swarm. In the next Chapter, we present literature review.

Chapter 2: Literature Review

2.1 Chapter Overview

This Chapter is organized as follows. In Section 2.2, we present the background of the study. In Section 2.3, we present a review of related works and the limitations of the existing works. In Section 2.4, we present the research gap. These Sections are then followed by the summary of this Chapter in Section 2.5.

2.2 Background of the study

2.2.1 Geese

Birds are described as warm-blooded vertebrate creatures [19]. Various birds' attributes have set them apart from each other, categorizing them into different types. With over 10000 various species of birds across the world [20], attributes such as their external anatomy, behaviour, breeding and ecology differ from bird to bird. Figure 4 shows the different types of birds with unique fowl vents.

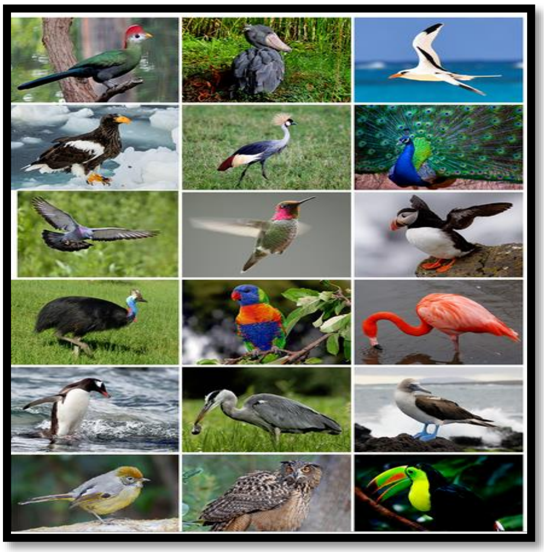


Figure 4: Different fowl vent distinguishers [24]

This research is only centred on Goose birds. Goose (also known as Geese in plural) are heavy-bodied birds that are widely recognized for their nomadic and V-formation attributes [16], [21], [22]. Geese fall into two categories which are the non-migratory and migratory geese. Non-migratory geese are those that live in an environment that has adequate food and water supply and hence do not need to migrate to any other location as their daily needs are met. On the other hand, Migratory geese are those that live in an environment that has inadequate food and water supply forcing them to be nomadic. Our research will solitary be centred on migratory geese. Figure 5 shows geese flying in a leader-follower formation also known as V-formation.

Figure 5: Snow Geese Flying in a leader-follower (V) Formation [83]

Out of all the birds that are existing, we chose to use geese birds as our focal inspiration for our algorithm. The reason for selecting geese was:

- Their Capability of maneuvering while maintaining their formation which helps them avoid collision and also helps each goose to visually see where they are going [21].
- Their Capability to travel thousands of kilometres between breeding grounds and temperate winter as a flock of geese[14], [15]
- How they collaborate by taking turns to share the responsibility of leading the flock. When the leader goose tires, it rotates back into the formation to become the follower and another goose flies to the point position and becomes the leader [21].

Migration of Geese Birds

The term migration means periodic or time to time movements. There are three different types of migration distances, there is short distance migration, medium distance and long distance migration [23]. Various Species including geese birds have been known to migrate over large distances. The journey requires them to have considerable navigational skills as they are prone to be exposed to harsh conditions throughout [24]. Geese fly between 40 and 50 miles an hour or even go to an extent of flying 400 to 500 miles per day [24]. Figure 6 shows the migration of the Canada goose. Their movement keeps pace with the progress of spring. The increase in daylight during spring triggers migration northwards.

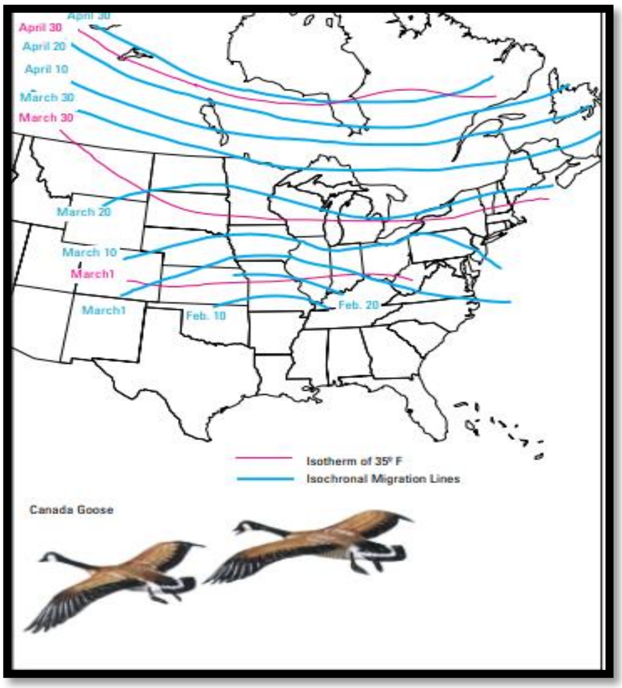


Figure 6: Shows the migration of Canada goose. [24].

Formation in Geese Birds

Geese fly together in flocks and they frequently align themselves in formations [15]. The formation portrayed by geese birds is one that allows one bird to fly in front of the flock while the rest follow. The benefits of flying in these formation is to increase aerodynamic performances, hence yielding energy saving abilities. Cutts and Speakerman [15] conducted research that showed that 2.4% of energy was saved in the formation flight of Pink-Footed Geese.

The arranged formation of 3 birds increases the distance by 25% while a formation of 25 birds advance the distances by 70% as compared to a single flying bird [25]. The second benefit shown by Beauchamp [26] is that geese that travel in flocks tend to head in the right direction more often. This can be likened to the knowledge that during migration inexperienced individuals attain an understanding of the flocks' migratory route [26], [27]. The other benefit is that flocking helps the birds to avoid collisions as each bird has visual contact with the rest of the birds in the formation and also it is aware and can see where they are headed [27]. Geese birds believe in starting a migratory mission together as a flock and ending it without losing any bird in the process, so the third benefit of moving as a group is that there is less risk of predation attack.

2.2.2 Unmanned Aerial Vehicles Swarm

Unmanned Aerial Vehicle

An unmanned aerial vehicle, commonly referred to as a drone; is a flying machine that functions without the presence of a human (on-board)[1], [2], [28]. It is usually controlled from afar (remotely) or onboard [2] as such pilot safety is not an apprehension anymore.

Swarm of unmanned aerial vehicles

Zhu *et al.* [1] define a swarm as a collection of objects or particles that are in coordination with each other. He further adds to say a UAV swarm is a group of vehicles that work together, interconnecting with each other and assisting other members of the swarm in tasks to accomplish set missions.

The definition of UAV swarm according to context of this research

A swarm is a collection of two or more drones working together and communicating with each other to achieve a specific goal. The UAVs in a swarm are given an assignment to do and they then divide it amongst themselves

The advantages of a UAV swarm are:

Scalability: A swarm of Unmanned Aerial Vehicles can increase the range coverage [29].

Workload sharing: In a swarm of UAVs the tasks allocated to them can be shared amongst the UAVs, reducing the workload and hence reducing the battery consumption [1], [30].

Task enablement: Swarm UAVs can do tasks that are impossible for a single UAV. They can be allocated different functions in one mission. By having more than one UAV assigned to a mission, the probability of success dramatically increases [30], [31].

Improved performance: Tasks are performed more efficiently. More than one UAV assigned to a mission, increases the probability of success dramatically.

Distributed action: A swarm UAVs can work in different places at the same time. This enables them to be able to collect data from multiple vantage points simultaneously.

Application of Unmanned Aerial Vehicles

Unmanned Aerial Vehicles have transformed industries with more than two hundred limitless applications [32]. Their ability to gather data has remarkably increased their use in numerous industries. For the reason that there are a lot of applications of UAVs in this fragment, only a select few will be discussed. Figure 7 gives a holistic potential listing of the different applications of UAVs.

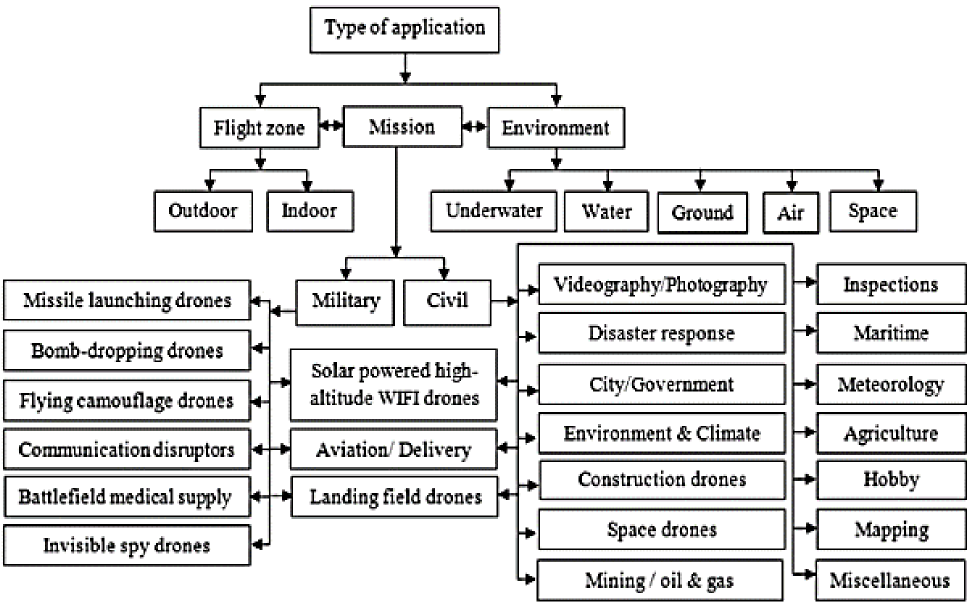


Figure 7: Different applications of Unmanned Aerial Vehicles [32].

- Unmanned Aerial Vehicles in Agriculture

Unmanned Aerial Vehicles are transforming industries, including the agricultural sector. Farmers are now able to see their fields from above. The elevated view from above has paved a way for precision agriculture. UAVs are helping in the collection of data, mapping agricultural land, managing farms, data analysis, and also application of pesticide and fertilizers [33]. UAVs commonly known as Drones collect data related to crop yields, livestock health, soil quality, nutrient measurements, weather and rainfall results, and other areas that need inspection[34].

The collected data will be analyzed and farm decisions will be made based on the results inferred from the analysis [33]. In order to produce high yields crops require consistent fertilization and spraying and drones have been equipped with large reservoirs which are filled with fertilizers, herbicides and pesticides making the whole process safer and cost-effective [34]–[36]. Figure 8 illustrates an unmanned aerial vehicle monitoring a field and the other identifying an animal.

a) b)

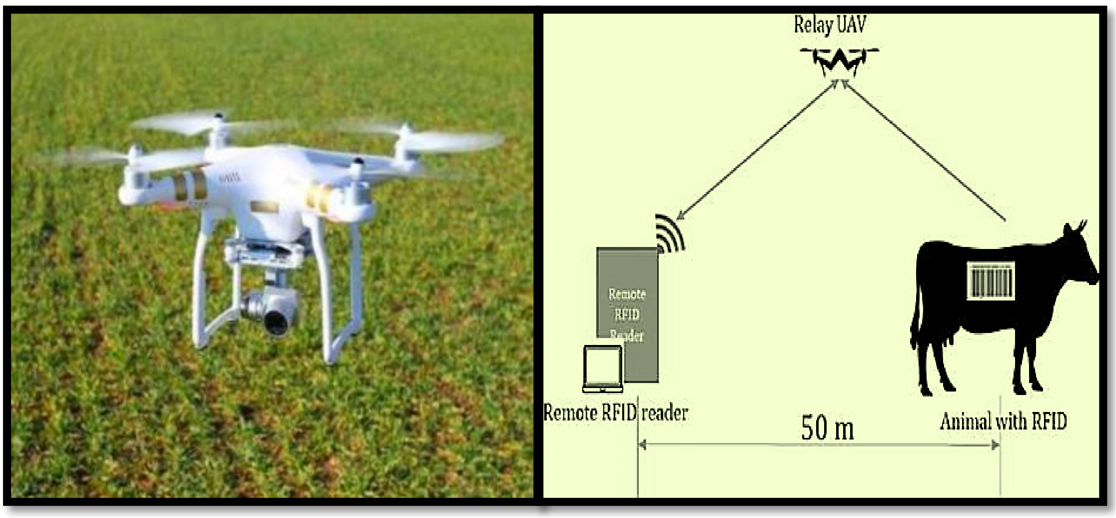


Figure 8: Drones in Agriculture: a)shows a drone monitoring the field [84] and b) shows a drone identifying an animal [85]

- Unmanned Aerial Vehicles in Transportation

Transport and logistics industries have moved to the use of UAVs because of their capability to maneuver around and above areas such as stockrooms and shipping container points and stations [37]. The health sector has also moved to UAVs for transportation of blood products, medication, and emergency first kits [38], [39]. Business enterprises are also shifting to the use of UAVs for transportation. For example, Amazon is aspiring to deliver pizza using Unmanned Aerial Vehicles [33]. The advantages of using these vehicles are their ability to go where there is no passage road, UAVs are immune to traffic delays and they are low overhead costs [38].

- Unmanned Aerial Vehicles in Construction Inspection

The construction industry is now one of the areas where drones are significantly used. Unmanned Aerial Vehicles are applied in construction in many different ways. The first application of unmanned aerial vehicles in construction is building inspection. In most cases going to the rooftop of a building can be demanding, it requires the use of ladders, cherry pickers, or even the erection of the scaffold, which are all costly and time- consuming.

Hence using unmanned aerial vehicles will reduce the costs, time and safety risks involved with inspecting the rooftop. The second application of unmanned aerial vehicles in construction is site inspections [6], [40], [41]. Site inspections on a construction site can be very hazardous and complex, with the help of unmanned aerial vehicles the visual assessment saves lives as risks are reduced as well as save time and money [6]. UAVs are able to cover a larger distance in a very short time and because of their easy usability and access the inspections can be done regularly.

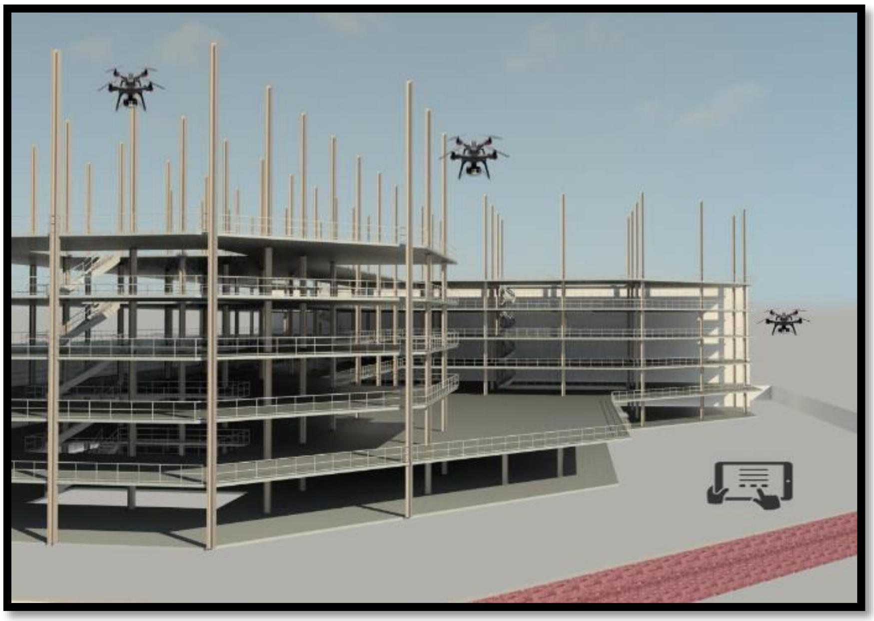


Figure 9: UAV monitoring a construction project [42]

In addition, UAVs are used for monitoring the progress of buildings in construction which is the most critical component in construction management [42]. Figure 9 shows a UAV swarm monitoring a construction site. The current monitoring process is error-prone, labor-intensive and time-consuming. The progress evaluation using UAVs gives the chance of recognizing the current conditions in a project proficiently, to identify differences between the as-built and as-planned evolvements, and to help in deciding on counteractive actions, as well. Other uses for UAVs in construction are as follows; promotional videos, health and safety inductions, site logistics, and other applications.

- Unmanned Aerial Vehicles in Videography/Photography

Drone photography has been the fastest-growing photography trend in recent years. Using drones you can get up high to photograph landscapes, cityscapes, real estate, and weddings. They allow one to photograph and video from an entirely new perspective.

There has been rapid advances in drone technology in recent years. Their deployment has shown to make jobs easier and less costly, they have tremendously reduced risks. Their visuals have positively impacted various industries ranging from videography/photography, inspection, agriculture, construction, health, transportation, and other various industries.

Types of UAVs

The unmanned aerial vehicle can be differentiated by the following attributes: type, degree of autonomy, size and weight, and the power source. These specifications are important to help get a better understanding of Unmanned Aerial Vehicles. That is the reason why this segment elaborates on the types of UAVs. There are two types of Unmanned Aerial Vehicles being the Fixed Wing and Rotary Wing that will be explored in conjunction with their benefit and detriment.

- Fixed Wing Unmanned Aerial Vehicle

According to Hassanalian *et al.* [32] and Liew *et al.* [43] a fixed wing unmanned aerial vehicle is one that uses static wings to make flying possible by creating lift triggered by the unmanned aerial vehicle forward airspeed. Hassanalian and colleagues [32] further add that fixed Wing UAVs utilize a motor and propeller as their thrust method. The design allows for them to be able to be impelled to the right site or route. When they run out of power, their grinding aptitudes naturally come on-stream [44], this allows them to be prominent in the survey and mapping industry.

Typical Uses:

Due to their data focused designs, fixed-wing drones are usually used for commercial purposes which include aerial mapping, inspections, security, and surveillance, to name but a few [45]-[46].

- Rotary Wing Unmanned Aerial Vehicle

Commonly referred to as the ‘multi rotor system’, the rotary-wing drone is one that uses rotatory wings to generate lift. Multi-rotors are characterized by multiple rotors, which tend to make less noise and do not require a landing strip when compared to their fixed-wing counterparts. Ranging from single rotary-wing (small drones) substantially big drones, their popularity has grown over the years. Unlike their competitors, the rotary-wing drones are not qualified for survey and mapping operations. Rather, they are best suited for search and rescue along with various other uses such as package delivery work. In addition, the rotary-wing has made the work of filmmakers and photographers less complex to execute.

Typical Uses

The rotary wing drone is utilized in sectors varying from that of the fixed wing. Those include aerial photography, leisure, construction and also security.

- The difference between the rotary UAV and fixed wing UAV

Table 1: Comparing Fixed Wing UAV with Rotary Wing UAV

	FIXED WING UAV	**ROTARY WING UAV**
ENDURANCE	Good flight endurance [47]	Poor flight endurance [47]
DISTANCE	Covers large areas [47]	Covers small areas [32]
ALTITUDE	Higher Altitude [32], [47]	Lower Altitude [47]
FLIGHT TIME	Long flight time [32], [47], [48]	Short flight time [47]
COSTS	Expensive [47]	Cheap [48]
SKILLS	Requires operational skills as it is hard to fly [47]	Easy to fly [47], [48]
PAYLOAD	Can carry more weight [47]	Limited payload Aptitudes [48]

Table 1 shows a comparison between Fixed Wing UAV and Rotary Wing. The main advantage of the fixed-wing is its ability to cover larger distances and good flight endurance, however, it is very expensive [47]. The other disadvantage is that it requires skill in order to be able to fly it and land it [47]. On the other hand, the Rotary wing type of UAV is very easy to control and manoeuvre [47], [48] and also very much affordable as compared to the fixed-wing UAV [48], all this being its advantages. The disadvantages of the rotary-wing are the limited flying time [47]and payload capabilities [48].

2.2.3 Formations

In a UAV swarm, there is a need for a control strategy in order to achieve coordinated flight of a group of UAVs. These control formations help UAVs with an approach on how they can interact with each other and the environment. As such, this Section reviews the two standard strategy types of formation control, those being the Virtual structure formation and the Leader-follower formation strategy.

- Virtual Structure formations

Virtual structure formation was first introduced in 1997 by Lewis and associates [49]. The reason why they initiated this structure was to force a group of robots to behave as if they were molecules set in a firm structure[49]. This concept evolved as authors kept adding more new viewpoints to it. According to Lewis *et al.* [49] Virtual structure formation is a collection of elements that maintain a (semi-) rigid symmetrical connection to each other and to a position of reference. This definition is echoed by Ren *et al.* [50] , Li *et al.* [51] and recently by Zhang *et al.* [52].

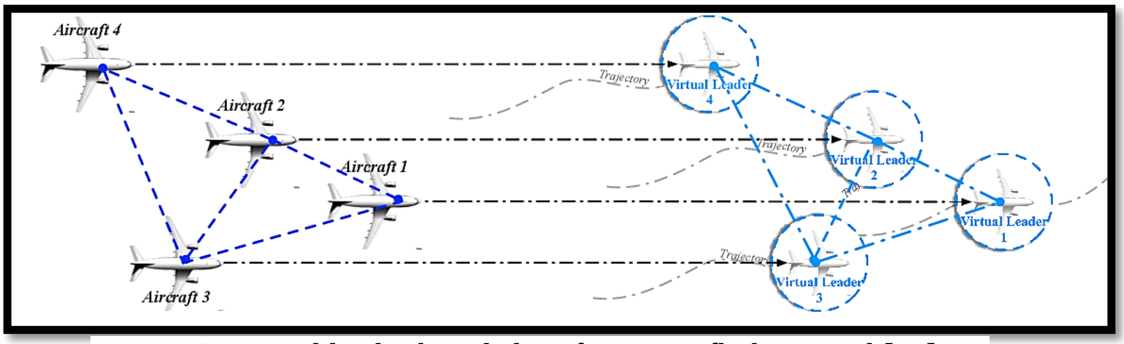


Figure 10: Virtual leader-based close formation flight control [52]

In a virtual structure formation, a virtual leader coordinates the motion and behaviour of the UAVs in a formation. A route is disseminated to the virtual leader which will also be prescribed to the whole formation. The entire formation is treated as a single module. The main detriment of the existing virtual structure execution is the centralization feature that it has, which leads to a single point of failure for the whole system. The other disadvantage is that the more the number of UAVs in a formation flight, the more it becomes complicated. The other thing is that the virtual structure is undesirable due to the rigidness of the formation, which then limits the range of applications that can make use of such a formation [9]. Figure 10 shows a pictorial representation of the Virtual leader-based close formation.

