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Theme

A new collision avoidance method for a surveillance algorithm in FANETs

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dedicates

I dedicate this final project to :
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ملخص

في السنوات الأخيرة، أصبحت شبكات الطائرات بدون طيار واحدة من أكثر التقنيات شعبية، بفضل نطاق تطبيقاتها الواسع. واحدة من المجالات التطبيقية المهمة للشبكات هي المراقبة باستخدام الطائرات بدون طيار، حيث تحدد العديد من العوامل، بما في ذلك استهلاك الموارد، أداء هذه المهمة. أدى ذلك إلى قيام الباحثين بتطبيق نماذج حركية جديدة، وهي التحدي الرئيسي في ضمان استهلاك الطاقة الأمثل.

بالإضافة إلى ذلك، شهد المجال الجوي وجودًا كبيرًا للطائرات بدون طيار، مما ألهم الباحثين والمطورين في المجالات العسكرية والمدنية. تقوم الطائرات بدون طيار بمهامها بشكل احترافي، ولكن مجال المهمة ليس خاليًا من العوائق، سواء كانت ثابتة أو متحركة. في حال حدوث تصادم، ستفشل المهمة. يتطلب هذا الوضع وجود أساليب وخوارزميات تسمح للطائرات بدون طيار باتخاذ قرارات حول كيفية تجنب الاصطدام بهذه العوائق.

في هذه الأطروحة، سوف نكتسب فهمًا أفضل لشبكات الطائرات بدون طيار وندرس النماذج الحركية المختلفة الموجودة وكيفية عملها. سنقترح نموذجًا حركيًا جديدًا لضمان استهلاك الطاقة الأمثل وطريقة جديدة لتجنب التصادم لتحسين نجاح المهمة. لاختبار وتقييم هذه الأساليب، سوف نستخدم محاكي لمقارنة الأساليب المقترحة مع النماذج الحركية الحالية وتقنيات تجنب التصادم من حيث استهلاك الطاقة وكفاءة تجنب العوائق.

الكلمات المفتاحية : طائرة بدون طيار، طريقة المراقبة باستخدام الطائرات بدون طيار، سرب الطائرات بدون طيار، تجنب التصادم، العوائق.

Abstract

In recent years, Flying Ad hoc Network (FANET) has become one of the most popular technologies, thanks to its wide range of applications. One significant application area of FANET networks is surveillance using drones or Unmanned Aerial Vehicles (UAVs), where many factors, including resource consumption, determine the performance of this mission. This has led researchers to implement new mobility models in FANETs, which is the main challenge in ensuring optimal energy consumption.

Additionally, the airspace has seen a predominant presence of UAVs, inspiring researchers and developers in both military and civilian fields. UAVs perform tasks professionally, but the mission field is not free from obstacles, both fixed and moving. In the event of a collision, the mission will fail. This situation requires methods and algorithms that allow UAVs to make decisions on how to avoid colliding with these obstacles.

In this dissertation, we will gain a better understanding of drone networks and study the different existing mobility models and how they work. We will propose a new monitoring method to ensure optimal energy consumption and a new collision avoidance method to enhance mission success. To test and validate these methods, we will use the NS-3 simulator to compare our proposed methods with existing mobility models and collision avoidance techniques in terms of energy consumption.

Keywords : UAV, NS-3, surveillance method using drones, GM, RWP, UAV Swarm, Collision Avoidance, Obstacles.

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List of