- Leader Follower formations

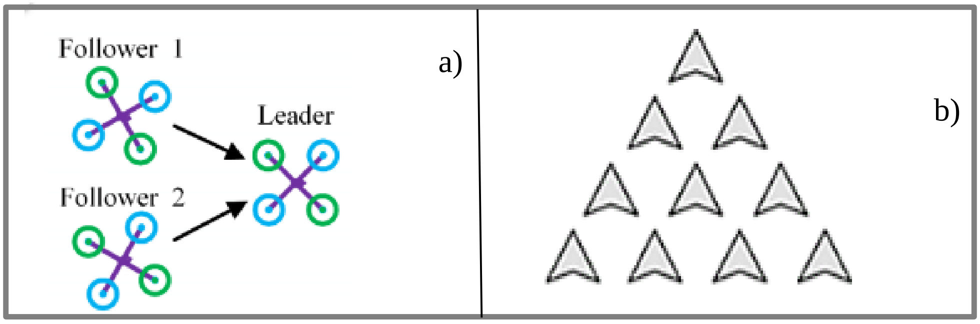


Figure 11: UAVs in a Leader-follower formation a) [53] b) [54]

Cooperative tasks are more efficiently performed with desired robustness using multiple robots than with single benefits. However, multiple mobile robots need formation control to ensure that they move effectively as a whole to jointly perform certain tasks. Even though there are numerous formation approaches, this segment focuses only on the leader-follower approach.

The leader-follower strategy was originally introduced by a German economist Heinrich Freiherrvon Stackelberg [55]. The concept was later adopted in various fields, including in the robotics area. This approach involves one drone leading one or more follower drone(s). The leader-drone is typically capable of tracking a path commanded by a ground-control station. The follower-drones track the leader position and maintain some safe distances between the drones, to avoid collisions. Figure 11 shows a leader-follower formation.

In a leader-follower approach, one UAV is assigned the role of the leader, and the remaining UAVs are set as followers as they follow their designated leader. All these UAVs pursue a team objective apportioned to them. According to Qiu *et al.* [56] in a leader-follower formation structure, a leader follows a pre-defined trajectory, while the followers keep the position and direction with a specified distance to the leader. The advantage of this approach is that it is easy to understand and implement. The main disadvantage is the leader UAV will use more battery as compared to the follower's UAV(s).

2.2.4 Communication Architecture

The communication arrangement is the most important factor of a UAV swarm. It permits interactions in command and control messages and allows remotely collected mission data to be sent to processing centres. In this Section, three types of communication architectures will be discussed, those being centralized, decentralized and hybrid.

- Centralized Communication Architecture

Centralized architecture is defined as a communication structure that uses client/server design where one or more client nodes are directly linked to a central server. In the context of our research, Hejase *et al.* [9] define it as a communication controller that consists of a ground station as a central node with UAVs directly connected to it. The information is gathered and processed in the ground station. Figure 12 shows a visualization of the centralised architecture.

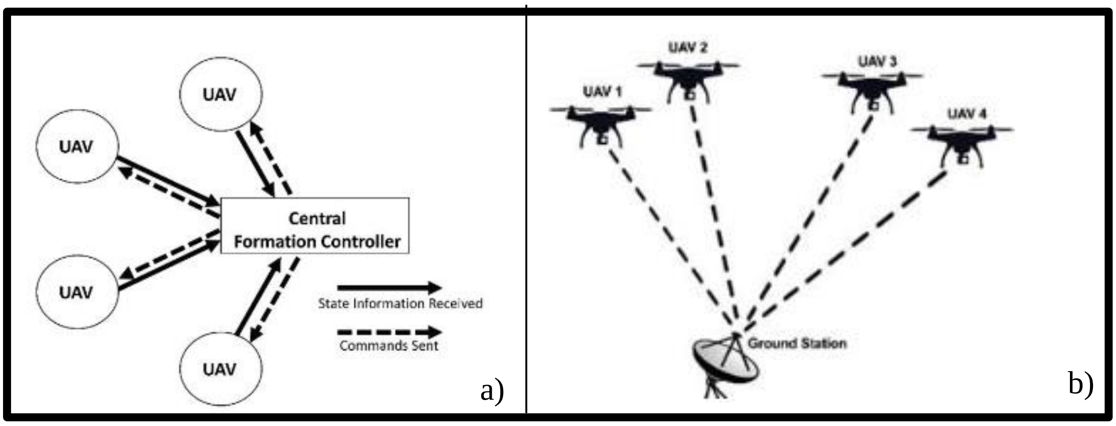


Figure 12: Centralized Architecture Visualization: a) [9] b) [57]

- Decentralized Communication Architecture

According to Ren and associates [50], a decentralized architecture is a communication network in which all UAVs in a swarm have access to the same number of communication channels. Figure 13 shows a pictorial presentation of a decentralized communication architecture. In a decentralized communication architecture, a central node is not required and two UAVs can communicate with each other either directly or indirectly. This implies that information data that are not destined to the ground station can be routed through a UAV instead of the ground station.

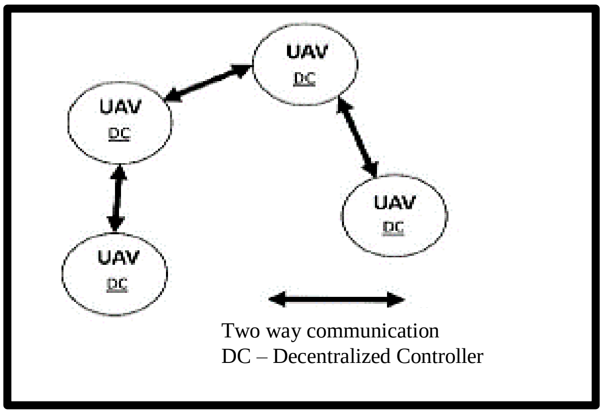


Figure 13: Decentralized Architecture Visualization

- Communication Architecture comparison

Table 2 shows the difference between a centralized communication architecture and a decentralized communication architecture.

Table 2: Communication Architectures Appraisal

Communication architecture	**Advantages**	**Disadvantages**
Centralized	According to Hejase *et al.* [9] Giulietti *et al.* [58] the first advantage of the centralized structure is that it offers the most robust and optimal resolutions because the entire state data is gathered and processed in a single place, making the formation more accurate and logical [9], [58] - Choutri *et al.* [54] adds to say the centralized architecture is simple and effortlessly operational	- It is hard to gauge a formation running on a centralized architecture because the more UAVs in the formation, the more difficult it will be to gather and process all state data centrally [58]. - Data conveyed amongst two UAVs will experience a comparatively elongated delay because the data needs to be routed through the ground station [59]. - In the UAV communication architecture, if the ground station encounters faults, the whole UAV swarm will be interrupted [54], [59].
Decentralized	- However, communication loads and fault reaction times are considerably better making decentralized controllers more feasible to implement in practical situations. - Formations based on decentralized schemes are easily scalable since the communication requirements do not considerably increase with the addition of UAVs to the formation	- Less optimal and accurate than centralized controllers

2.3 Related Work

2.3.1 Current solutions

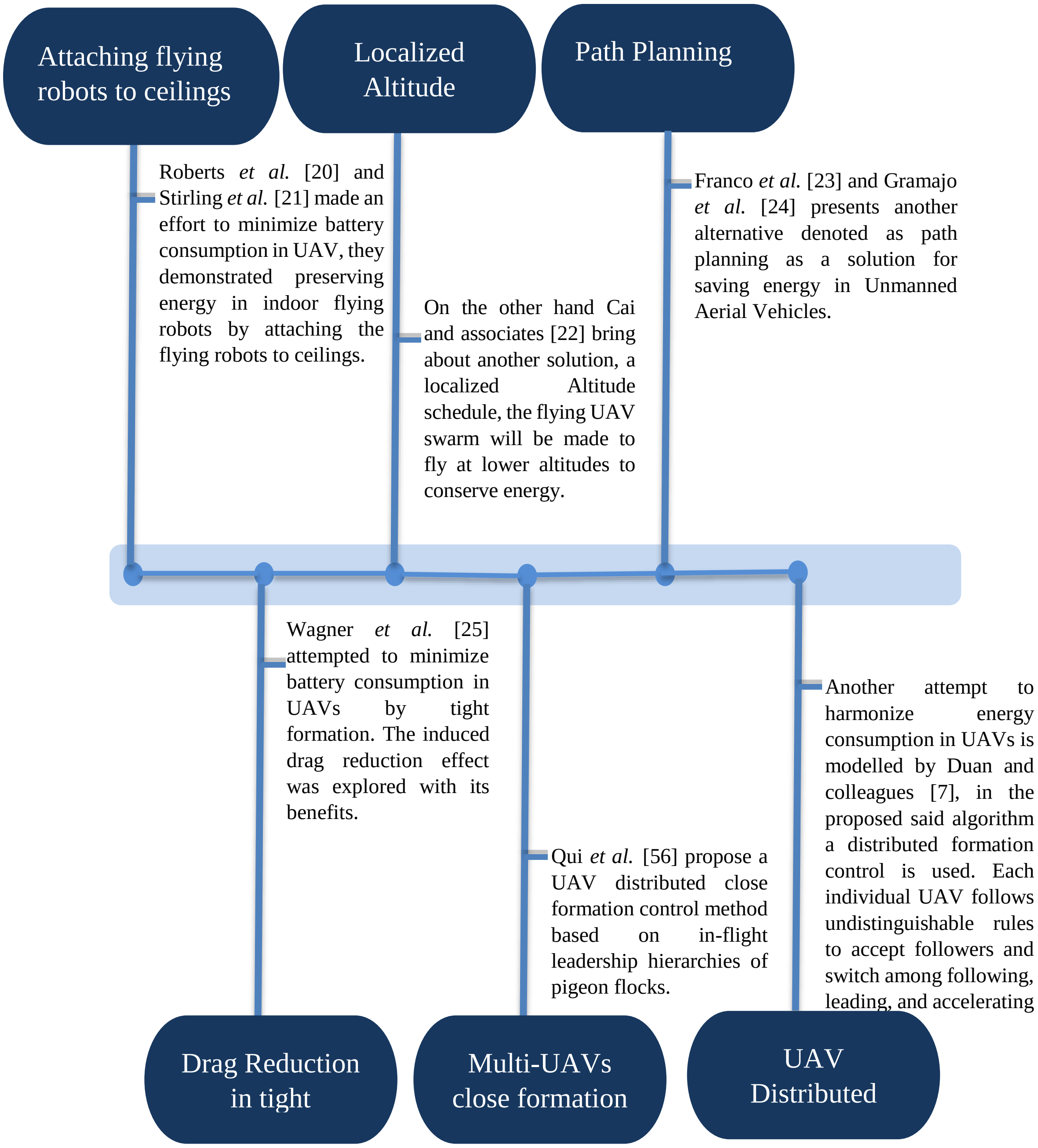


Figure 14: Diagram presenting the existing related works

Figure 14 shows all the gathered existing works of authors who were trying to solve the same problem of unequal responsibility propagation.

Consistent Battery Consumption

Attempts have been done to equalize energy consumption amongst the Unmanned Aerial Vehicles in a swarm. Roberts and collaborators [60] tackled the issue of aerial search within an indoor setting by using ceiling attachment as a means of preserving energy and also by propositioning a model to assess the endurance of a hovering robot. They attached all the unmanned aerial vehicles to the ceiling so that the energy can be consumed equally. They tested the model on their designed quad rotors and ceiling arrangement and effectively operated the model with a minimal error, however, the model used did not have an awareness feature bearing knowledge of the position of the other unmanned aerial vehicles or how much energy is available.

Stirling and colleagues [29] modified the solution presented by Roberts *et al.* [60] by designing an algorithm that is fully distributed and scalable. The similarity between the two authors was the notion of attaching the flying robots to ceiling to preserve energy. However, the algorithm that was designed by Stirling *et al.* [29] depends on a local sensing and low bandwidth communication. To advance the reduction of energy being utilised, the swarm was arranged in a way that it initialised only one agent per interval, which in turn lowered the overall flight time and reducing the collision possibility. These studies have exclusively focused on indoor navigations and not outdoor, which means that this is a restraint as it limits the scope of the research.

On the other hand, Cai his affiliates [61] brought about another solution, that is, a localized altitude schedule. The flying unmanned aerial vehicle in a swarm were made to fly at lower altitudes to conserve energy. What occurred was, the minimum possible altitude based on the targets of each drone was computed and the unmanned aerial vehicle were made to fly covering the minimum and maximum altitude only [61]. The specified altitude meant energy depletion will be equalized in all the UAVs. Calabrie *et al.* [23] criticized this algorithm with a justification that this solution would mean the unmanned aerial vehicles covers a small area, because the higher the altitude, the larger the observed area.

Franco *et al.* [62] and Gramajo *et al.* [63] proposed a solution known as path-planning for saving energy in unmanned aerial vehicles. Path-planning is said to be an important primitive for autonomous mobile robots that lets robots find the shortest – or otherwise optimal – path between two or more points [64] and [65]. Gramajo *et al.* [63] attempted to solve the issue by the propositional design of an optimization formulation for the path planning of a single UAV that maximizes the spatial coverage of an area under the constraints of limited energy and non-constant energy consumption. Similarly, Franco and Colleagues [62] proposed an energy-aware path planning algorithm that minimizes energy consumption modifying what Gramajo and associates have done by additionally satisfying a set of other requirements, such as coverage and resolution. These researches were only limited to a single Unmanned Aerial Vehicle.

Extended flight formation

Wagner and his affiliates [25] attempted to extend the flight formation in unmanned aerial vehicles by tight formation. They explored the induced drag reduction effect by increasing the steam wise spacing between the unmanned aerial vehicles by five wingspans. They made use of the wake rollup, atmospheric effects on circulation decay, and vortex motion. Although this is a good to extend flight formations, a number of studies demonstrate the importance of knowing the position of unmanned aerial vehicles instead of a blind extended flight formation [7], [56]. Qiu and his associates [56] propose a UAV distributed close formation control method based on in-flight leadership hierarchies in order to extend the flight range. The proposed method allows a UAV flock to not only fly in a line close formation under conditions with delay, noise and accidents, but also to reconfigure formation.

Another attempt to extend the flight range in UAVs is modelled by Duan and colleagues [7]. They proposed a distributed formation control algorithm, were each individual UAV followed undistinguishable rules to accept switching among following, leading, and accelerating modes. The UAV swarms were set to fly in a changing and compact line formation to increase the swarm range. All the proposed algorithms showed insight on how energy can be consistently be consumed and how flight formation can be extended but they have proved to have limitations which need to be remedied in this study.

2.3.2 Limitations of the existing solutions

Table 3: Limitations of the existing solutions

Research Summary	Deficiencies in Research	References
Attaching flying robots to ceilings	• These studies have exclusively focused on indoor navigations and not outdoor which means this is a restraint as it limits the scope. • Does not have an awareness feature that helps one see the available energy, this works in a blind state.	[29], [60]
Localised Altitude Schedule	• Critiques that this algorithm would mean that the UAV covers a small area because the higher the altitude the larger the observed area.	[29], [61]
Multi-UAVs close formation control based on wild geese behaviour mechanism	• Have not been tested in a real life scenario but restricted to simulation • Only focuses on saving fuel but not changing leadership position in order to maintain the swarm quantity	[66], [67]
Formation Rotation Control Inspired by Leader-Follower Reciprocation of Migrant Birds	• Attempts not only being validated in practical outdoor experiments but rather simulated with software's indoor • Only focus on just balancing the battery consumption but not harmonizing to maintain the whole swarm without dropping any UAV. As these UAVs are being balanced they in the end loses some UAVs in the process.	[7]
Energy Optimization For UAV Network	• Not Stable • The power level cannot be seen, so it optimising the energy without being aware of the available energy • Not aware of how much each UAV consumes battery, that means it is a blind state as the UAV behaviour cannot be identified	[68]
Drag Reduction Through extended Formation Flight	It does not work on a swarm of more than 3 UAVs Does not rotate leadership	[25], [69]

Table 3 shows the shortcomings of the existing solutions. A serious weakness arises when other UAVs are dropped during the mission, even though the notion is to increase the ‘whole’ swarm formation radius. In a UAV Swarm, all UAVs are equally important as each one of them is allocated a task which it has to accomplish and if any UAV breaks out because it has consumed more battery due to the more tasks allocated to it then it will result in the termination of the mission because each UAV has a role to play in order for the mission to be successful.

Apart from these attempts only being validated in practical outdoor experiments but rather simulated with software’s indoors; 2. These only focus on just balancing the battery consumption but not harmonizing to maintain the whole swarm without dropping any UAV. As these UAVs are being balanced, they lose some UAVs in the middle of the mission. 3. The fuel quantities are subtracted by the same amount of quantity without taking into consideration the leader or the follower differences in the roles, which means they allocate all the UAVs the same roles. 4.The other disadvantage is that the attempts are not aware of the energy available to qualify if the UAV can lead or not, what they do is just allow each UAV to take the role of leading the swarm whether the battery is lower or not. 5. The calculation of the remaining fuel is the biggest detriment of these studies because for one to be able to rotate UAVs in order to balance the consumption one needs to be mindful of the available battery which will influence the continuation of the swarm or discontinuation not blindly flying the swarms.

2.4 The Gap

In a leader-follower formation, one UAV is assigned the role of the leader, and the remaining UAVs are set as followers as they follow their designated leader. The leader is responsible for: 1. managing the whole swarm 2. Leading the swarm to the destination 2. Connecting the whole swarm with the base station 3. Collecting data from the base station and sending it to the followers and collecting data from the followers and itself to the base station 4. Carrying out tasks allocated to each individual UAV to accomplish a mission. On the other side, the role of the follower UAVs is to carry out tasks allocated to them and send the collected information to the connected leader UAV. This unequal leader- follower role allocation has resulted in failed missions because the leader will consume battery faster than the follower UAV, and in turn exit the swarm, leaving the follower UAVs idle with no direction compelling them to abort the mission. The problem of unequal responsibility propagation has necessitated this study in order to find solutions to this issue.

2.5 Summary

Algorithms discussed in this chapter make use of the leader-follower formation proposed by Hejase *et al.* [9]. However, the algorithms proposed by Hejase and colleagues can be further improved to aid some functionalities of the algorithm such as rotational sequence feature, available energy alertness feature and harmonization feature. This dissertation has explored the development of a geese inspired UAV swarm energy-aware and harmonization scheme. The algorithm has embedded functionalities such as rotational sequence, energy-aware and harmonization as an improvement of the already existing solution mentioned in Figure 14. In the next Chapter, we present the methodology.

Chapter 3: Methodology

3.1 Chapter Overview

This Chapter expounds on the constructs adopted by this research to achieve the objectives stated in Section 1.3 (Chapter 1). It is organized as follows. In Section 3.2, we present the research design and methodology. In Section 3.3, we then present the method application.

3.2 Research Design and Methodology

3.2.1 Justification of Methodology

The methodical approach adopted in this research is shown in Figure 15. It has been divided into three segments, those being quantitative, experimental design and pre-test-post-test design. The first task was to select the type of research approach which satisfies the objectives, and the one this research focused on was the quantitative research approach. Within the quantitative research approach, there was a need to select the type of research design that was going to be used and the experimental research design approach was chosen as the second methodical approach. The third task within the experimental design is the pre-test and post-test design.

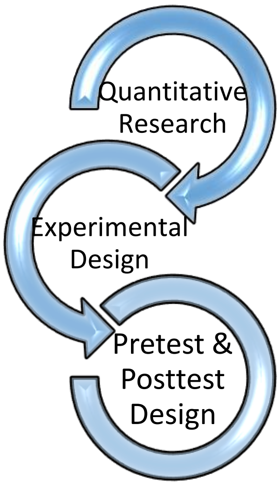


Figure 15: Methodical Approach Phases

Research Category: Quantitative approach

The investigative approach that was followed for the purposes of this research was the quantitative approach. According to research, in this approach the researcher decides what to study; asks specific, narrow questions; collects quantifiable data from participants; analyses these numbers using statistics; and then conducts the inquiry in an unbiased, objective manner [70], [71]. The reasons for using quantitative approach was that it allows greater objectivity as it involves many subjects leading to accurate results [70]. In addition, quantitative approach allows for the research to be replicated, analysed and compared with other studies without biasness [72]. However, the main weakness of the quantitative approach is that the results are limited as it provides numerical descriptions rather than detailed narratives. The type of quantitative approach which was chosen was the experimental approach.

The aim of this research was to address a practical problem which in our case was an unequal sharing of responsibilities of Unmanned Aerial Vehicles within a swarm. The reason for adopting a quantitative approach was to produce a generalizable understanding of responsibility propagation to make available an archetypal sample that can be replicated by other researchers. The quantitative approach was the most suitable approach for answering the research questions. Reasons being for research questions to be resolved and fulfilled there was a need for experiments to be conducted and thus an experimental data collection approach is a type of quantitative methodology [70]. To test reliability, the parallel form reliability was used to determine how consistent our method was. The algorithm was developed and tested on different environments and with different numbers of UAVs, hence the reason for selecting the parallel form reliability criteria.

Data Collection Method: Experimental approach

The qualitative method that was used for information collation is the Experiment method. This method was used as a means of collecting data. The experimental approach involves the discrepancy of two rudimentary conditions: exposure and non-exposure to the treatment condition of the self-determining variable [73]–[75]. In the context of this research, we found out the effects of not having the energy-aware and harmonization algorithm and the effects of having the algorithm on Unmanned Aerial Vehicles. The experimental approach was used to implement the energy-aware and harmonization algorithm and find out if it truly harmonises battery consumption of UAV in the swarm.

In addition, the reason for using the Experimental approach was to set the foundation of the algorithm, deploy it and see its effects in the UAV swarm. The Experimental approach enabled the study of cause and effect because it involved the deliberate manipulation of one variable while trying to keep all other variables constant [74], [75]. The other reason for selecting the experimental approach for data collection was the effect of the replica, with the experimental approach the experiments were repeated easily for validity [75]. The last motive for selecting experimentation as our data collection method was because it yielded numerical amounts of quantitative data that was analysed thereafter [73].

Analysis Method: Pre-test – Post-test Design

The method that was used for analysis is referred to as the Pre-test – Post-test design. The pre-test information regarding the behavioural composition of UAV swarms was recorded as well as the post-test information on the implementation of the algorithm on UAV swarms. The results were then used to measure the difference between the two subjects, that being the Pre-test and Post-test method as it is used to measure the degree of change taking place. The effects of the Energy Aware and Harmonization Algorithm were examined. The reason for using the pre-test and post-test approach was because this method has a strong level of internal and external validity in addition this type of method did not require a large sample size.

3.2.2 Objective based Design

Objective 1
Evaluate the Battery consumption rate of a standard UAV in three states; when stationery, hovering and flying
Objective Goal (Purpose)
In the first phase we captured the battery consumption of a stationary, a hovering drone, a flying drone which moves back and forth so as to see the battery life span of a UAV. The reason for this was to substantiate the starting point of the consumption of battery in a UAV. All of the three experiments was the initiation of our research foundation so that we can be able to compare and justify our solution with facts that we have tested not assumption hence the importance of the set Objective.
Location of the Objective Experiment

This stationary drone experiment was done indoor, the hovering and flying drone were done outdoors at the drone port of the university.

Equipment

Parrot A.R 2.0 Drone was used as the agent and node.js was used as a client for controlling Parrot AR Drone 2.0 quad-copter

Repetition

This experiment was repeated for accuracy. Investigation the battery consumption of a stationary UAV was done twice using different batteries and comparing with the initial results.

Objective Experimental Procedure

STEP 1: Switched on Parrot A.R 2.0 Drone

STEP 2: Connected the computer to the drone directly via Wi-Fi

STEP 3: Opened Node.js and wrote a code that collects the battery percentage of the drone

Stationary Drone: We performed all the 3 steps and collected the battery percentage of the UAV every 5 minutes. Repeated Step 3 using a different battery and captured the battery consumption using the same Parrot A.R 2.0 Drone

Hovering Drone: After doing the above 3 steps, we inscribed a code in Node.Js that allows the drone to hover and then ran it and recorded the battery percentage of the drone every 5 minutes to see how much battery was being consumed.

Flying Drone: We completed the above 3 steps and continued by running a code in Node.js that allows the drone to move around and ran it then recorded the amount of battery consumed every 5 minutes.

Question

At what rate does a stationery drone, a hovering drone and a flying drone consume battery?

Objective 2:

Assess Battery utilization in UAVS within a swarm (leader and follower UAV).

Objective Goal (Purpose)

In the second phase we captured and assessed the battery consumption of UAVs in a swarm to see how much energy the leader UAV uses and how much energy is consumed by the follower UAV. This was to verify the concept indicated by research that the leader UAV works more than the follower drone.
Location of the Objective Experiment
This Objective was done outdoor at the University drone port.
Equipment
Parrot A.R 2.0 Drone was used in the Objective as the agent and node.js was used as a client for controlling Parrot AR Drone 2.0 quad-copter
Repetition
This Objective was repeated for accuracy.
Objective Experimental Procedure
STEP 1: Switched on three Parrot A.R 2.0 Drones **STEP 2:** Connected the computer to the UAV that was the leader directly via Wi-Fi **STEP 3:** Opened Node.js and wrote a code that flies the three UAVs together assigning one as the leader and the other one as the follower drone, along with the code that shows the battery percentage of each drone. **STEP 4:** Captured the battery percentage in both the drones every 5 minutes
Question
At what rate does UAVs within a swarm consume battery? (The leader and the follower drones).

Objective 3:
Design an energy aware harmonizing scheme / algorithm
Objective Goal (Purpose)
In this phase we designed a systematic plan of the algorithm reasons were for us to comprehend and appreciate how the algorithm would harmonize the battery consumption by taking into consideration the number of UAVs in the swarm and the available battery of the UAVs.
Objective Experimental Procedure

STEP 1: Set Mission Rules and Constraints

STEP 2: Design the mission approach instructions

STEP 3: Transform the instructions into an algorithm

Question

What is the systematic plan of the energy-aware and harmonising algorithm?

Objective 4:

Implement and Test the Energy-Aware and Harmonization Algorithm

Objective Goal (Purpose)

This is the part where the Algorithm was implement and test. This is the most important part where the algorithm was actuated then tested to see if the results prove that the algorithm was the solution to lack of harmonization in UAV Swarms.

Location of the Objective Experiment

This Objective was done in two environments, the first being indoors and the other being outdoors.

Equipment

Parrot A.R 2.0 Drone was used in the Objective as the agent and node.js was used as a client for controlling Parrot AR Drone 2.0 quad-copter

Repetition

This experiment was repeated with the addition of more UAVs.

Objective Experimental Procedure

STEP 1: Switched on Parrot A.R 2.0 Drone

STEP 2: Opened Node.js and wrote a code that flies drones as a swarm of three UAVs and also recording the battery percentages of each UAV

STEP 3: Repeated Step 2 but with five UAVs in a swarm instead of the initial three UAVs

Question

How is the Energy-Aware and Harmonisation Algorithm going to be implemented and tested?

3.2.3 Experimental Design

This Section comprises three phases that present the investigational plan. The first part is the requirements which outline the prerequisites of the experiments. The requirements phase is then followed by the Data preparation phase and then the environmental setting. Figure 16 shows how an experiment station was set up.

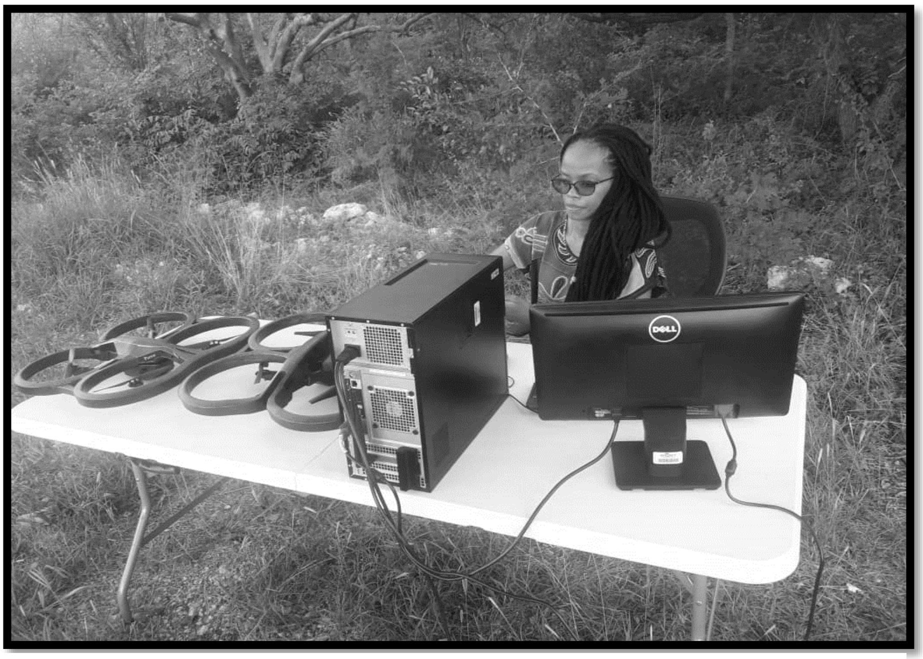


Figure 16: Setting up the experiment

Requirements

This segment outlines the hardware and software requirements to run these experiments. Node.js is the software that was used to code the drones so that they can follow up the set instructions of the Geese Inspired UAV Energy-Aware and Harmonization Algorithm.

- Unmanned Aerial Vehicles

Agent: Drone

Model: Parrot AR Drone 2.0

Type: Macro - Quadrotor

Figure 17: Parrot AR Drone 2.0

Unmanned Aerial Vehicles known as Drones were used as agents. They were used as what is commonly referred to as algorithm actuators. Parrot AR Drone 2.0 was chosen from the many types of Drones available because it was the only programmable drone that was accessible [76]. Figure 17 shows a Parrot AR Drone 2.0 which was used. The AR stands for Augmented Reality. An AR.Drone 2.0 is a quad-rotor that allows one to see the world from above [77]. The mechanical assembly encompasses four rotors joined to the four ends of a crossing to which the battery and the RF hardware are attached. The Parrot AR Drone 2.0 was manufactured as an improvement of the Parrot Company's initial Parrot 1.0 with improvements mostly in performance. The Parrot has a flight time of 36 minutes.

This drone serves as an affordable model that is deemed a lively, swift, and well balanced drone that shoots stable videos and photos [78]. The remote-controlled quad-copter has a 720p high definition camera capable of streaming live video or recording to an IOS or Android device [76]. In addition, the Parrot is also equipped with a stabilization system to achieve smooth indoor and outdoor environment flight. The Parrot is equipped with sensors to stop the drone from getting out of flight control range and the indoor hull to ensure that the drone does not break even if it crashes[76]. In addition to GPS enabled location system, the drone propellers are protected from damage by the design of the indoor and outdoor hull [79]. Figure 18 shows the interior and exterior of an AR Drone that was used in this research.

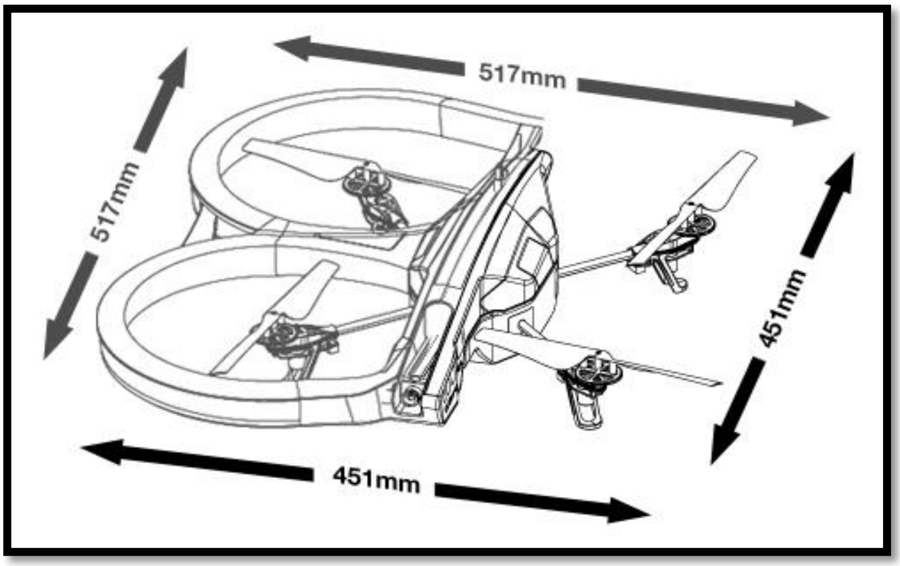


Figure 18: Indoor and Outdoor hulls of an AR Drone 2.0 [79]

Parrot AR Drone 2.0 was used to:

- Evaluate the rate it consumes battery when it is stationary, hovering and flying.
- Assess the rate it consumes battery when there are more than one and in a leader follower-formation.
- Implement and Test the Energy-Aware and Harmonization Algorithm after we developed it.

- Node JS

The software that was used to run the code is node js. Node.js is an open-source, cross-platform JavaScript run-time environment that executes JavaScript code outside of a browser. Node.js lets developers use JavaScript to write command-line tools and for server-side scripting—running scripts server-side to produce dynamic web page content before the page is sent to the user's web browser. Consequently, Node.js represents a "JavaScript everywhere" paradigm [7], unifying web application development around a single programming language, rather than different languages for server- and client-side scripts.

Though .js is the standard filename extension for JavaScript code, the name "Node.js" does not refer to a particular file in this context and is merely the name of the product. Node.js has an event-driven architecture capable of asynchronous I/O. These design choices aim to optimize throughput and scalability in web applications with many input/output operations, as well as for real-time Web applications (e.g., real-time communication programs and browser games) [8].

The Node.js distributed development project, governed by the Node.js Foundation [9], is facilitated by the Linux Foundation's Collaborative Projects program [10].

- Control Station or Base Station

The typical ground station consists of a wireless router along with a computer to capture, process and display of data. It fulfils requirements such as open system architecture, compatibility with different platforms like airborne, ship and ground, execution of data in real-time, ability to control multiple UAVs, payload control, and communication with other ground control stations.

Data Preparation and Analysis

Microsoft Excel 2019 was used for data entry during the experiments. Data were collected without any restrictions of size or dimension based on the flexibility of Excel. The captured data was then organised and structured in preparation for data analysis. Data preparation was done in order to check for inconsistencies and anomalies in the data entered. This helped rectify any typing errors that had occurred during data capture.

Similarly, Microsoft Excel was used, however, this time for analysis. Data were cleaned and aggregated in order to explore it and identify patterns in it, thereby fulfilling and getting answers for research questions.

Environment – Setting

The experiment was carried out in two different environmental settings for comparison and validation. Experiments were carried out indoors and outdoors, respectively. In order to effectively determine the effect of the algorithm on the drone, two sets of experiments were run for each setting; a control which was done by flying the drone without running the algorithm, and then for comparison, a treatment was conducted where the energy-aware and harmonization algorithm was run.

- Indoor Setting

The first experiment was conducted in a controlled and enclosed environment, being the BIUST multipurpose hall which is an open room. The size and height of the room were not considerable factors for this study. Three drones were deployed and the energy-aware and harmonization algorithm was run.

The indoor experiment was necessary because indoor environments offer fewer disturbances. There are fewer uncertainties in a controlled environment. Furthermore, an indoor setting provides protection from weather conditions such as uncontrolled wind forces. An indoor setting minimizes the effects that are present in the outdoor environment, which are not the interest of the study. The elimination of undesirable conditions leads to more accurate results. It was important to conduct the flight in a controlled environment in order to hold constant variables that are not of importance which the study was not concerned with quantifying. This ensured that there were no deviations in the environment in which the flight was conducted that had the potential to affect the outcome of the experiment, leaving only the actual variables that were being investigated.

- Outdoor Setting

The second experiment was conducted in an outdoor setting at the BIUST drone port. This is a designated drone flight area that is subject to normal weather conditions. Given its outdoor nature, this environment offers low control over operations because independent variables continuously change. Some of the changing independent variables include wind speed, wind direction, and humidity. These variables have an impact on the experiment results.

3.2.4 Summary

The approach used in this study is the experimental approach under quantitative research. Three stages were used, the first was categorizing the type of research this study is, and in our case it was classified as quantitative research. The second stage was identifying the type of quantitative research method it was. It was concluded that this is an experimental type because experiments had to be carried out in order to come up with a set solution. The third stage was identifying the types of experimental approach, and it was found out that it is the pre-test post-test type of experiment. Whereby one tests the entity before and after the experiment to see the difference if there is any.

The methodical approach was then followed by an objective based design. This is where the test subjects were identified, the experimental procedures were outlined and the design plan was defined. The experimental design outlined the hardware and software requirements, data preparation and analysis, and lastly the setting. These approaches proved to be clear indicators for undertaking and fulfilling all the research questions.

3.3 Method Application

This section describes the application of the methodology on the full scheme design and execution adopted by this research. It gives a full representation of the algorithm designed and shows the step by step phases followed in the development of the Geese Inspired UAV Swarm Energy-Aware and Harmonization Algorithm as shown in Figure 19.

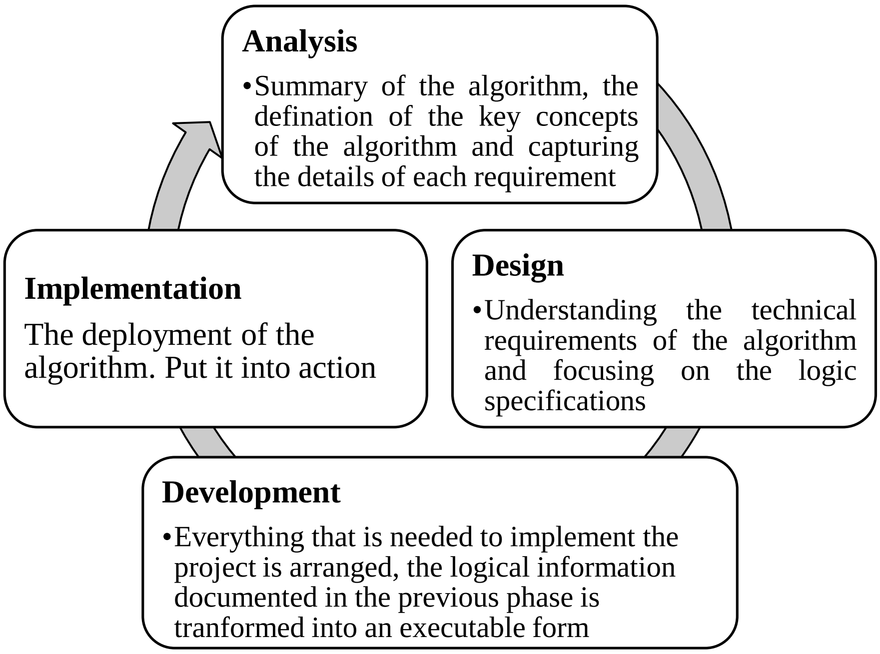


Figure 19: Development Phases of the Energy-Aware and Harmonization Algorithm

The first segment is algorithm analyses. This is where a full explanation of the algorithm takes place and it entails: the leader-follower reciprocation mechanism, energy-aware computational movement, harmonization algorithm approach, and the rules and constraints of the algorithm. It is subsequently followed by the second Segment, which is the design of the algorithm. This segment comprises of the flow chart which shows the sequence of processes of the energy-aware and harmonization algorithm in a diagrammatic representation. In addition, the segment also encompasses the use case diagram which will give an interactive visualization of the leader and follower approach in Unmanned Aerial Vehicles. The third Segment is the development phase where the building of the algorithm is explicated and designed. It comprises of the pseudo code algorithm and the step by step explanation of the algorithm. The fourth segment is the implementation stage. This is where the full demonstration of how the algorithm works is shown, including the system architecture. The setup of the experiment will then be shown in the last Section of chapter 3.

3.3.1 Analysis

To solve the problem of lack of comparable responsibility propagation an energy-aware and harmonization algorithm based on the behavioral makeup of birds called Geese is proposed.

The algorithm ensures equal responsibility propagation by virtually rotating UAVs safeguarding that battery is drained evenly amongst the UAVs. This denotes that the battery life of the UAV in a swarm will deplete in an evenly proportional pattern, in turn leading to the success of the all or nothing designated mission.

- Leader Follower Reciprocation Mechanism

In this algorithm, a leader-follower approach is adopted where one Unmanned Aerial Vehicle is assigned the role of a leader and the other remaining Unmanned Aerial Vehicles become followers [8]. When the leader reaches a certain battery level which is comparatively lower than any of the follower Unmanned Aerial Vehicles in that particular swarm it will rotate roles with the follower UAV having the highest battery level, the follower Unmanned Aerial Vehicle will take over the role of being a leader and the first leader UAV will be a follower. This is to ensure that all the Unmanned Aerial Vehicles in a swarm share responsibility as research shows that the follower drones work less than the leader Unmanned Aerial Vehicle [80]. The leader UAV is responsible for directing the follower UAV to the designated location. It is responsible for communication with the base workstation and it also keeps the information about its self which shows that the leader UAV works more than the follower UAV making the battery consumption higher, hence the need to rotate leadership [80].

Figure 20 shows the virtual rotation analogy of the rotation. The UAVs alternated the leadership role while they maintained their positions. Figure 20 was further explained in Figure 21, Figure 22, Figure 23 and Figure 24. Figure 21-24 gives a full demonstration of how the proposed algorithm worked in a set-up of four UAVs (in order to entirely comprehend the algorithm).

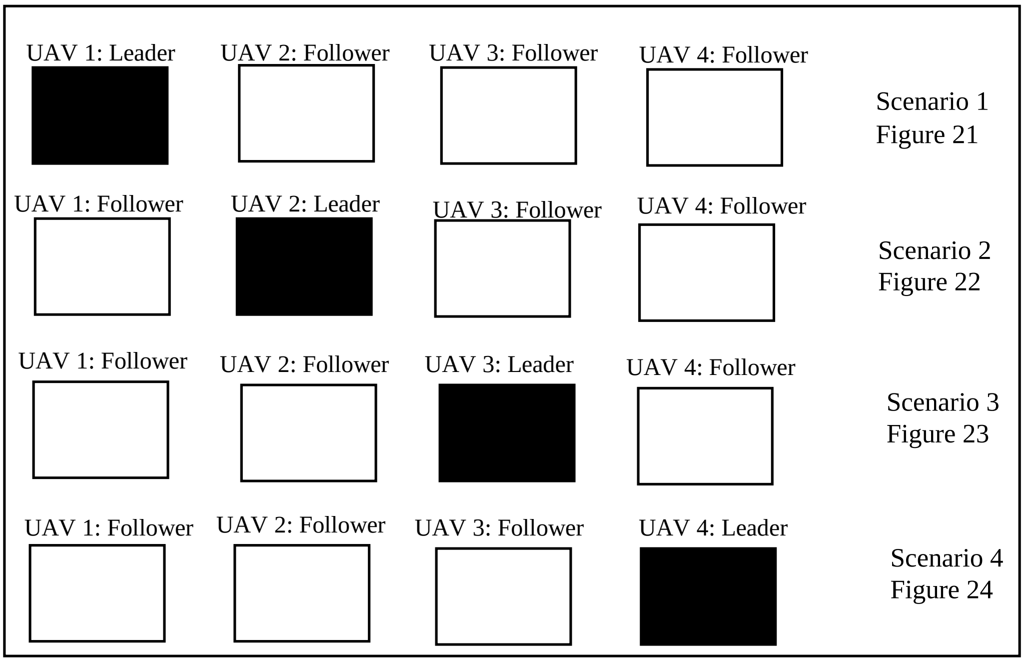
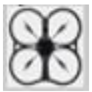
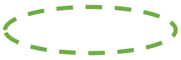


Figure 20: Virtual Rotation Illustration (Sharing Responsibility equally)

In the following scenarios this image  represents an Unmanned Aerial Vehicle which is referred to as UAV in the diagram.  The oval shape exemplifies where the rotation will take place between the Unmanned Aerial Vehicles.

Scenario 1:

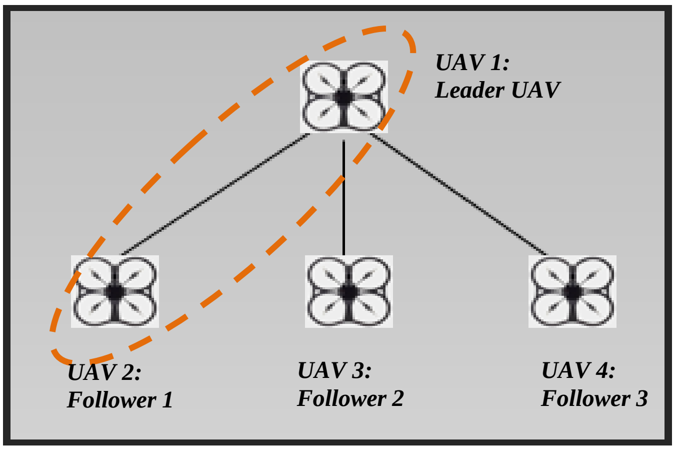


Figure 21: UAV 1 as the leader and UAV 2, 3, 4 as followers

The mockup of the virtual rotation process based on the threshold is shown in Figure 21. UAV 1 in the diagram is the leader and UAV 2, UAV 3, UAV 4 are the followers. When UAV 1 reaches a certain limit referred to a threshold, the algorithm executes the leader-follower virtual rotation process handing over the leadership role to UAV 2 and making UAV 1 the follower, assuming that UAV 2 has more battery energy level than UAV 3 and UAV 4. This is because the virtual rotation process is not a random selection process but a clear calculated process based on the highest energy or battery level of all the UAVs in the swarm.

A threshold is referred to as a start point of rotation determination [81].The threshold is calculated by the average battery percentage of all the Unmanned Aerial Vehicles in a swarm divided by the total number of drones in a swarm, therefore, when the resulting Figure is subtracted from the battery percentage of the leader, the rotation sequence is executed. The computation shown in equation (1) is used for calculating the threshold. In Figure 21 we assume that all the UAVs have a 100% battery percentage As such, the 100% of battery energy level divided by the number of Unmanned Aerial Vehicles, and subtracting the outcome from the battery percentage level of the leader (i.e., 100% divided by 4 UAVs is equals to 25%) .therefore 25% is our threshold This means that when 25% of the battery level of the leader has been depleted the battery of all the drones will checked and if there is a drone with more battery that the leader UAV then rotation will be initialized to allow the UAV with more battery to lead the swarm.

$$\frac{\sum_{i+1}^{m}(BatteryLevel)}{m}/m \ = threshold$$

Equation 1: Threshold Computational formula

Scenario 2:

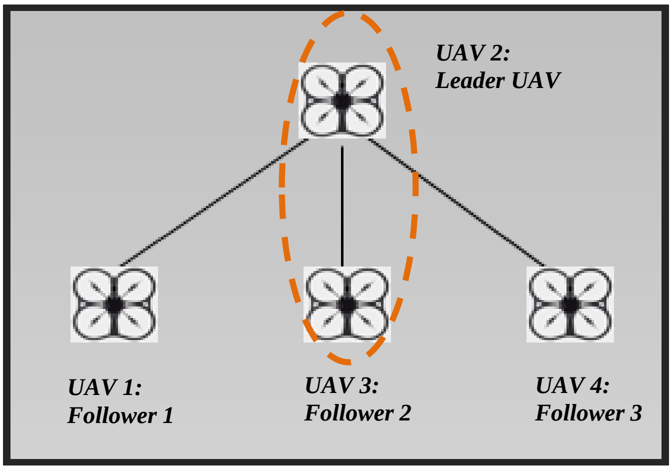


Figure 22: UAV 2 as the leader and UAV 1, 3, 4 as followers

In Figure 22, we see UAV 2 taking the lead after UAV 1 has reached its energy level virtual rotation threshold. So UAV 2 continues to be the leader and performing the roles of receiving the data from the follower UAVs and reporting to the base station. It continues being the leader until it reaches the second virtual rotation threshold, in which it has to rotate with the UAV that has the highest energy level which is the follower UAV 3 as shown in Figure 22. It will continue with the Energy-aware checking algorithm until it reaches the virtual rotation threshold, then it rotates the leader with the next highest battery level. It will continue with the mission command with regular energy-aware checking prompts to establish the next virtual rotation threshold.

Scenario 3:

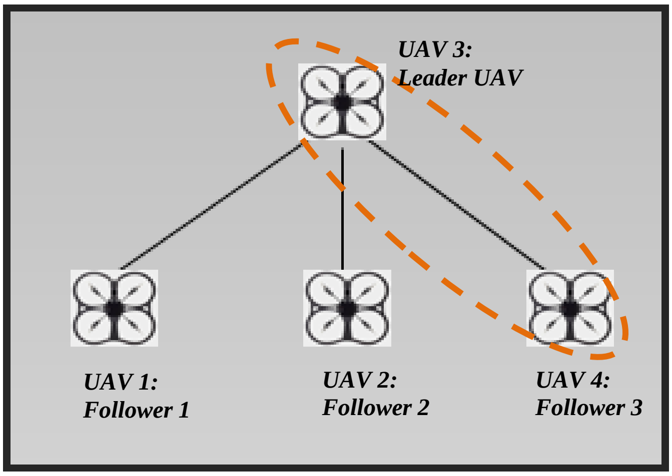


Figure 23: UAV 3 as the leader and UAV 1, 2, 4 as followers

In Figure 23, UAV 3 takes the lead. This means that UAV 2 had reached its rotation threshold, therefore, it will be forced to exchange with UAV 3, which will continue being the leader until the energy-aware prompts the threshold for rotation.

Scenario 4:

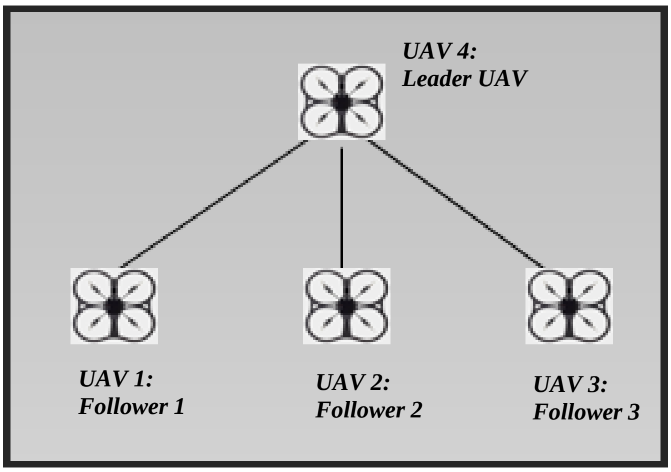


Figure 24: UAV 4 as the leader and UAV 1, 2, 3 as followers

Figure 24 shows the last stage of the role rotation phase when all the UAVs have taken the leadership role. This means that the energy levels in all the UAVs would have significantly decreased because they would have taken the leader and follower task. The leader position demands the highest levels of battery energy levels than followers. At this phase, the drones should be closer to finishing the mission command because the battery levels should be significantly lower than before, which means landing should be nigh.

When the battery energy levels reach 20% or less, the algorithm prompts the swarm to abort the mission, therefore it will use the remaining battery level to return to the base station. When the battery is more than 20%, the virtual rotation will continue. The rotation process is not executed according to the numbering of the drones, but it is assigned to the drone with the highest battery level. The drones are supposed to evenly get to lead, with the dependent notion of distance, therefore, ensuring even battery consumption.

The drones will be in a leader-follower formation and when the leader reaches a certain battery level it will rotate positions. This will result in the follower drone taking over as the leader and the first leader becomes the follower so that all the drones in a swarm can share responsibility. The research shows that the follower drones work less than the leader drone, as it is responsible for directing the follower drones to the designated location. It is also responsible for communication with the base workstation and also keeps the information about itself, which shows that the leader drones work more than the follower drones, making the battery to be consumed more, hence the need to rotate leadership.

- Energy-Aware Computational Movement

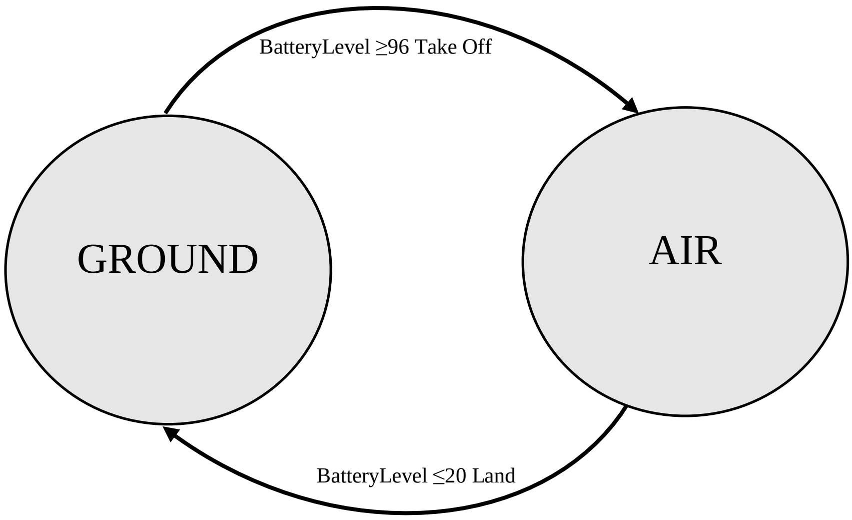


Figure 25: Energy-Aware Transition graph showing the flight model of a single UAV in a swarm

In order to encapsulate the fundamental notion, the flight comportment is simulated using a state machine diagram in Figure 25 which was adapted from Witt and associates [82]. There are two states that function those are: the “Ground State” and the “Air State” [82]. In the ground state, there are two options of action to decide on. If each Unmanned Aerial Vehicle in a swarm has a battery percentage that is equal to 96% or more than 96% then the UAVs can switch to the takeoff state. If the energy level is lower than 96% then it will remain in the ground state. In the takeoff state, the algorithm will send frequent battery checking prompts using the centralized networking communication system. These frequent prompts are designed to be an alerting mechanism to the base station so that it can be aware when to execute the rotation threshold sequence well on time and also to be aware as to which drone is next in the queue for the leader position. During the flight time when the battery level of the Unmanned Aerial Vehicles in the swarm is equal to 20% or less than 20%, then the Unmanned Aerial Vehicles will be forced to all land as this is an all-or-nothing mission. This model helps in the mindfulness of the energy levels of the Unmanned Aerial Vehicles in the swarm.

- Harmonization Algorithm

The harmonization algorithm is mainly based on synchronization of Unmanned Aerial Vehicle to ensure the best results and also guarantee equal responsibility propagation. The Harmonization Algorithm sequence makes sure that every UAV within a swarm flies within the specified degree zone to avoid collision and maximizing survey accuracy. There is a division of labor with the algorithm because of how the roles are shared equally to ensure that no Unmanned Aerial Vehicle will deplete its energy level before the others, as this algorithm uses an all for one and one for all principle. The main purpose of this algorithm is to divide the workload evenly across all the drones in a swarm to avoid exhausting the energy levels of the leader drone. All the drones in a swarm will be connected to a closed network to establish a strong communication base between the followers, the leader, and the base station. A strong intercommunication sequence is very crucial as it will be used to prompt the energy level checking mechanisms between the Unmanned Aerial Vehicles in a swarm.

- Assumptions and constraints and Rules

Research Assumptions

  - The leader Unmanned Aerial Vehicle does not physically change positions with the follower Unmanned Aerial Vehicles. What transpires is the leader UAV works more than the follower UAVs because it connects the follower drones with the base station and also receives commands of the directions whilst the followers just function to do achieve their given tasks and at the same time follow the leader. These functions are referred to as the leader and follower barring the work that each one has been allocated to. So when they rotate, they rotate responsibilities and not their physical locations.
  - The drones are homogeneous: meaning they are of the same type and size.

Research Constraints

  - The research will be carried out both indoors and outdoors. This has been further explained in Section 3.2.7
  - In this research we used Parrot A.R 2.0 Quadroter. This is the macro type of a UAV (explained in Section 3.2.7).

Research Rules

  - Swarm: The UAVs are to fly as a swarm keeping the leader follower formation in place.
  - Speed: The UAVs fly at the same direction with a constant speed.

1338 ## 3.3.2 Design

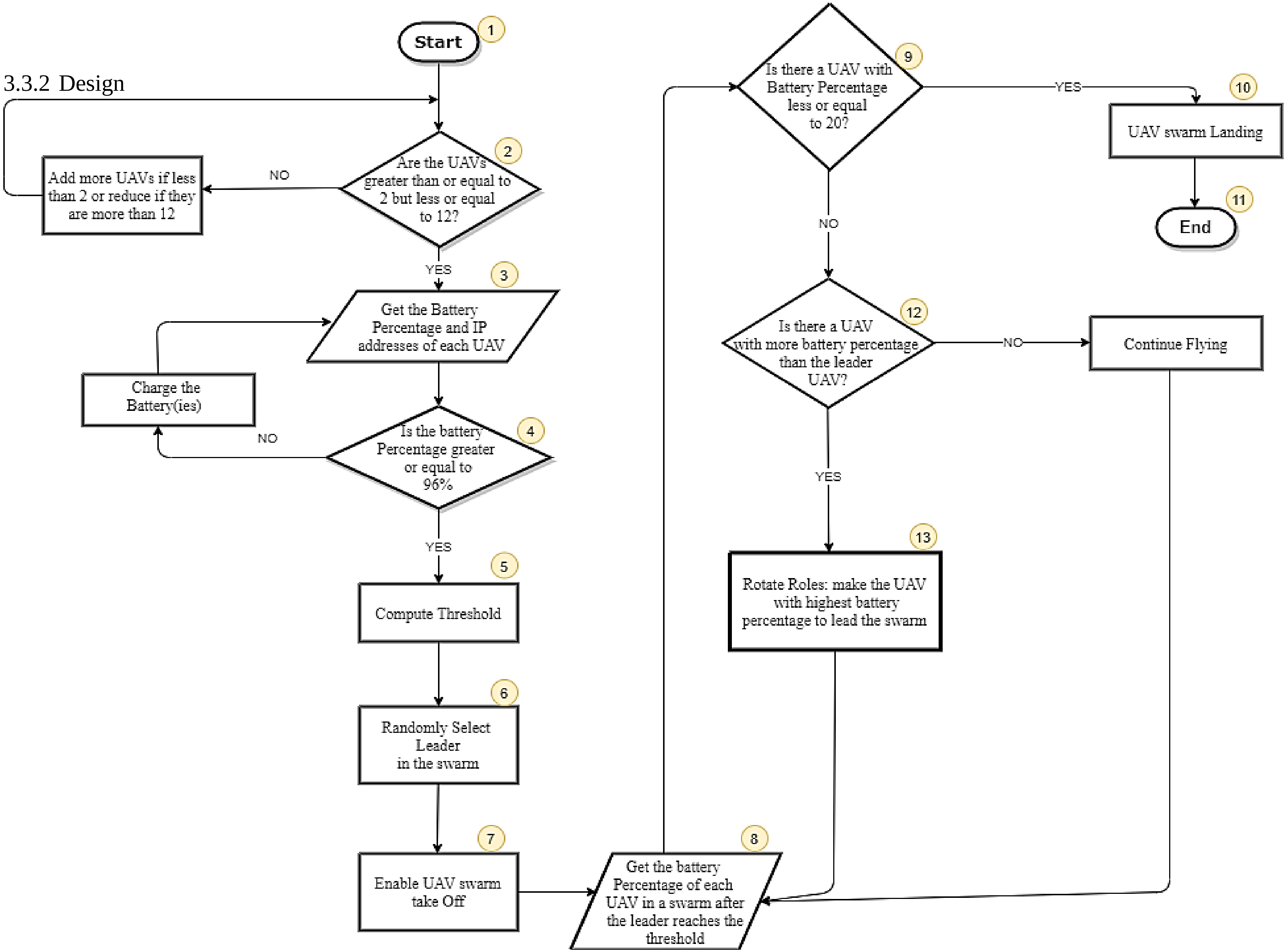


Figure 26: Flow chart showing a sequence of the algorithm activities

Figure 26 show the step by step execution of the geese inspired UAV energy-aware and harmonization algorithm. The flow chart is described below.

Step 1- This first step shows the start of the execution of the algorithm

Step 2- Is to check whether the UAVs (drones) are equal to or more than two and equal to or less than 12. (i.e., when the drones are less than two, they do not qualify to be called a swarm, and when they are more than 12, they exceed the limit set)

If the drones are less than two or more than 12, then the algorithm will return the process to step 1 until the number of drones is within the specified range.

But if the number of drones in the swarm are within the specified range then the algorithm moves to the next step, step 3

Step 3- The algorithm gets the battery percentage and the I.P address of each drone in the swarm

Step 4- The algorithm then checks the energy levels of each drone in the swarm whether they are 96% or more

If No, then the algorithm will return to step 3, till all the batteries are fully charged &

If yes, then the algorithm will proceed to step 5

Step 5- What happens here is the algorithm computes the threshold based on the average battery level of all the drones divided by the number of drones, and the result to be subtracted from the battery level of the leader.

Step 6- The algorithm then goes on to randomly choose the leader

Step 7- The UAVs take off as the take-off command is initiated.

Step 8- There’s another periodic battery level checking prompt. The threshold gives the rotation point. When the leader has reached the threshold the battery of each UAV is compared against that of the leader UAV.

Step 9- If the battery level is 20% or less, we skip the other steps and go to step 10, which is executing the swarm landing sequence then step 11 and then the end. If the battery level is still more than 20%, we continue to step 12.

Step 10- swarm landing

Step 11- end

Step 12- Check if there is a follower UAV with more battery percentage than the leader UAV in the swarm, and if yes we go to step 13. If no, then we continue flying and go back to step 8

Step 13- The rotation is instigated between that the follower UAV with the highest battery percentage and the preceding leader UAV.

- Use Case

ROLES OF A LEADER UAV AND FOLLOWER UAV IN A SWARM

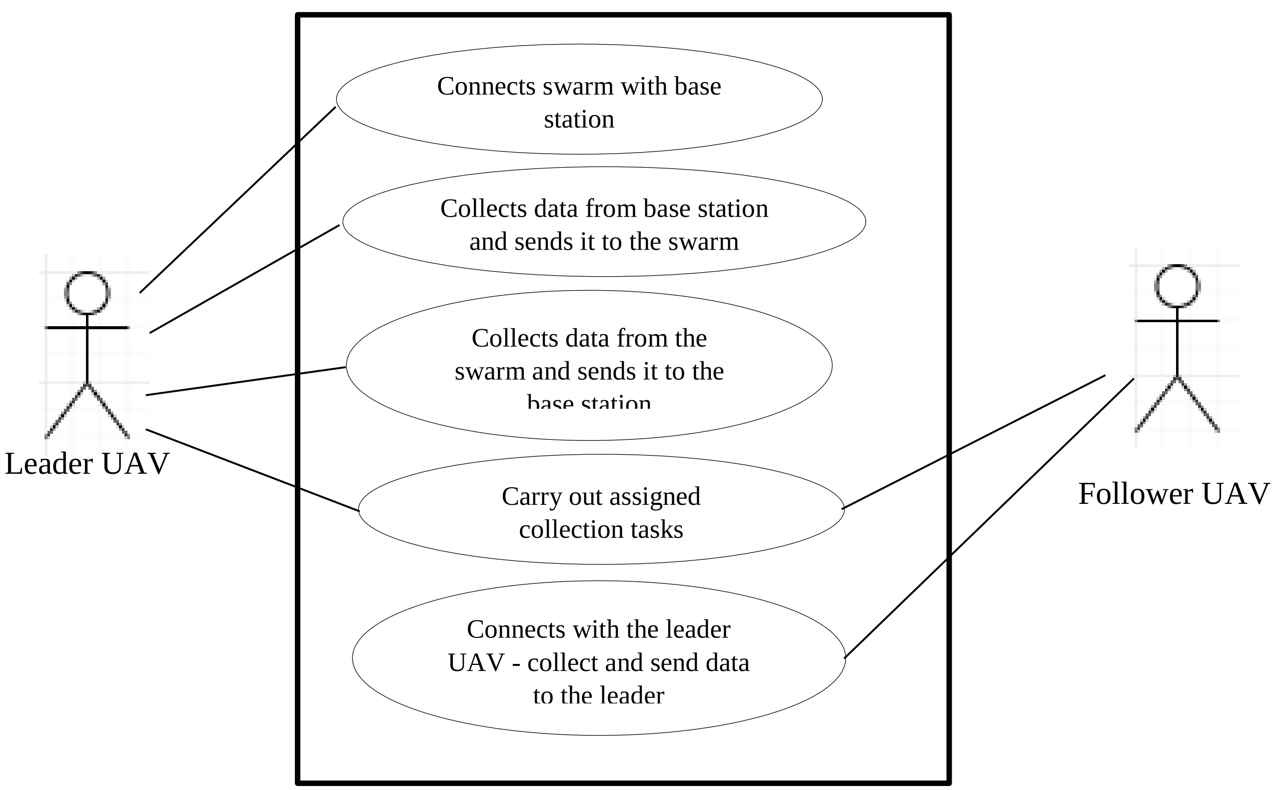


Figure 27: Use Case Diagram showing the responsibilities of a leader and follower UAV

The leader-follower approach will be adopted in the Energy-Aware and Harmonization Algorithm. This approach involves one UAV leading one or more follower UAV(s). In the Leader-Follower approach, the leader and follower UAVs are allocated tasks to accomplish as shown in Figure 27, hence the roles of the leader UAV are not the same as the roles of the follower UAV.

The leader UAV is responsible for connecting the swarm of UAVs with the base station, collecting data for a mission duty allocated to it and sending it to the base station. In addition, it is responsible for relaying commands between the base station and follower UAVs in the swarm. On the other hand, the follower UAV carries out assigned tasks such as image capture and inspections (depending on the mission being achieved). The follower UAV will then collect and send data to the leader. A follower UAV is wholly dependent on the leader UAV.

3.3.3 Development

UAV Swarm Energy Aware and Harmonization Pseudo Code

Algorithm 1: Inialization of Energy Aware and Harmonization Algorithm

```
if m≥2 & m≤12 then
    foreach d ∈ S do
        getBatteryLevel(); // Battery Available in percentage
        DroneAddress = getDrone address();   // IP address of each drone
        Position = getDronePosition(); // x,y,z values of each Drone
            positioning
        if each d ∈ S BatteryLevel ≥96 then
            threshold = (∑_{i+1}^{m} BatteryLevel / m) / m
    leader = random(DroneAddress).size;
     leaderDrone = DroneAddress(leader);
     foreach d ∈ S do
        enableTakeOff();
```

Figure 28: Algorithm 1 Pseudo Code

Algorithm 2: Energy Aware and Harmonization Algorithm

```
leadingDrone.power=getpower(leadingDrone);
  p = leadingDrone.power-threshold

if p ≤20 then
    foreach d ∈ S do
        drone.land
if leadingDrone.power >p then
    Do nothing
else
    foreach d ∈ S do
        Address = getDroneAddress(maximumpower);
         leadingDrone = Address();
```

Figure 29: Algorithm 2 Pseudo Code

Description of the UAV Swarm Energy Aware and Harmonization Algorithm

Figure 28 and Figure 29 shows the Pseudo code of the developed algorithm which has been divided into two parts. The modules of the developed algorithm are described below.

<u>STEP 1:</u> UAV Swarm Constraint

if $m \geq 2$ *&* $m \leq 12$ **then**

This is where the verification of the number of UAVs that are available in a swarm takes place. If the number of UAVs is between 2 and 12 then we proceed with the next step in the algorithm. In a situation where the number of UAVs is less than 2 or more than 12 then it means none of the requirements of the algorithm have been met, and the algorithm will not move to the next step until the conditions have been met. The minimum number is 2 because a swarm is a group of vehicles that work collectively, collaborating and communicating with each other to accomplish an objective; hence 1 UAV does not meet the requisite of a swarm which is our focus in this research. The reason why we restricted the maximum to 12 is to make our experiment controllable.

<u>STEP 2:</u> Amass UAV - Battery Percentage, Address

```
foreach d ∈ S do
    getBatteryLevel(); // Battery Available in percentage
    DroneAddress = getDrone address();    // IP address of each drone
```

For each Unmanned Aerial Vehicle (UAV), we get the available battery level (the battery percentage) and we also capture the IP address of each UAV. The reason for obtaining the battery level is that the emphasis of this algorithm is being aware of the energy being consumed during swarm flight and ensuring equal responsibility propagation amongst the UAVs. This can only be done if we are sentient of the battery percentage hence the need to record the battery level. The purpose of collecting the IP address of each UAV is that the allocation of tasks and the rotation of UAVs will be done using the Internet Protocol that has been assigned to each UAV. Therefore, after verifying the UAV available in a swarm, we will continue by checking the battery that is available in each UAV and also the IP Address.

<u>STEP 3:</u> Computing Threshold

if *each* $d \in \mathcal{S}$ *BatteryLevel* ≥ 96 **then**

$$threshold = \frac{\sum_{i+1}^{m} BatteryLevel}{m} / m$$

Subsequently, after checking the battery that is available in each UAV, we will confirm if the battery level of each UAV is equal or greater than 96%. If it is not equal or greater than 96%, we will then charge the batteries before we move to the next step. However, if all the Unmanned Aerial Vehicles have 96% or more battery percentage then we will proceed to the next step which is calculating the threshold.

Our rotation will be based on the threshold. If the leading UAV has reached the threshold, we will rotate it to allow the one with the higher battery level to be the leader. The threshold will be calculated as follows; we get the initial battery level of all the UAVs in a swarm, and we sum it and divide by the number of UAVs in a swarm to get the main mean of all UAVs and then divide the average by the number of UAVs giving us the threshold.

<u>STEP 4:</u> Leader Selection

```
leader = random(DroneAddress).size;
 leaderDrone = DroneAddress(leader);
```

After calculating the threshold, the leader of the swarm will be randomly chosen, and then the rest of the other UAVs will be the followers.

STEP 5: Take Off Enabled

```
foreach d ∈ S do
    enableTakeOff();
```

After fulfilling the requirements above, all the UAVs in a swarm will take off and fly, that being the commencement of the mission.

STEP 6: Leading UAV Power

```
leadingDrone.power=getpower(leadingDrone);
 p = leadingDrone.power-threshold
```

As they have taken off, we will be aware of the leading battery percentage which is referred here as power. The algorithm will check if the leading power has subtracted the threshold or not.

STEP 7: UAV land

```
if p ≤20 then
    foreach d ∈ S do
        drone.land
```

If the battery percentage of any of the UAVs in the swarm is less or equal to 20, then the mission will be aborted. All the drones in the swarm will land taking into consideration that this is an all or nothing mission, which means that if one drone leaves the swarm will result in all drones leaving the swarm because the mission cannot continue with any of the drones missing.

STEP 8: Computing Threshold

```
if leadingDrone.power >p then
    Do nothing
```

If the leading UAV has a battery percentage that is more than the battery percentage with a subtracted threshold referred to as P, we will not do anything but rather continue flying.

```
else
    foreach d ∈ S do
        Address = getDroneAddress(maximumpower);
        leadingDrone = Address();
```

Else; if the leading UAV battery percentage (power) is less than the battery percentage with a subtracted threshold, we get the Drone-IP-address of the UAV with the maximum battery level and assign it to the leader role making the initial leader to assume the role of a follower drone.

3.3.4 Implementation

System Architecture

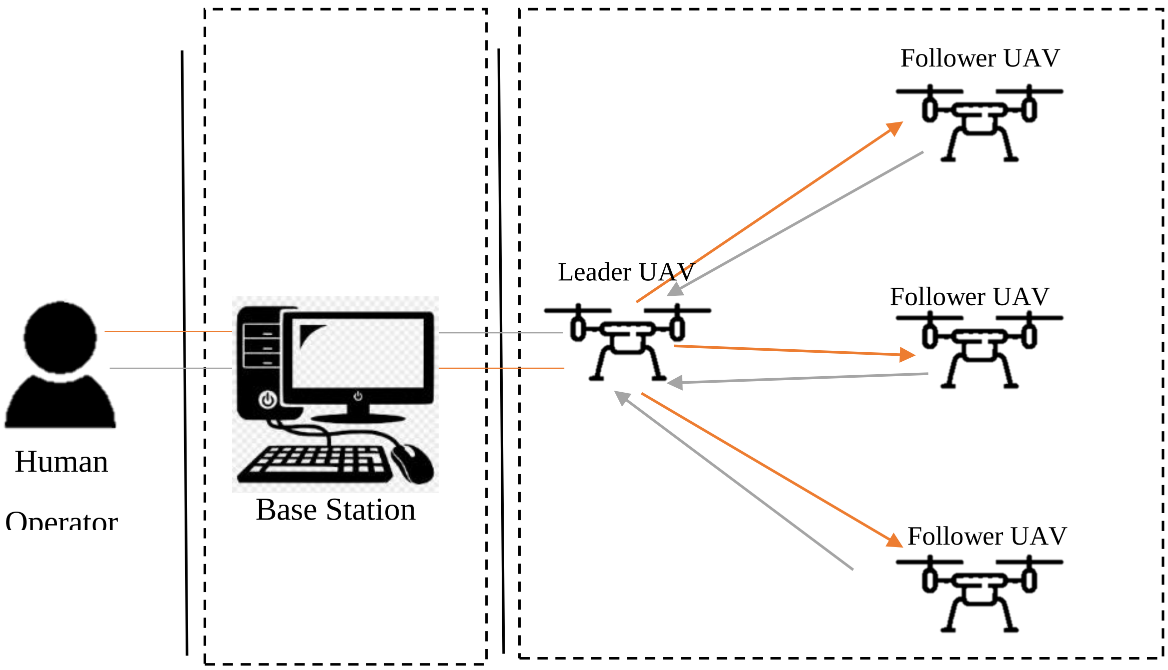


Figure 30: Shows the system architecture of the energy-aware and harmonization scheme

Figure 30 shows the depiction of the system architecture. This is the setup that was executed. The human operator (see Figure 30), will provide commands and information to the base station. The base station (see Figure 30) is a personal computer, where much of the coordination and control of the swarm will be performed. Figure 31 shows different tasks of the base station. The tasks for the leader and follower UAVs have been presented in Figure 27.

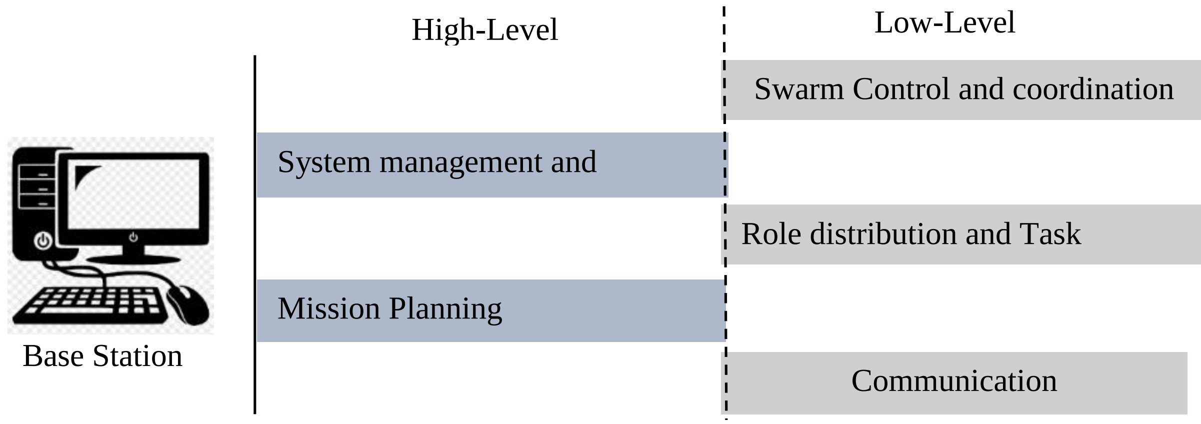


Figure 31: High-level and low level tasks of a base station

System management and monitoring

The system will set procedures and processes to ensure that the mission and tasks are fulfilled to achieve the objectives of this research.

Mission Planning

Mission planning depends on the operator and it is treated as an input to the system. The operator specifies the kind of mission that has to be done by the UAVs in the swarm.

Role distribution and Task allocation

The system will then evaluate, based on the UAV information the most suitable vehicle(s) for the roles and will allocate tasks based on the available battery. That is where the leader-follower formations are actuated.

Swarm Control and coordination

Then there will be an appraisal on how the UAVs in a swarm will be rotated and coordinated to avoid collision or loss of any UAV within the swarm. There will be a continuous checking of the amount of energy remaining on each UAV to be operational, and if any UAV is malfunctioning. It will be ensured that the all or nothing mission target is achieved.

Communication

Communication is a vital component of the system. It enables the coordination of the tasks. The system is able to maintain communication between the base station and the UAVs. The information received from UAVs is distributed between the different task modules of the system. On the other hand, the UAVs will receive the task assignment from the base station. Communication between the UAVs and base station is through the leader UAV which acts as a gateway between the two.

Geese Inspired UAV swarm energy-aware and harmonization algorithm illustration using three UAVs

Table 4 shows the code snippet of the algorithm. It is found in Appendix A and further elaborated in Appendix B, Appendix C and Appendix D.

Table 4: Description of the main code snippet

Code Snippet	Description
network = ['192.168.1.1','192.168.1.2','192.168.1.3'] //three UAVs	This is where constant initialization takes place. The IP addresses of the UAVs are defined and initialized
network.forEach(ip) -> swarm.add ip:ip number = swarm.length	The UAVs are then added to the swarm using their IP address which will assist in knowing the number of UAVs being added

if(number >=2 && number <= 12)
{
        level = 0,counter = 0
        swarm.forEach(drone) ->
                ip: drone.ip
                position: drone.control //get x,y,z
                batterylevel: drone.updateBattery(batteryPercentage)
	The conditional construct are defined. We get the position and the available battery. The number of UAVs are checked if they fall between 2 and 12

`swarm.forEach(drone) -->`
`counter +=counter`
`if (batterylevel >=96)`
`{`
`threshold`
`=((batterylevel+level)/counter) counter`
`level = level+batterylevel`
`}`
	The accepted battery level is defined to equal or greater than 96%. The threshold is calculated as per equation (1).

`leader = random(swarm.drone.ip)`
`leaderdrone = droneAddress(leader)`
 	
`swarm.forEach(drone) -->`
`if(drone.enabled())`
`{`
`drone.takeOff()`
`}`
`}`
	When all the above constructs have been met then the leader is chosen then the swarm will take off

STEP 1: Three drones are used to illustrate the algorithm. The step is shown in Figure 32.We obtain the following (source code in Appendix B):

- Number of drones in a swarm = 3
- IP Address of each drone
- Initial Battery level percentage for all the UAVs

UAV 1	UAV 2	UAV 3
Battery Percentage: 100	Battery Percentage: 100	Battery Percentage: 100
Drone IP Address: 192.168.1.1	Drone IP Address: 192.168.1.2	Drone IP Address: 192.168.1.3

Figure 32: Notations of three unmanned aerial vehicles

STEP 2: From the collected information in Step 1, it shows that the battery level of each drone was more than 96%, therefore, the next step was to calculate the threshold. Equation 1 shows the threshold computation formula that was used. This involved dividing the energy level available with the number of drones is a swarm.

STEP 3: The leader was then randomly selected. Then the tasks were allocated amongst the UAV as shown in Figure 33.

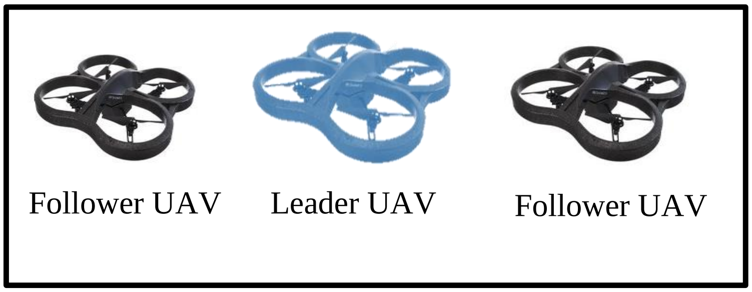
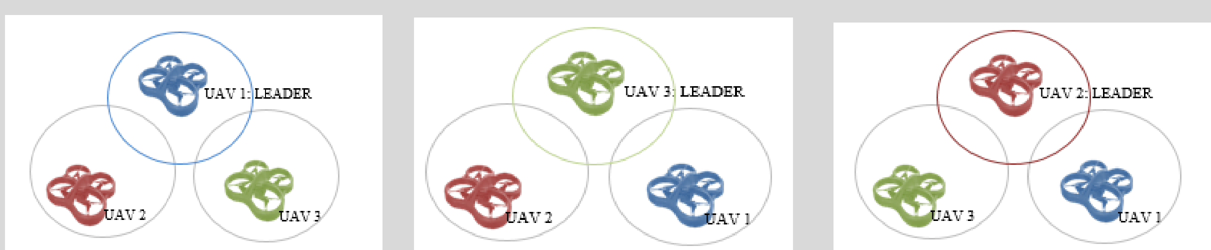


Figure 33: The selected UAV taking the role of the leadership

STEP 4: Then take off was enabled. The leader reached the threshold and the battery for all the follower drones was checked and the drone with the highest energy became the leader. This step was iterated until all the battery was equally drained amongst the UAVs as responsibilities were shared equally in the swarm.



UAV 1 was randomly selected as the leader the eventually it reached the threshold. All the UAVs' battery level was checked to see the one which has the highest energy.

UAV 3 was found to have the highest battery percentage as compared to the other UAVs. As a result UAV 3 became the leader. It eventually reached the threshold and all the UAVs battery level was checked to see the one which has the highest energy.

UAV 2 was found to have the highest battery percentage as compared to the other UAVs. As a result UAV 3 became the leader. It eventually reached the threshold and all the UAVs battery level was checked to see the one which has the highest energy.

Figure 34: Roles rotation process

3.4 Summary

What is Geese Inspired UAV swarm energy-aware and harmonization scheme?

An algorithm that ensures equal responsibility propagation of UAVs in a swarm so that the battery is drained evenly amongst the unmanned aerial vehicles.

What are the advantages of this algorithm?

1. Equal responsibility propagation among UAVs in a swarm
2. Real time update of the available energy in UAVs
3. Consistent battery consumption

How is the algorithm developed?

The algorithm was developed using 4 phased methodology. The first phase was analysis where we gathered all the requirements of developing this algorithm. The second phase was the design phase where we broke down the functions into manageable tasks. The third phase was the development phase which we were putting together the tasks which were broken down at the design phase to do develop the algorithm. This was then followed by the implementation of the algorithm which is the actual execution of the developed algorithm.

This methodology is good as it enabled good progress monitoring. The step by step development progress was seen which boosted efficiency. Dividing the functions into four phases helped us to focus on individual stages which enabled errors to be rectified faster. The only detriment of this methodology is that one could not move to the last stage before completing the first or preceding phase.

What are the tools for developing this algorithm?

- *Design:* Flow Chart and Use Cases
- *Development:* Pseudo Code
- *Implementation:* Code sing java script in Node js

In the next Chapter, we present the results.

Chapter 4: Results

4.1 Chapter Overview

The Chapter is organized as follows. In Section 4.2, we present results. In Section 4.3, we present the evaluation and discussion of the results. These Sections are then followed by the summary of this Chapter in Section 4.4.

The purpose of this study is to rectify the problem of inconsistent battery consumption in a swarm of Unmanned Aerial Vehicles which is caused by a lack of equal responsibility propagation and this has led to the development of a Geese Inspired UAV swarm Energy-Aware and Harmonization algorithm. The Energy-Aware and Harmonization algorithm is entirely about using an interconnection network between the Unmanned Aerial Vehicles to share roles within a swarm. When there is a collaboration and deliberation between Unmanned Aerial Vehicles in a swarm, it makes the sharing of responsibilities within a swarm even more efficient. The leader does not have to bear the responsibilities of being a leader alone, hence the instigation of the energy-aware and harmonization algorithm.

This algorithm uses the energy-aware sequence to compute the threshold which will alert when each rotation should be triggered. The threshold is calculated by the average battery percentage of all the Unmanned Aerial Vehicles in a swarm divided by the total number of drones in a swarm, therefore, when the resulting figure is subtracted from the battery percentage of the leader, the rotation point is established and when the leader reaches the threshold the rotation sequence is executed. The cycle continues until the battery percentages of the UAVs reach the landing point (home point). This cycle enables an even pattern of battery usage within a swarm of Unmanned Aerial Vehicles. The energy-aware approach is the mechanism that is used to check the batteries of the drones in a swarm to determine when to execute the rotation sequence and to establish which UAV is taking the Leadership role. The even exhaustion of battery power enables all the drones in a swarm to have the same interval frame of mission execution and uniform aerial surveillance coverage.

This chapter presents the results that were obtained from the experiments then further discusses and analyses these results. The first three findings are those that form the foundation of our experiments. The first one shows the rate at which a stationary UAV consumes battery. The second one shows the battery consumption of a hovering UAV, and the last one shows the battery consumption of a flying UAV. These three experiments are referred to as elementary as they give us the basics of our research information which we will make use of in the key tryouts. The results of the elementary experiments will be presented and discussed below each experiment. All this then ushers in the presentation, discussion, and analysis of the key results of the energy-aware and harmonization algorithm. The key results are those that show the incorporation of the algorithm and its outcomes. The results will be presented in two categories; the indoor experiment and the outdoor experiment.

This chapter will aid the answering of the following research questions:

- **(RQ1)-** At what rate does a stationery drone, a hovering drone and a flying drone consume battery?
- **(RQ2)-** At what rate does UAVs within a swarm consume battery?
- **(RQ3)-** How is the Energy-Aware and Harmonisation Algorithm going to be implemented and tested?

4.2 Presentation of elementary Results

4.2.1 Stationary Unmanned Aerial Vehicle

The first research question assessed the rate at which energy was being consumed in a stationary Unmanned Aerial Vehicle. This enabled the adequate acquisition of knowledge bases of UAVs. It abetted the researcher in knowing the fundamental information on how much and at what rate the Parrot A.R 2.0 consumes battery. Knowing how much battery was consumed by a stationary UAV aided in measuring the effectiveness of the Energy-Aware and Harmonization algorithm. The experiments show the correlation between two variables being; time and the battery percentage. That is percentage rate of the UAV battery energy that is being consumed every after 5 minutes. The time is in minutes denoted by the (m) symbol and the percentage is denoted by Percentage Symbol (%).

Table 5: Shows the Battery consumption of a stationary UAV every 5 minutes.

Time	Percentage	Time	Percentage	Time	Percentage
0	100	85	71	170	32
5	100	90	69	175	31
10	100	95	66	180	29
15	99	100	64	185	26
20	97	105	61	190	24
25	96	110	59	195	21
30	94	115	56	200	19
35	92	120	54	205	16
40	91	125	52	210	14
45	89	130	51	215	12
50	86	135	49	220	11
55	84	140	46	225	9
60	81	145	44	230	6
65	79	150	41	235	4
70	76	155	39	240	1
75	74	160	36	245	0
80	72	165	34		

In this experiment, the script which displays the current percentage of battery life left was run on a connected UAV and the results were recorded at every 5 minutes interval. Table 5 shows the recorded battery at every 5 minutes interval in a stationary UAV. The overall battery consumption of the stationary UAV lasted for 4 hours 5 minutes. This means the battery life of a stationary Parrot A.R 2.0 is 4 hours 5 Minutes. For reproducibility and verification, the same experiment was repeated to check if the same results will be recorded. The same Unmanned Aerial Vehicle was used but with a different battery. Table 6 shows that there was a slight time difference between the first battery being -battery 1 and the second battery being -battery 2 but it also lasted for 4 hours 5 minutes.

Table 6: Battery consumption of a stationary UAV every 5 minutes using a different Batteries.

Time	Percentage
0	100
5	100
10	100
15	98
20	96
25	93
30	94
35	92
40	91
45	87
50	84
55	82
60	80
65	78
70	76
75	74
80	72
85	71
90	69
95	66
100	64
105	62
110	59
115	56
120	54
125	52
130	51
135	49
140	46
145	44
150	42
155	39
160	36
165	34
170	32
175	31
180	29
185	26
190	24
195	21
200	18
205	16
210	14
215	12
220	11
225	9
230	6
235	4
240	1
245	0

Figure 35 and Figure 36 show a graphical representation of the battery consumption rate in a stationary UAV. Figure 35 shows the results of the first experiment on a stationary UAV. Figure 36 shows the contrasting outcomes of the two different experiments (same UAV with different batteries). Figure 37 depicts the results of the two experiments and the mean time of the experiments.

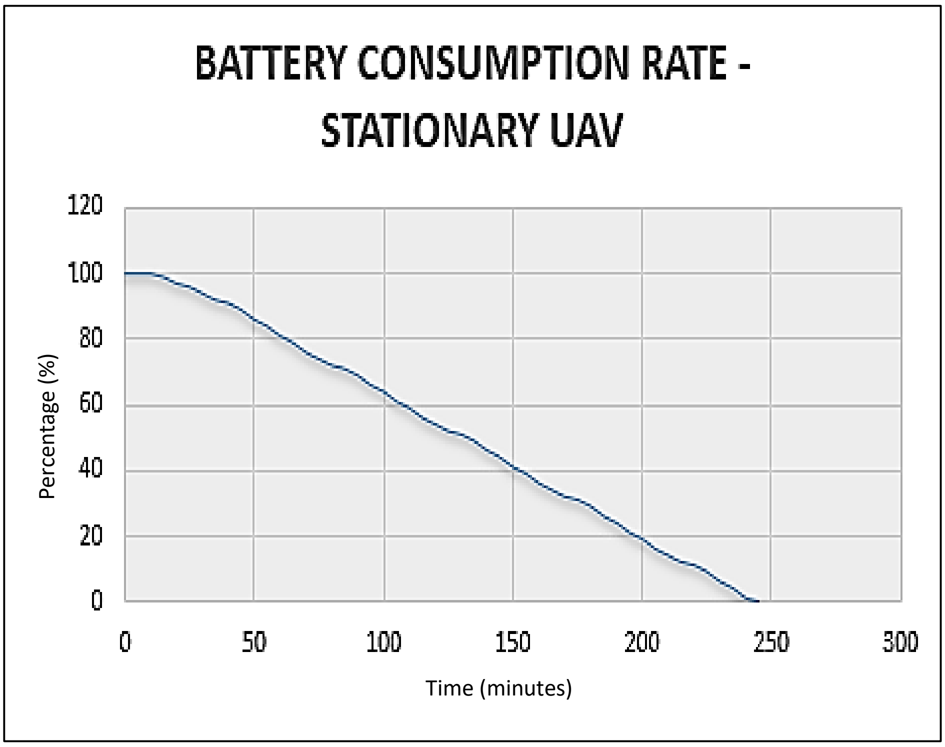


Figure 35: Battery ratio consumed every 5 minutes in a stationary Unmanned Aerial Vehicle (UAV).

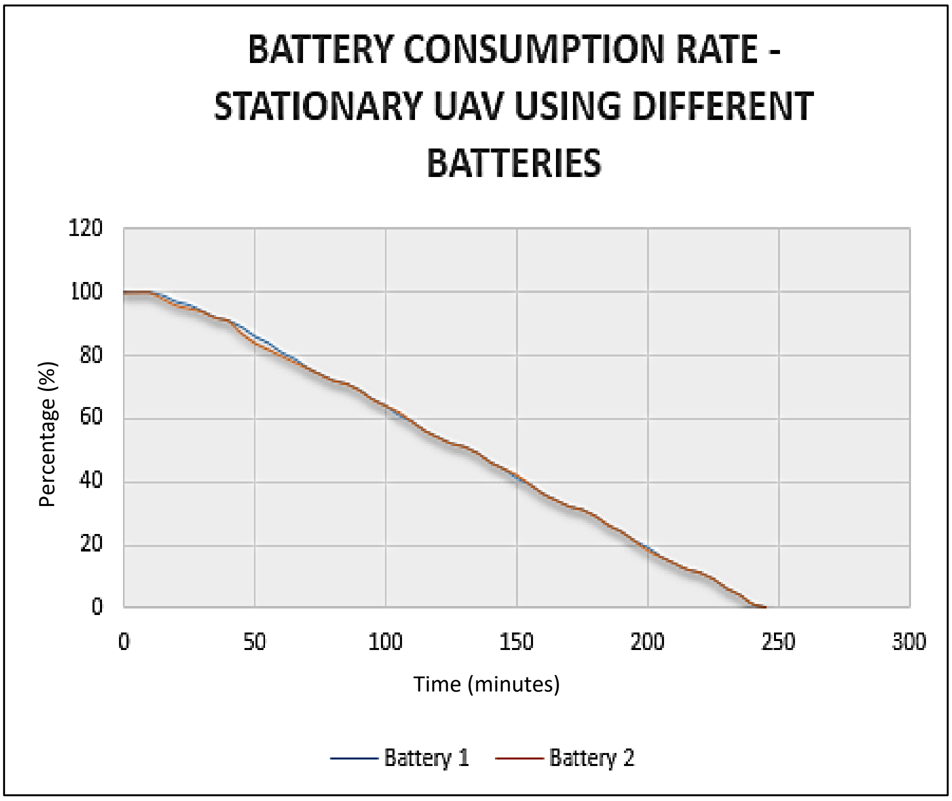


Figure 36: This graph shows the battery consumption rate of a stationary UAV using a different battery from the one in Figure 32.

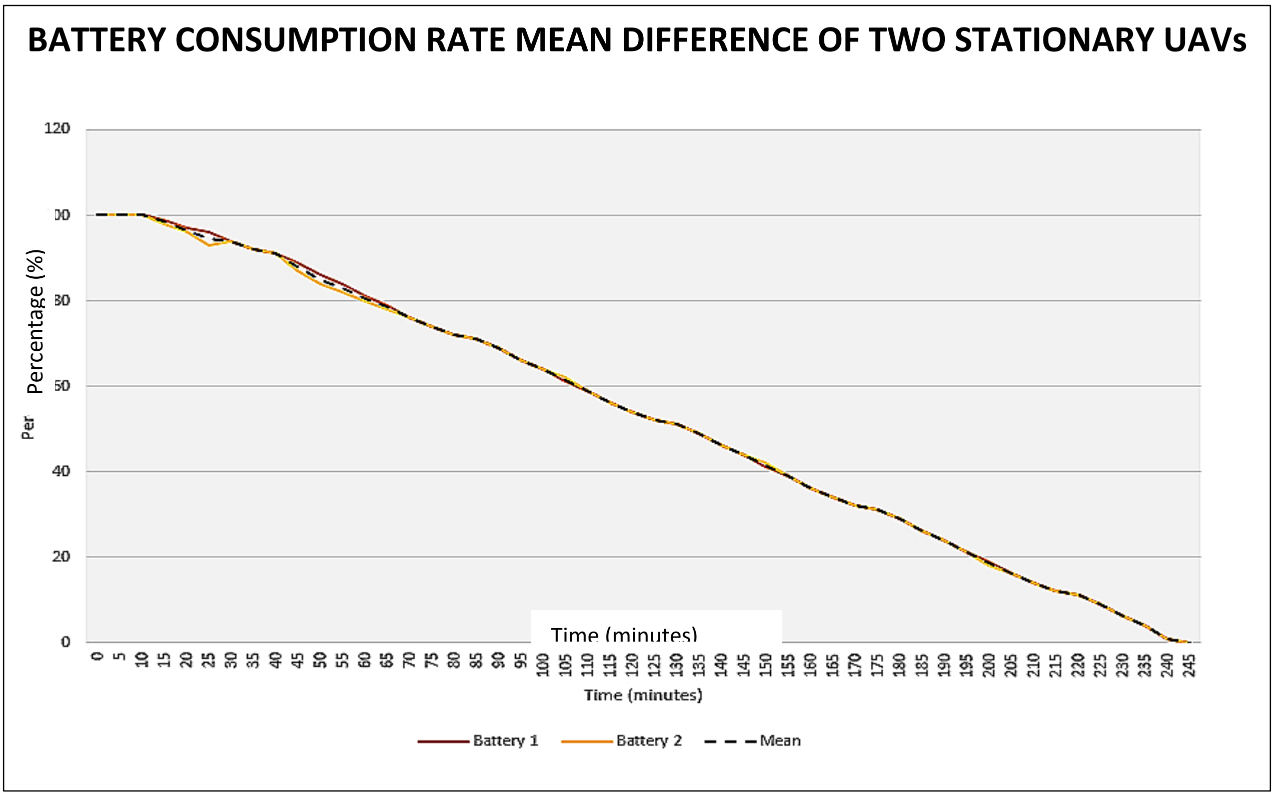


Figure 37: This graph depicts the mean of experiments shown in Figure 35 and Figure 36 alongside with their results.

The variable which was not the same in the two experiments (Figure 35 and Figure 36) was the Battery. Two different batteries of the same model were used, and according to the results, they have shown to have a 14% slight dissimilarity but they all switched off at 245minutes.

4.2.2 Hovering Unmanned Aerial Vehicle

Table 7: Battery Consumption of a Hovering Unmanned Aerial Vehicle (indoor)

Time (m)	Percentage
0	100
5	92
10	83
15	73
20	65
25	57
30	48
35	39
40	29
45	18
50	9
55	0

Table 8: Battery Consumption of a Hovering Unmanned Aerial Vehicle (outdoor)

Time (m)	Percentage
0	100
5	88
10	67
15	49
20	32
25	25
30	15
35	6
40	0

Table 7 shows that a hovering Unmanned Aerial Vehicle without any other activity taking place and in a controlled environment an AR Drones takes 55 minutes. Table 8 shows the results of a hovering Unmanned Aerial Vehicle in an uncontrolled environment. It was performed outside at the drone port, where the wind and velocity have not been controlled, this AR Drone only hovered for 40 minutes and landed because of no battery.

4.2.3 Flying Unmanned Aerial Vehicle

Table 9: Battery Consumption rate of a flying Unmanned Aerial Vehicles

Time (m)	Percentage
0	100
5	81
10	68
15	40
20	21
23	0

Table 9 shows the results of a flying unmanned aerial Vehicle, the overall time flying time of an AR Drone is 23 minutes. This experiment was done in a controlled environment.

4.3 Evaluation and Discussion of results

This Section encompasses the presentation and discussion of the main findings gathered from the experiment where the energy-aware and harmonization algorithm was instigated. The focus of this Section will be on the outcomes of the introduction and implementation of the algorithm. In the first experiment (5.3.1) of this Section, we evaluate the battery consumption of a leader Unmanned Aerial Vehicle against the follower Unmanned Aerial Vehicles to assess how much battery is consumed by Unmanned Aerial Vehicles in a swarm. The second experiment (5.3.2) shows the deployment of the Energy-Aware and Harmonization algorithm in three Unmanned Aerial Vehicles in an indoor setting. The third experiment (5.3.3) shows the deployment of the Energy-Aware and Harmonization algorithm in three Unmanned Aerial Vehicles in an outdoor setting. The last experiment (4.3.4) shows the deployment of the Energy-Aware and Harmonization algorithm in five Unmanned Aerial Vehicles in an indoor setting.

4.3.1 Battery utilization in UAVS within a swarm (Leader-Follower Formation)

The assessment of battery consumption of UAVs in a swarm to see how much energy the leader UAV uses and how much energy is consumed by the follower UAV was completed. The appraisal was performed using the leader-follower approach where one drone was leading and the other drones following [56]. Three Unmanned Aerial Vehicles (UAV) were used and UAV 1 was given the responsibility of being a leader and UAV 2 and UAV 3 were the follower drones. They were placed as shown in Figure 38. They were placed at the BIUST drone port and flown from there as a swarm. The outcomes of the experiment are depicted in Table 10. The results are further discussed using the graph in Figure 39.

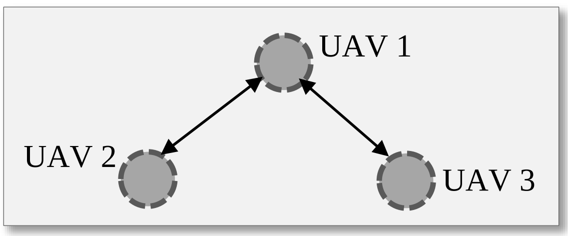


Figure 38: The Swarm Formation Setup that was followed in the experiment

Table 10: Experimental Results of Battery utilization in UAVs within a swarm

Time (m)	**Unmanned Aerial Vehicle (UAV 1) Leader**	**Unmanned Aerial Vehicle (UAV 2) Follower 1**	**Unmanned Aerial Vehicle (UAV 3) Follower 2**
0	100%	100%	100%
5	67%	85%	87%
10	34%	70%	74%
15	1%	55%	61%
20		40%	48%
25		25%	35%
30		10%	22%
35			9%

Figure 39 shows the battery consumption pattern of the UAVs in a swarm in an outdoor setting, to analyse the performances of UAVs in a swarm without the Energy-Aware and Battery synchronization algorithms. It was discovered through this experiment that the battery usage of the UAVs in a swarm was uneven, because of differences in fixed responsibility roles of each UAV. The leader UAVs battery level declined significantly faster than the follower UAVs. In exactly 15minutes, the leader had depleted all the energy in the battery, while UAV2 and UAV3's battery levels were at 55% and 61 %, respectively. At this point, the leader had been forced to land and abort the mission, leaving the follower UAVs alone. The remaining UAVs in the swarm continued the mission but they were reporting to a Leader that was now offline, which resulted in errors because the data could not reach the base station. UAV2 had its battery level depleted exactly 30minutes after the mission began, and UAV3 followed 35 minutes later.

This mission failed because 1. The leader of the formation had long left the swarm which means the roles that were to be accomplished by the leader were left unattended 2. The second Unmanned Aerial Vehicle labelled as UAV 2 left the mission as well leaving UAV 3 alone and that now was no longer a swarm 3. A swarm mission is set to be successful if all the UAVs in a swarm fulfil their designated responsibilities and if the other leaves the mission earlier it means their roles are left unattended. This is what transpired in this experiment because of the workload of the leader UAV the battery got depleted before the other UAVs battery can be depleted leading to the loss of the leader in the process hence a failed mission. These results confirm the necessity of an Energy-aware and Harmonization algorithm in order to balance the battery consumption of UAVs in a swarm so that they can start and finish as a mission as a swarm.

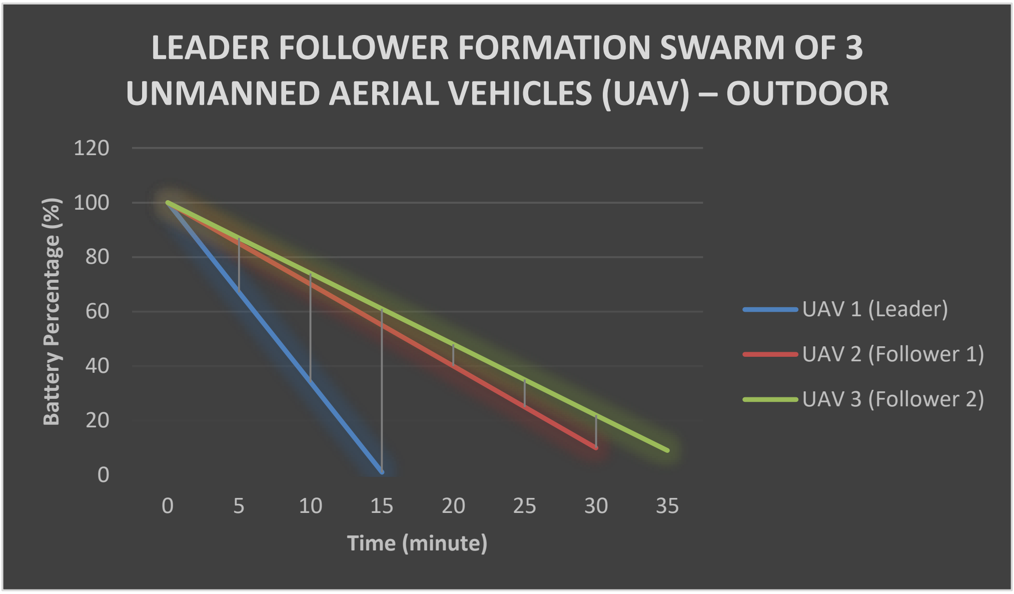


Figure 39: Unmanned Aerial Vehicle Swarm using Leader-Follower formation

4.3.2 Energy-Aware and Harmonization algorithm using three (3) unmanned aerial vehicles (UAV) – Indoor

To validate the viability of the developed algorithm, three (3) Unmanned Aerial Vehicles in a swarm were set out to fly in a leader-follower formation. Amongst the three UAVs, a leader was randomly selected and the other UAVs claiming the follower responsibility. The UAV rotated responsibility amongst themselves ensuring that battery consumption is harmonized in the whole swarm arrangement. The initial states are shown in Table 11 followed by the calculation of the threshold which acted as a pivot point where we could then rotate the responsibility of each UAV taking into consideration the amount of battery consumed. The calculation is shown alongside the threshold in Figure 40.

Table 11: Initial States (Preliminary Experimentation Term)

UAV	**Battery Percentage**
1	100%
2	100%
3	100%

$$\sum_{i+1}^{m} \left(\frac{batteryLevel}{m}\right)/m = threshold$$

$$threshold = \frac{100}{3} = 33.333 = 33$$

Figure 40: A mathematical Expression to calculate the threshold

Table 12: Shows Experimental 2 Results

Lap	**Unmanned Aerial Vehicle (UAV)**	**Battery Percentage**	**Roles**
1	1	100%	Leader
	2	100%	Follower
	3	100%	Follower
2	1	67%	Follower
	2	85%	Follower
	3	87%	Leader
3	1	52%	Follower
	2	70%	Leader
	3	54%	Follower
4	1	39%	Leader
	2	37%	Follower
	3	38%	Follower
5	1	5.7%	IMMEDIATELY THE DRONES LANDED BECAUSE THE BATTERY LEVEL OF UAV 1 WAS LESS THAN 20
	2	22%	
	3	26%	

According to the results in Table 12, UAV 1 Started at the beginning of the experiment as the leader with 100% battery and UAV 2 and UAV 3 were the followers with the same battery percentage of 100%. The second lap shows that the leader is now UAV 3 with 87% battery and UAV 1 and UAV 2 with 67% and 85% batteries levels consecutively. The third lap then shows that UAV 2 becomes the leader with 70%

battery level and UAV 1 and UAV 3 being the followers; UAV 1 with 52%, UAV 3 with 54% battery levels. At this stage all Unmanned Aerial Vehicles had taken part in being the leaders, they shared the role enabling battery to be consumed equally amongst them. This was confirmed by the results of lap 4 which shows UAV 1 = with 39% battery level, UAV 2 = with 37% battery level and UAV 3 = with 38% battery level. The difference being between 1% and 2% showing the harmony and success of the algorithm proposed. This is further elaborated in Figure 41.

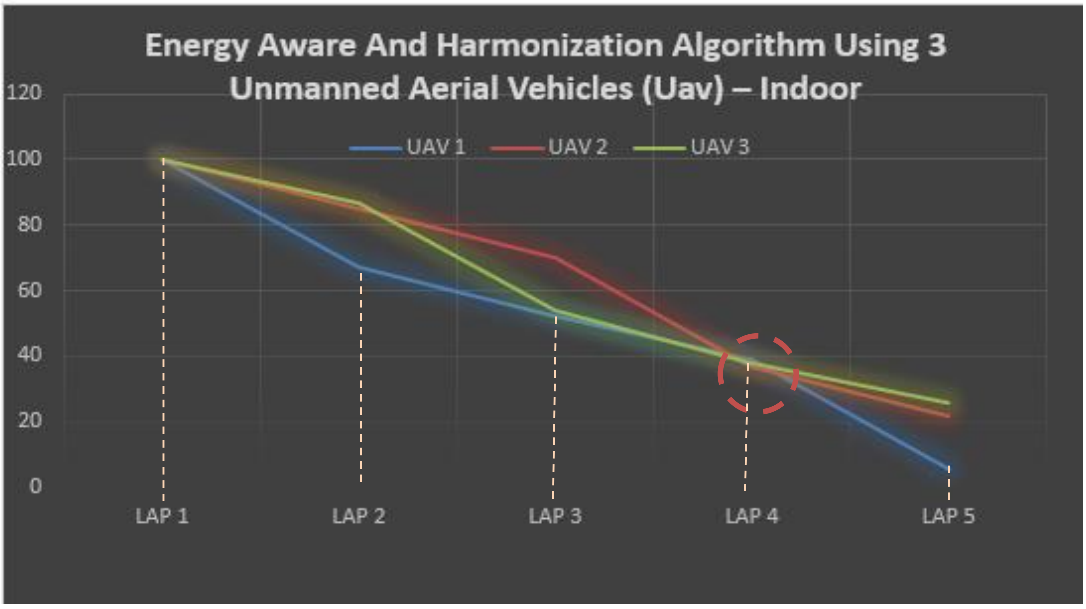


Figure 41: Energy-aware and Harmonization algorithm using three (3) unmanned aerial vehicles (UAV) – Indoor

The graph in Figure 41 shows the performance results of UAVs in a swarm with the enhancement of the Energy-Aware and Harmonization Algorithm. The three UAVs in this swarm were tested in an indoor setting. The Algorithm randomly chose the leader since all the UAVs in the swarm had the same battery level percentage of 100%. UAV 1 was chosen to be the leader, and UAV 2 and UAV 3 were made followers. On the first lap, the battery consumption of the leader was very steep, and it lost a lot of energy in the first lap due to the demanding responsibilities of a leader.

On the other hand, the follower UAVs had a steady and minimum battery usage in the first lap, and UAV3 and UAV 2 had similar battery consumption. In the second lap, the Energy-Aware and Harmonization Algorithm executed the rotation sequence which determined the next leader UAV in the swarm based on the highest battery level percentage criteria and in this case, that was UAV3. Immediately after rotation was initiated, UAV1 battery usage decreased, and it started stabilising, yet UAV 3 which was now the leader, had a sudden increase in battery usage, and UAV2 was still at average usage. When the leader reached the threshold, the energy-aware executed the rotation sequence again, marking the beginning of the third lap.

With the UAV2 being the leader in this lap, the steep and sudden decline of the battery of the leader was absolute, while UAV 1 and UAV3 started to reduce their battery usage and stabilised. On the fourth lap, all the UAVs had executed the leadership role, and the energy-aware and harmonization algorithm computed the leader for the next lap based on the highest battery percentage of all the UAVs in the swarm, and UAV1 was the Leader. This last lap was determined by The Energy-Aware and Harmonization algorithm when it computed the threshold, and when the Energy prompt sequence reported that the leader had less than 20% battery remaining, the UAV Swarm Landing sequence was initiated and all the UAVs in the swarm landed.

The algorithm was a success in an indoor setting, and the battery efficiency of the drones escalated a notch as they had longer battery lifetime than if the leader was not rotated. The Energy-Aware and Harmonization algorithm also helped to eradicate errors in the swarm like followers sending information to the leader UAV who is out of formation and out of the swarm. The algorithm makes sure there is always a leader, and that in turn makes sure that all the data captured by the UAVs in the swarm in preserved and stored to the base station through the Leader.

4.3.3 Energy-Aware and Harmonization algorithm using 3 unmanned aerial vehicles (UAV) – Outdoor

The setting of the third experiment was changed from indoor to outdoor to certify the feasibility of the developed algorithm in a different scenery. Three (3) Unmanned Aerial Vehicles in a swarm were positioned to fly in a leader-follower formation. Amongst the three UAVs, a leader was randomly elected and the other UAVs claiming the follower responsibility. The UAV rotated responsibility amongst themselves ensuring that battery consumption is harmonized in the whole swarm. The results of this experiment are depicted in Table 13.

Table 13: Shows Experimental 3 Results

Lap	**Unmanned Aerial Vehicle (UAV)**	**Battery Percentage**	**Roles**
1	1	100%	Leader
	2	100%	Follower
	3	100%	Follower
2	1	67%	Follower
	2	75%	Follower
	3	77%	Leader
3	1	42%	Follower
	2	52%	Leader
	3	44%	Follower
4	1	17%	IMMEDIATELY THE DRONES LANDED BECAUSE THE BATTERY LEVEL OF ALL THE UAVs WAS LESS THAN 20
	2	19%	
	3	18%	

According to the results in Table 13, UAV 1 Started off at the beginning of the experiment as the leader with 100% battery and UAV 2 and UAV 3 were the followers. The second lap shows that the leader is now UAV 3 with 77% battery and UAV 1 and UAV 2 with 67% and 75% batteries sequentially. The third lap then shows that UAV 2 becomes the leader with 52% battery and UAV 1 with 42%, UAV 3 with 44% as followers. At this stage all Unmanned Aerial Vehicles had taken part in being the leaders, they shared the role-enabling battery to be consumed equally amongst them. This was confirmed by the results of lap 4 which shows UAV 1 = with 17% battery, UAV 2 = with 19% battery and UAV 3 = with 18% battery, giving a mean of 18% and a difference of 1%.

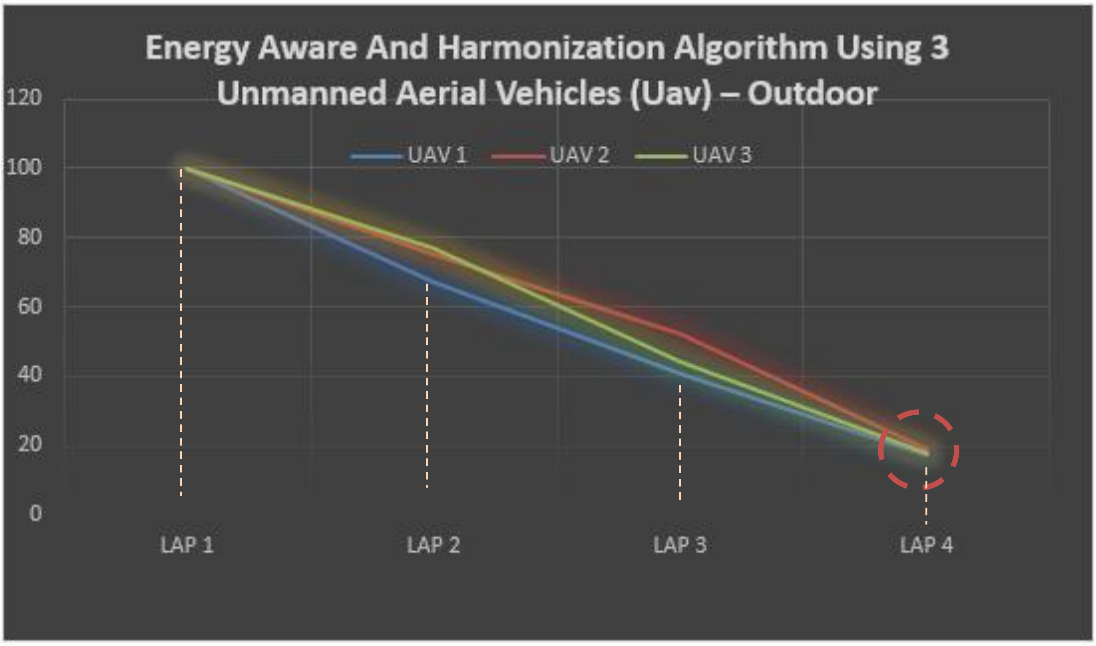


Figure 42: Energy-Aware and Harmonization algorithm using three (3) unmanned aerial vehicles (UAV) – Outdoor

The graph in Figure 42, shows the performance results of UAVs in a swarm with the deployment of the Energy-Aware and Harmonization Algorithm. The focus of this experiment was to test the Energy-Aware and Harmonization Algorithm in a swarm of three (3) Unmanned Aerial Vehicles outside hence being identified as an outdoor setting experiment. The Algorithm randomly chose the leader since all the UAVs in the swarm had the same battery level percentage of 100%. UAV 1 was chosen to be the leader and UAV 2 and UAV 3 were made followers.

All UAVs start at a 100% battery percentage, this then launches a lap. From the graph lap one, all the UAVs start off as precipitous and immediately they regress as they take wing. The way the regress is vigorous because in an outdoor setting there are many factors that affect the battery consumption of the UAV as compared to an indoor setting. Factors such as wind are not easily controlled and thus affect the battery that is why there is a huge decline when comparing with the initial battery percentage. In Lap two UAV 3 becomes the leader whilst UAV 1 and UAV 2 become the followers. There is a rotation of responsibility between UAV 1 AND UAV 3 with the aim to harmonize battery consumption. The flying continues and in Lap three UAV 2 becomes the leader swapping roles with UAV 3 which becomes the follower UAV. The battery consumption of the UAVs continues to decline. Lap four validates the feasibility of the Energy-Aware and Harmonization Algorithm because it shows the battery being balanced amongst the UAVs. Even though the rates are below 20% which is the landing point set out in the algorithm, the 1% difference shows that rotating responsibility indeed balances the energy consumption rate in UAVs in a swarm. UAV 1: 17% UAV 2: 19% UAV 3 18%

4.3.4 Energy-aware and Harmonization algorithm using 5 Unmanned Aerial Vehicles (UAVs) – Indoor

The last experiment which was conducted was to check the viability of the Energy-Aware and Harmonization using five Unmanned Aerial Vehicles Indoors. The results are shown in Table 14.

Table 14: Energy-aware and Harmonization algorithm using 5 Unmanned Aerial Vehicles (UAVs) – Indoor

LAP	Unmanned Aerial Vehicle (UAV)	Battery Percentage	Roles
1	1	100%	Leader
	2	100%	Follower
	3	100%	Follower
	4	100%	Follower
	5	100%	Follower
2	1	80%	Follower
	2	85%	Follower
	3	87%	Follower
	4	83%	Follower
	5	88%	Leader
3	1	65%	Follower
	2	72%	Leader
	3	70%	Follower
	4	71%	Follower
	5	68%	Follower
4	1	52%	Follower
	2	52%	Follower
	3	58%	Leader
	4	54%	Follower
	5	53%	Follower
5	1	39%	Follower
	2	32%	Follower
	3	38%	Follower
	4	40%	Leader
	5	36%	Follower
6	1	23%	IMMEDIATELY THE DRONES LANDED BECAUSE THE BATTERY LEVEL OF HA REACHED THE MINIMUM LEVEL OF 20%
	2	24%	
	3	22%	
	4	20%	
	5	21%	

Figure 43 shows the performance results of UAVs in a swarm with the enhancement of Energy-Aware and Harmonization Algorithm in an outdoor setting. The five UAVs in this swarm had the same battery level of 100% before we initiated the experiment. The leader was randomly chosen by the Energy-Aware and the harmonization algorithm, and UAV1 was chosen. The energy-aware and harmonization algorithm computed the threshold to be 20%, that is, every time the leader loses 20% of its battery percentage, the rotation of the leader will be initiated. There was a rather steep decline in the battery percentage of the leader in the first lap, while the other follower UAVs in the swarm had a lower battery usage rate in the first lap.

The leader UAV1 reached its threshold and the Energy-Aware and Harmonization Algorithm elected UAV5 as the leader based on the highest battery percentage criteria of all the UAVs in the swarm. In the second lap, the battery usage rate of UAV5 increased a notch while that of UAV1 decreased. When UAV5 lost 20% of its battery life, it reached its threshold, and the rotation sequence was implemented and the energy-aware and harmonization algorithm chose UAV 2 as the leader marking the beginning of a new lap, the third lap. UAV2 had lost 15percent on the first lap, and 13 percent on the second, which is with the same range, but when it became the leader of the swarm in the third lap, it lost 20 percent on its third lap which is because of the leader roles it was performing, consequently reaching its threshold. On the fourth lap, UAV3 was chosen leader, with 58% battery percentage which was the highest battery percentage in that lap. After 20% battery percentage was used from the UAV3 battery pack, the rotation sequence implemented by the energy-aware and harmonization algorithm saw UAV4 being made leader marking the beginning of the fifth lap.

This lap had UAV4 with the highest battery percentage of 40% because it was the only UAV that had not yet taken the leader responsibilities. After 20% of the battery, the battery of the leader UAV was depleted, the threshold was reached, so was the minimum level of 20%. When the minimum level was reached, the algorithm executed the landing process, forcing all the UAVS in the swarm to land. The remaining battery percentage of all the UAVs was reserved for landing and sending the captured data, which avoids loss of data and damage to the UAVs. Based on the results above, the execution of the Energy-aware and Harmonization Algorithm was a success, because it extended the battery life of all the UAVs in the swarm and it made sure that all the data captured was sent to the base station through the leader then finally it made sure that all the UAVs in the swarm land safely before all the battery life was depleted while in flight.

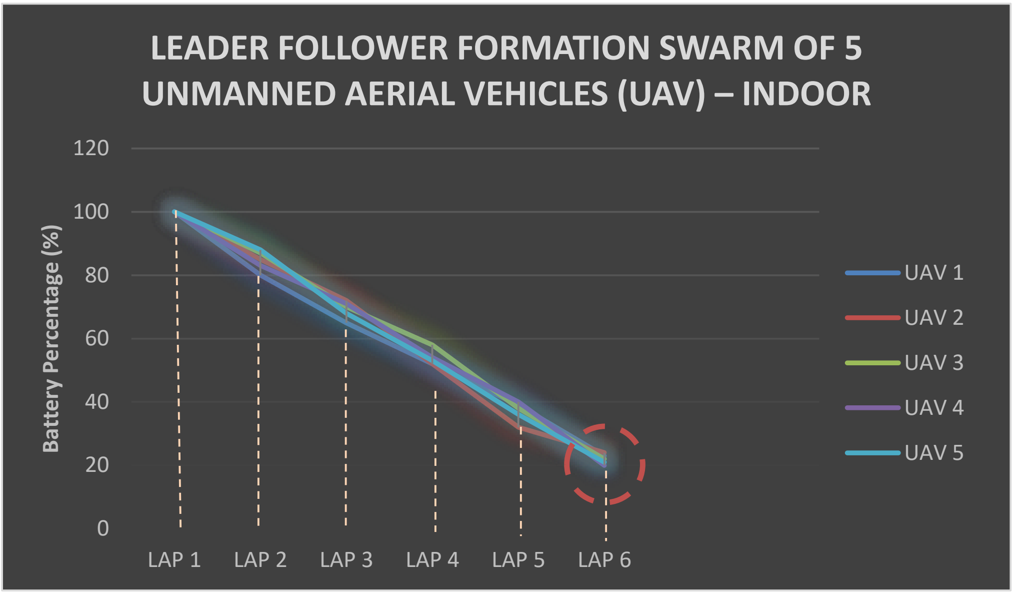


Figure 43: Leader Follower Formation Swarm of 5 Unmanned Aerial Vehicles (UAV) – Indoor

4.4 Summary

The first experiment was the indoor experiment with three unmanned aerial vehicles. The second one was the outdoor experiment with three unmanned aerial vehicles. The third one was an outdoor experiment with five unmanned aerial vehicles. According to the results of all these three experiments, the development of the Geese Inspired UAV Swarm Energy-Aware and Harmonization Algorithm was achieved. Unmanned Aerial Vehicles in a swarm shared the leadership role equally hence the equal battery consumption and no UAV was lost in the mission earlier than others. When the battery was low they all landed waiting to be charged and continue with the mission.

The algorithm was a success in an indoor setting, and the battery efficiency of the drones escalated a notch as they had longer battery lifetime than when the leader was not rotated. The Energy-Aware and Harmonization algorithm also helped to eradicate errors in the swarm-like followers sending information to the leader UAV who was out of formation and out of the swarm. The algorithm makes sure there is always a leader, and that in turn makes sure that all the data captured by the UAVs in the swarm is preserved and stored to the base station through the Leader. The more the UAVs, the more the flight range increases as the initial formation, hence the reason experiment 3 with 5 drones reached lap 6. The other observation is when the environment is controlled, there is less energy consumption hence the increased flight range indoor. In the next Chapter, we present the conclusion.

Chapter 5: Conclusion

5.1 Chapter Overview

This Chapter establishes the conclusions based on the findings of the study and in accordance with the research objectives established in Chapter one. It comprises of three sections: Section 6.1 presents the conclusion of the study which gives an overview of the answer to the main research question. Section 6.2 presents the limitations encountered throughout the research. Section 6.3 presents the future works that will consolidate this study research in the near future. Section 6.4 shows the summary of Chapter 6.

5.2 Conclusion of the research

The use of UAVs swarms has increased drastically in recent years and they are revolutionising industries from one end to the other. However, despite their advantages, research has shown that their biggest limitation is the lack of equal responsibility propagation which has led to numerous unsuccessful UAV swarm missions [7]. This is because when the responsibilities are not shared equally, the leader unmanned aerial vehicle will consume more battery than the follower UAVs because it is given more work than the followers and in turn this will result in the loss of the leader UAV; hence limiting the range of the whole swarm resulting in a failed mission termed as ‘unsuccessful’.

As a resolution, this study aimed to develop geese inspired scheme to model the UAV swarm rotation. The model ensured that there is leadership rotation which allowed equal responsibility propagation, safeguarding that battery is drained evenly amongst the UAVs in a swarm. The leader-follower reciprocation mechanism and the energy-aware computational movement ensured harmonization in a swarm of UAVs by facilitating the rotation of UAVs while being aware of the amount of energy available on each UAV.

Various experiments were conducted in accordance to the research objectives. The first experimental comparison was performed where the amount of battery consumed was measured in a single UAV in different scenarios (i.e., stationery, hovering, flying, and leader-follower structure), the reason being to get the bases and control point of our experiments. The second experimental layout was the actual focus of our research where we actuated the developed algorithm and tested it in different setups ((i.e., indoor setting, outdoor setting, and augmented number of UAVs). The energy-aware and harmonization algorithm was adapted and at each point we were fully aware of the amount of battery that we had and gearing up for the next step to be taken in order to ensure that responsibility is equally shared amongst the UAVs.

The findings of these experiments proved that the algorithm successfully harmonises the battery consumption of a UAV swarm leading to consistent battery consumption. The development of the Geese Inspired UAV Swarm Energy-aware and Harmonization Algorithm ensured that UAVs in a swarm equally share responsibility by rotating the leadership role on the basis of the amount of battery a leader had at that particular time. If there is a UAV in swarm with more battery than the leader then that UAV will get the role of leading the swarm allowing consistent and equal role propagation. The summary is shown in Figure 44 which depicts the gabs and the resolution in fulfilling the main objective.

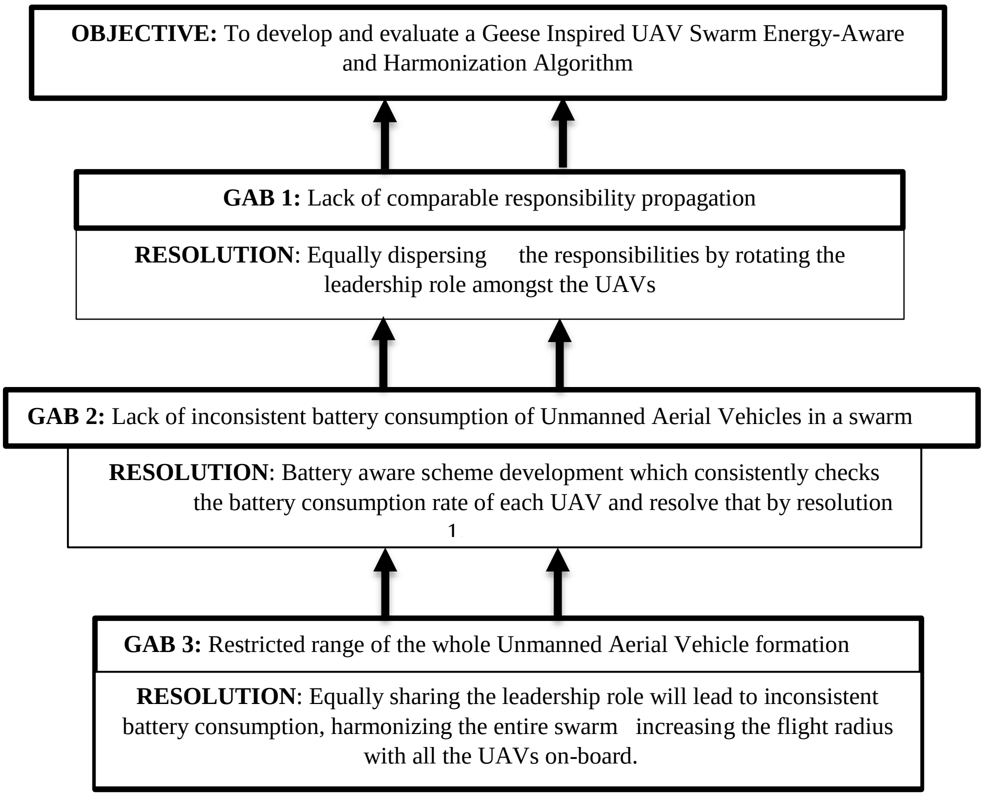


Figure 44: Shows the gabs that were identified along with their resolutions

5.3 Achievement of Objectives

Table 15 shows where the objectives stated in Section 1.3.2 were achieved.

Table 15: The location of achievement of Objectives

Specific Objectives	**Where the objectives were achieved in the document**
Evaluate the battery consumption rate of a standard UAV in three states; when stationery, hovering and flying.	Chapter 4. Section 4.2
Assess battery utilization in UAVs within a swarm in a leader and follower formation.	Chapter 4. Section 4.3
Design an energy-aware harmonising scheme / algorithm.	Chapter 3. Section 3.3
Implement and Test the Energy-Aware and Harmonisation Algorithm.	Chapter 3. Section 3.3

Evaluate the algorithm Energy-Aware and Harmonisation Algorithm.	Chapter 4. Section 4.3

5.4 Limitations of the research

The sample size was minimal as a result of the number of unmanned aerial vehicles that were available. The research was based on the number of UAVs available which led to a limited exploration of the research because it was impossible to test if this algorithm would work in many UAVs. There was a need to retest in order to validate and verify the results, this was time-consuming because it required me to charge UAV batteries repeatedly.

5.5 Future Works

While this research has provided useful insights into harmonizing battery consumption in Unmanned Aerial Vehicle swarms, further work needs to be done in this area. Future work needs to explore other Unmanned Vehicles without only focusing on Unmanned Aerial Vehicles because lack of comparable responsibility propagation is a mutual problem experienced by all unmanned vehicles. Furthermore, there is a need for future works to explore the results by adding more UAVs surpassing the maximum of 5 that was used in this study.

5.6 Summary

The geese inspired UAV energy-aware and harmonization algorithm allows responsibilities to be shared equally amongst unmanned aerial vehicles in a swarm. The real-time update on the energy-level of each unmanned aerial vehicle allows the threshold sequence to be executed at the right time to enable rotation between the leader and the following unmanned aerial vehicle. We look forward to continued development in applying this algorithm in different aerial vehicles in order to harmonize battery consumption.

Bibliography

[1] X. Zhu, Z. Liu, and J. Yang, “Model of collaborative UAV swarm toward coordination and control mechanisms study,” *Procedia Comput. Sci.*, vol. 51, no. 1, pp. 493–502, 2015.

[2] Y. Wei, M. Brian Blake, and G. R. Madey, “An operation-time simulation framework for UAV swarm configuration and mission planning,” *Procedia Comput. Sci.*, vol. 18, pp. 1949–1958, 2013.

[3] M. Gupta, D. Saxena, S. Kumari, and D. Kaur, “Issues and applications of swarm robotics,” *Int. J. Res. Eng. Technol. Sci.*, vol. VI, no. July, pp. 1–5, 2016.

[4] P. L. Haibin Duan, “Bio-inspired Computation in Unmanned Aerial Vehicles,” Beijing China, People’s Republic: Springer Berlin Heidelberg, 2014, pp. 1–50.

[5] A. G. Madey, “Unmanned Aerial Vehicle Swarms: The Design and Evaluation of Command and Control Strategies using Agent-Based Modeling,” *Int. J. Agent Technol. Syst.*, vol. 5, no. 3, pp. 1–13, 2013.

[6] S. Janssen, “Assessing the perception of drones in the construction industry,” University of Twente, 2015.

[7] H. Duan, S. Member, and H. Qiu, “Unmanned Aerial Vehicle Distributed Formation Rotation Control Inspired by Leader-Follower Reciprocation of Migrant Birds,” pp. 23431–23443, 2018.

[8] R. Rafifandi, D. L. Asri, E. Ekawati, and E. M. Budi, “Leader – follower formation control of two quadrotor UAVs,” *SN Appl. Sci.*, vol. 1, no. 6, pp. 1–12, 2019.

[9] M. Hejase, H. Noura, and A. Drak, “Formation Flight of Small Scale Unmanned Aerial Vehicles : A Review,” no. January, 2015.

[10] J. Chung, “Cooperative Control of UAVs Using a Single Master Subsystem for Multi-task Multi-target Operations,” in *Robot Intelligence Technology and Applications 3*, 2015, pp. 193–212.

[11] Z. Hou and I. Fantoni, “Distributed leader-follower formation control for

multiple quadrotors with weighted topology," *2015 10th Syst. Syst. Eng. Conf. SoSE 2015*, pp. 256–261, 2015.

[12] R. D. Arnold, H. Yamaguchi, and T. Tanaka, "Search and rescue with autonomous flying robots through behavior-based cooperative intelligence," *J. Int. Humanit. Action*, vol. 3, no. 1, p. 18, 2018.

[13] L. Beaudoin *et al.*, "Potential Threats of UAS Swarms and the Countermeasure ' s Need," no. HAL Id : hal-01132236, 2015.

[14] I. L. Bajec and F. H. Heppner, "Organized flight in birds," *Anim. Behav.*, vol. 78, no. 4, pp. 777–789, 2009.

[15] Cutts and Speakman, "Energy Savings in Formation Flight of Pink-Footed Geese," *J. Exp. Biol.*, vol. 189, no. 1, pp. 251–61, 1994.

[16] M. Andersson and J. Wallander, "Kin selection and reciprocity in flight formation?," *Behav. Ecol.*, vol. 15, no. 1, pp. 158–162, 2004.

[17] K. Li, W. Ni, X. Wang, R. P. Liu, S. S. Kanhere, and S. Jha, "Energy-efficient cooperative relaying for unmanned aerial vehicles," *IEEE Trans. Mob. Comput.*, vol. 15, no. 6, pp. 1377–1386, 2016.

[18] J. J. Ruiz, F. Caballero, and L. Merino, "MGRAPH: A Multigraph Homography Method to Generate Incremental Mosaics in Real-Time from UAV Swarms," *IEEE Robot. Autom. Lett.*, vol. 3, no. 4, pp. 2838–2845, 2018.

[19] Alexander Wetmore, "SSS_09_Wetmore_Miller_Gidley_1931.pdf." .

[20] G. F. Barrowclough, J. Cracraft, J. Klicka, and R. M. Zink, "How many kinds of birds are there and why does it matter?," *PLoS One*, vol. 11, no. 11, pp. 1–15, 2016.

[21] A. E. Smith *et al.*, *Managing Canada Geese in Urban Environments*. Cornell University CooperativeExtension, Ithaca, N.Y: JackBerryman Institute Publication 16, and Cornell University CooperativeExtension, Ithaca, N.Y., 1999.

[22] G. Boere and T. Dodman, "Understanding the Flyway Approach to Conservation," *Flyw. approach to Conserv. wise use waterbirds Wetl. A Train. Kit*, pp. 1–108, 2010.

[23] T. Alerstam, A. Hedenstro, and A. Susanne, “Long-distance migration : evolution and determinants Long-distance migration : evolution and determinants,” 2003.

[24] A. D. Rocha *et al.*, “Shorebirds: A Vulnerability Assessment for the Great Barrier Reef,” *J. Avian Biol.*, vol. 413, no. 1, pp. 1–119, 2018.

[25] S. A. Ning, “Aircraft Drag Reduction Through Extended Formation Flight,” 2011.

[26] G. Beauchamp, “Long-distance migrating species of birds travel in larger groups,” *Society*, no. April, pp. 692–694, 2011.

[27] C. I. D., K. Jens, F. N. R., and L. S. A., “Effective leadership and decision-making in animal groups on the move,” *Nature*, vol. 433, no. 3, pp. 513–516, 2005.

[28] G. Limnaios, “Current Usage of Unmanned Aircraft Systems (UAS) and Future Challenges : A Mission Oriented Simulator for UAS as a Tool for Design and Performance Evaluation,” *J. Comput. Model.*, vol. 4, no. 1, pp. 167–188, 2014.

[29] T. Stirling, S. Wischmann, and D. Floreano, “Energy-efficient indoor search by swarms of simulated flying robots without global information,” *Swarm Intell.*, vol. 4, no. 2, pp. 117–143, 2010.

[30] S. Waharte, N. Trigoni, and S. J. Julier, “Coordinated search with a swarm of UAVs,” *2009 6th IEEE Annu. Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Networks Work. SECON Work. 2009*, vol. 00, no. c, pp. 1–3, 2009.

[31] W. Amir and F. Wajdi, “Formation and organisation in robot swarms.,” 2009.

[32] M. Hassanalian and A. Abdelkefi, “Classifications, applications, and design challenges of drones: A review,” *Prog. Aerosp. Sci.*, vol. 91, no. September, pp. 99–131, 2017.

[33] G. Singhal, B. Bansod, and L. Mathew, “Unmanned Aerial Vehicle classification , Applications and challenges : A Review,” *Preprint*, no. November, 2018.

[34] R. Giacomo and G. David, *Unmanned Aerial Systems (UAS) in Agriculture:*

Regulations and Good Practices. 2017.

[35] H. Shakhatreh *et al.*, “Unmanned Aerial Vehicles: A Survey on Civil Applications and Key Research Challenges,” pp. 1–58, 2018.

[36] H. Yao, R. Qin, and X. Chen, “Unmanned aerial vehicle for remote sensing applications - A review,” *Remote Sens.*, vol. 11, no. 12, pp. 1–22, 2019.

[37] M. Heutger, M. Kuckelhaus, D. Niezgoda, and S. Endriß, “Unmanned Aerial Vehicle in Logistics - A DHL perspective on implication and use cases for the logistics industry,” *DHL Cust. Solut. Innov.*, pp. 1–24, 2014.

[38] T. Amukele, P. M. Ness, A. A. R. Tobian, J. Boyd, and J. Street, “Drone transportation of blood products,” *Transfusion*, vol. 57, no. 3, pp. 582–588, 2017.

[39] A. Konert, J. Smereka, and L. Szarpak, “The Use of Drones in Emergency Medicine: Practical and Legal Aspects,” *Emerg. Med. Int.*, vol. 2019, p. 3589792, 2019.

[40] F. Ahmed, M. Amir, and N. Anwar, “Construction monitoring and reporting using drones and unmanned aerial vehicles (UAVs),” *tenth Int. Conf. Constr. 21st century*, no. July, pp. 1–8, 2018.

[41] Q. F. M. Dupont, D. K. H. Chua, A. Tashrif, and E. L. S. Abbott, “Potential Applications of UAV along the Construction’s Value Chain,” *Procedia Eng.*, vol. 182, no. 3, pp. 165–173, 2017.

[42] S. Dastgheibifard and M. Asnafi, “A Review on Potential Applications of Unmanned Aerial Vehicle for Construction Industry,” *Sustain. Struct. Mater.*, vol. 1, no. July, pp. 44–53, 2018.

[43] C. F. Liew, D. Delatte, N. Takeishi, and T. Yairi, “Recent Developments in Aerial Robotics : A Survey and Prototypes Overview,” pp. 1–14.

[44] O. Dahl and T. Svensson, “Automatic Takeoff and Landing of Unmanned Fixed Wing Aircrafts A Systems Engineering Approach,” 2016.

[45] H. Hildmann and E. Kovacs, “Review: Using Unmanned Aerial Vehicles (UAVs) as Mobile Sensing Platforms (MSPs) for Disaster Response, Civil Security and Public Safety,” *Drones*, vol. 3, no. 3, p. 59, 2019.

[46] J. A. Besada *et al.*, “Drone Mission Definition and Implementation for Automated Infrastructure Inspection Using Airborne Sensors,” pp. 1–29, 2018.

[47] C. Vi and W. G. Vi, “COMPARISON OF A FIXED-WING AND MULTI-ROTOR UAV FOR ENVIRONMENTAL MAPPING APPLICATIONS : A CASE STUDY,” vol. XLII, no. September, pp. 4–7, 2017.

[48] P. M. Basset, A. Tremolet, and T. Lefebvre, “Rotary Wing UAV pre-sizing : Past and Present Methodological Approaches at Rotary Wing UAV pre-sizing : Past and Present Methodological Approaches at Onera HAL Id : hal-01103131,” no. January, 2014.

[49] M. A. Lewis and K. H. Tan, “High Precision Formation Control of Mobile Robots Using Virtual Structures,” *Auton. Robots*, vol. 4, no. 4, pp. 387–403, 1997.

[50] W. Ren and R. W. Beard, “Decentralized Scheme for Spacecraft Formation Flying via the Virtual Structure Approach,” *J. Guid. Control. Dyn.*, vol. 27, no. 1, pp. 73–82, 2004.

[51] X. Li and J. Xiao, “Robot formation control in leader-follower motion using direct Lyapunov method,” *Int. J. Intell. Control Syst.*, vol. 10, no. 3, pp. 244–250, 2005.

[52] Q. Zhang and H. H. T. Liu, “Robust Cooperative Formation Control of Fixed-Wing Unmanned Aerial Vehicles,” pp. 1–18, 2019.

[53] F. Wu, J. Chen, and Y. Liang, “Leader-Follower Formation Control for Quadrotors,” *J. Phys. Conf. Ser.*, vol. 755, no. 1, 2016.

[54] K. Choutri, M. Lagha, L. Dala, and M. Lipatov, “Quadrotors UAVs swarming control under leader-followers formation,” *2018 22nd Int. Conf. Syst. Theory, Control Comput. ICSTCC 2018 - Proc.*, pp. 794–799, 2018.

[55] R. Rout, “Control of Autonomous Underwater Vehicles,” 2009.

[56] H. Qiu and H. Duan, “Multiple UAV distributed close formation control based on in-flight leadership hierarchies of pigeon flocks,” *Aerosp. Sci. Technol.*, vol. 70, pp. 471–486, 2017.

[57] M. A. Khan, I. M. Qureshi, and F. Khanzada, “A Hybrid Communication Scheme for Efficient and Low-Cost Deployment of Future Flying Ad-Hoc Network (FANET),” *Drones,* vol. 3, no. 1, p. 16, 2019.

[58] F. Giulietti, L. Pollini, and M. Innocenti, “Autonomous Formation Flight,” *IEEE Control Syst.*, vol. 20, no. 6, pp. 34–44, 2000.

[59] J. Li, C. Canada, Y. Zhou, C. Canada, L. Lamont, and C. Canada, “Communication Architectures and Protocols for Networking Unmanned Aerial Vehicles,” in *IEEE Globecom Workshops (GC Wkshps)*, 2013, no. December, pp. 1415–1420.

[60] J. F. Roberts, J. C. Zufferey, and D. Floreano, “Energy management for indoor hovering robots,” *2008 IEEE/RSJ Int. Conf. Intell. Robot. Syst. IROS*, pp. 1242–1247, 2008.

[61] D. Cai, J. Sun, and S. Wu, “UAVs Formation Flight Control Based on Behavior and Virtual Structure,” 2012, pp. 429–438.

[62] C. Di Franco and G. Buttazzo, “Energy-aware Coverage Path Planning of UAVs,” no. September, 2016.

[63] G. Gramajo, L. Beach, P. Shankar, and L. Beach, “Path-Planning for an Unmanned Aerial Vehicle with Energy Constraint in a Search and Coverage Mission,” 2016.

[64] A. Koubaa, I. Chaari, S. Trigui, and A. Ammar, “Introduction to Mobile Robot Path,” no. January, 2018.

[65] E. J. Dhulkefl and A. Durdu, “Path Planning Algorithms for Unmanned Aerial Vehicles,” no. August, 2019.

[66] Z. ZHOU, H. DUAN, and Y. FAN, “Unmanned aerial vehicle close formation control based on the behavior mechanism in wild geese,” *Sci. Sin. Technol.*, vol. 47, pp. 230–238, Mar. 2017.

[67] J. Ge, C. Fan, C. Yan, and L. Wang, “Multi-UAVs close formation control based on wild geese behavior mechanism,” in *2019 Chinese Automation Congress (CAC)*, 2019, pp. 967–972.

[68] M. Suresh Kumar, R. Vasantharaj, and R. Prabhakaran, “Energy optimization

for UAV communication using grid configured ADHOC network," *Int. J. Appl. Eng. Res.*, vol. 9, no. 23, pp. 23311–23319, 2014.

[69] G. Wagner, D. Jacques, B. Blake, and M. Pachter, "An analytical study of drag reduction in tight formation flight," in *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, 2001, p. 2002.

[70] Daniel Muijs, *Doing Quantitative Research in Education with SPSS*, vol. 29, no. 31. 2015.

[71] M. S. Rahman, "The Advantages and Disadvantages of Using Qualitative and Quantitative Approaches and Methods in Language 'Testing and Assessment' Research: A Literature Review," *J. Educ. Learn.*, vol. 6, no. 1, p. 102, 2016.

[72] A. Queirós, D. Faria, and F. Almeida, "Strengths and Limitations of Qualitative and Quantitative Research Methods," *Eur. J. Educ. Stud.*, vol. 3, no. 9, pp. 369–386, 2017.

[73] O. Mitchell, "EXPERIMENTAL RESEARCH DESIGN," 2016.

[74] S. M. Ross and G. R. Morrison, "EXPERIMENTAL RESEARCH METHODS," no. January 2003, 2014.

[75] R. Beaumont, "RESEARCH METHODS & EXPERIMENTAL DESIGN," 2009.

[76] P. Stephane, N. Brulez, P. Eline, and F. D'Haeyer, "AR . Drone User guide Contents." Parrot Inc, 2012.

[77] S. Al Habsi, M. Shehada, M. Abdoon, A. Mashood, and H. Noura, "Integration of a Vicon camera system for indoor flight of a Parrot AR Drone," *ISMA 2015 - 10th Int. Symp. Mechatronics its Appl.*, no. December, 2016.

[78] B. Title *et al.*, "Metadata of the chapter that will be visualized in SpringerLink," *Antimicrob. Compd.*, pp. 1–26, 2014.

[79] A. R. Merheb, H. Noura, and F. Bateman, "Emergency control of AR drone quadrotor UAV suffering a total loss of one rotor," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 2, pp. 961–971, 2017.

[80] E. Asmare, A. Gopalan, M. Sloman, N. Dulay, and E. Lupu, "A Mission

Management Framework for Unmanned Autonomous Vehicles," in *MobileWireless Middleware, Operating Systems, and Applications*, 2009, pp. 222–235.

[81] G. W. Luck, "An introduction to ecological thresholds," *Biol. Conserv.*, vol. 124, no. 3, pp. 299–300, 2005.

[82] F. Witt, "Energy Aware Particle Swarm Optimization as Search Mechanism for Aerial Micro-Robots Energy Aware Particle Swarm Optimization as Search Mechanism for Aerial Micro-Robots," Otto-von-Guericke University, 2016.

[83] Jaynes Gallery, "Snow Geese Flying In V Formation Photograph by Jaynes Gallery.pdf."

[84] S. Ahirwar, R. Swarnkar, S. Bhukya, and G. Namwade, "Application of Drone in Agriculture," *Int. J. Curr. Microbiol. Appl. Sci.*, vol. 8, no. 01, pp. 2500–2505, 2019.

[85] C. Yinka-Banjo and O. Ajayi, "Sky-Farmers: Applications of Unmanned Aerial Vehicles (UAV) in Agriculture," *Intech*, vol. i, no. tourism, p. 13, 2016.

Appendices

Deployment of the Energy-aware and Harmonization Code

This is the code snippet which deployed the Geese Inspired UAV swarm Energy-aware and harmonization algorithm. It is in this code that the practical leader follower rotation took place with the consistent check of the amount of battery available and comparing with the leader to ensure equal battery consumption. In this code ensured that as stated above no UAV was lost during the processes and if there is a UAV with a below minimal battery level then all the UAV will be stopped to avoid the sole loss of that particular UAV.

```
// Unmanned Aerial Vehicles IP addresses are defined
network = ['192.168.1.1','192.168.1.2','192.168.1.3'] //three UAVs

//network =['192.168.1.1','192.168.1.2','192.168.1.3','192.168.1.4','192.168.1.5']
//five UAVs


//Adding the Unmanned Aerial Vehicles in swarm using their ip address
network.forEach(ip) -->
        swarm.add ip:ip

number = swarm.length


//define conditional constructs
if(number >=2 && number <= 12)
{
        level = 0,counter = 0
        swarm.forEach(drone) -->
                ip: drone.ip
                position: drone.control //get x,y,z
                batterylevel: drone.updateBattery(batteryPercentage)

        swarm.forEach(drone) -->
                counter +=counter
                if (batterylevel >=96)
                {
                        threshold
                        =((batterylevel+level)/counter) counter
                        level = level+batterylevel
                }

        leader = random(swarm.drone.ip)
        leaderdrone = droneAddress(leader)

        swarm.forEach(drone) -->
                if(drone.enabled())
                {
                        drone.takeOff()
                }
}
```

```
//Define variables
leadingDronePower = drone.updateBattery(batteryPercentage)
p = leadingDronePower--threshold

//Define Conditional Constructs
swarm.forEach(drone) -->
        if( p =< 20 )
        {
                drone.land();
        }

if( leadingDronePower > p )
{
        //do nothing
}
else
{
        batterylevel = 0
        maxBatterylevel = 0
        counter = 0
        swarm.forEach(drone) -->
        batterylevel: drone.updateBattery(batteryPercentage)
        if( counter == 0 )
        {
                maxBatterylevel = batterylevel
        }
        else
        {
                if( maxBatterylevel >= batterylevel )
                {
                        batterylevel: drone.updateBattery(batteryPercentage)
                        leader = random(swarm.drone.ip)
                        leaderdrone = droneAddress(leader)
                }
        }
}
```

A swarm of three (3) Unmanned Aerial Vehicles initialization

```
// IP addresses of the three Unmanned Aerial Vehicles that were used
network = [
  '192.168.1.1',
  '192.168.1.2',
  '192.168.1.3',
]

swarm = require "./swarm"

//This is where the initialization of the Unmanned Aerial Vehicles takes place

network.forEach (ip) ->
  swarm.add ip: ip

//This is where the configuration of the three Unmanned Aerial Vehicles takes
place
//by activating the navigation data

swarm.do (drone) ->
  console.log('config drone:', drone.id)
  drone.config('general:navdata_demo', 'TRUE');
  drone.on 'navdata', (data) ->
    drone.navdata = data
    socket.publish "/drone/navdata/"+drone.id, data

//Initialization of the express server takes place here

app = express()
app.configure ->
  app.set('port', process.env.PORT || 4000)
  app.use(app.router)
  app.use(express.static(path.join(__dirname, 'public')))
  app.use("/components", express.static(path.join(__dirname, 'components')))
server = require("http").createServer(app)
```

```
//Initialization of the express server takes place here

app = express()
app.configure ->
  app.set('port', process.env.PORT || 4000)
  app.use(app.router)
  app.use(express.static(path.join(__dirname, 'public')))
  app.use("/components", express.static(path.join(__dirname, 'components')))
server = require("http").createServer(app)

//Initialization of the express server takes place here

bayeux = new faye.NodeAdapter(mount: '/faye', timeout: 45)
bayeux.attach(server)
bayeux.bind "handshake", (clientId) ->
  console.log "socket handshake!", clientId
bayeux.bind "disconnect", (clientId) ->
  console.log "socket disconnect!", clientId
socket = new faye.Client("http://localhost:#{app.get("port")}/faye")
```

```
//The configuration of routes will take place here

app.get "/drones", (req, res) ->
  drones = []
  swarm.forEach (drone) ->
    drones.push
      id: drone.id
      ip: drone.ip
      enabled: drone.enabled
  console.log "new client connection (sent %s drones)", drones.length
  res.end JSON.stringify(drones)

socket.subscribe "/drone/enable", (data) ->
  swarm.drones[data.id].enabled = data.status
  console.log 'set drone %s control to %s', data.id, data.status

socket.subscribe "/swarm/move", (control) ->
  console.log 'swarm move', control
  swarm.move(control)


socket.subscribe "/swarm/action", (command) ->
  console.log 'swarm action: ', command
  swarm.action(command)

server.listen app.get("port"), ->
  console.log "Express server listening on port " + app.get("port")

  res.header "Cache-Control", "no-cache, no-store" // avoid high disk usage on
client browser
  res.header "Content-Type", "image/png" // avoid client browser warning on
missing mime
  res.end swarm.drones[req.params.id].pngBuffer, "binary"
```

A swarm of five (5) Unmanned Aerial Vehicles initialization

```
// IP addresses of the five Unmanned Aerial Vehicles that were used
network = [
  '192.168.1.1',
  '192.168.1.2',
  '192.168.1.3',
  '192.168.1.4',
  '192.168.1.5',
]

swarm = require "./swarm"

//This is where the initialization of the Unmanned Aerial Vehicles takes place

network.forEach (ip) ->
  swarm.add ip: ip

//This is where the configuration of the three Unmanned Aerial Vehicles takes
place
//by activating the navigation data

swarm.do (drone) ->
  console.log('config drone:', drone.id)
  drone.config('general:navdata_demo', 'TRUE');
  drone.on 'navdata', (data) ->
    drone.navdata = data
    socket.publish "/drone/navdata/"+drone.id, data

//Initialization of the express server takes place here

app = express()
app.configure ->
  app.set('port', process.env.PORT || 5000)
  app.use(app.router)
  app.use(express.static(path.join(__dirname, 'public')))
  app.use("/components", express.static(path.join(__dirname, 'components')))
server = require("http").createServer(app)


//Initialization of the express server takes place here

bayeux = new faye.NodeAdapter(mount: '/faye', timeout: 45)
bayeux.attach(server)
bayeux.bind "handshake", (clientId) ->
  console.log "socket handshake!", clientId
bayeux.bind "disconnect", (clientId) ->
  console.log "socket disconnect!", clientId
socket = new faye.Client("http://localhost:#{app.get("port")}/faye")
```

```
//The configuration of routes will take place here

app.get "/drones", (req, res) ->
  drones = []
  swarm.forEach (drone) ->
    drones.push
      id: drone.id
      ip: drone.ip
      enabled: drone.enabled
  console.log "new client connection (sent %s drones)", drones.length
  res.end JSON.stringify(drones)

socket.subscribe "/drone/enable", (data) ->
  swarm.drones[data.id].enabled = data.status
  console.log 'set drone %s control to %s', data.id, data.status

socket.subscribe "/swarm/move", (control) ->
  console.log 'swarm move', control
  swarm.move(control)


socket.subscribe "/swarm/action", (command) ->
  console.log 'swarm action: ', command
  swarm.action(command)

server.listen app.get("port"), ->
  console.log "Express server listening on port " + app.get("port")

  res.header "Cache-Control", "no-cache, no-store" // avoid high disk usage on
client browser
  res.header "Content-Type", "image/png" // avoid client browser warning on
missing mime
  res.end swarm.drones[req.params.id].pngBuffer, "binary"
```

AR Drone swarm flying activation: controlling multiple drones (AR Drone) connected to the same network.

```
_ = require "underscore" //using the object underscore to operate functions
ardrone = require "ar-drone"


//flying drones as a swarm
swarm = []
swarm.drones = {}
swarm.forEach = (iterator) ->
  Object.keys(swarm.drones).forEach (id) ->
    iterator(swarm.drones[id])

swarm.do = (block) ->
  swarm.forEach (drone) ->
    block?(drone)
swarm.action = (command) ->
  swarm.forEach (drone) ->
    if drone.enabled
      drone.snooze drone.inactivityTime
      console.log("drone[#{command.action}]()")
      drone[command.action]?()
swarm.move = (control) ->
  swarm.forEach (drone) ->
    if drone.enabled
      drone.snooze drone.inactivityTime
      drone.move control
swarm.animate = (animation) ->
  swarm.forEach (drone) ->
    if drone.enabled
      drone.snooze animation.duration # TODO: research wheter the drone times-out
or not with longer snooze times
      drone.animate(animation.name, animation.duration)
swarm.add = (config) ->
  drone = ardrone.createClient(ip: config.ip)
  drone.id = config.id || config.ip.split(".").pop()
  drone.ip = config.ip
  drone.enabled = false
  drone.camera = 0
```

```
  drone.changeCamera = (camera) ->
    camera = !drone.camera + 0 if camera == "toggle"
    camera = 0 unless typeof camera == "number"
    drone.config('video:video_channel', ''+camera);
    drone.camera = camera
  drone.control =
    x: 0
    y: 0
    z: 0
    r: 0
  drone.isIddle = ->
    return drone.control.x == 0 && drone.control.y == 0 && drone.control.z == 0 &&
drone.control.r == 0
  drone.move = (control) ->
    if control
      _.extend drone.control, control
      console.log drone.control, control, drone.isIddle() if control
    else
      control = drone.control
    if drone.isIddle()
      drone.stop()
```

```
    # console.log("drone.stop", drone.ip)
  else
    if control.x < 0
      drone.left -control.x
      # console.log("drone.left", drone.ip, -control.x)
    else if control.x > 0
      drone.right control.x
      # console.log("drone.right", drone.ip, control.x)
    if control.y < 0
      drone.back -control.y
      # console.log("drone.back", drone.ip, -control.y)
    else if control.y > 0
      drone.front control.y
      # console.log("drone.front", drone.ip, control.y)
    if control.z < 0
      drone.down -control.z
      # console.log("drone.down", drone.ip, -control.z)
    else if control.z > 0
      drone.up control.z
      # console.log("drone.up", drone.ip, control.z)
    if control.r < 0
      drone.counterClockwise -control.r
      # console.log("drone.counterClockwise", drone.ip, -control.r)
    else if control.r > 0
      drone.clockwise control.r
      # console.log("drone.clockwise", drone.ip, control.r)
  return control

//Sends the commands every 30ms for drone movement, to avoid loss of the Wi-Fi
connection //commands are sent every less than two seconds

    drone.inactivityTime = 200
    drone.inactivityTimeout = +new Date + drone.inactivityTime
    drone.snooze = (length) ->
      console.log "drone %s snooze (keep alive off)", drone.ip if drone.inactive
      drone.inactive = false
      drone.inactivityTimeout = +new Date + length
    drone.keepAlive = ->
      if +new Date() > drone.inactivityTimeout
        console.log "drone %s inactive (keep alive on)", drone.ip unless
drone.inactive
        drone.inactive = true
        drone.move() // this takes care of stopping or moving the drone
    setInterval drone.keepAlive, 30

    // adding drone to a swarm
    swarm.drones[drone.id] = drone
    swarm.push drone

  module.exports = swarm
```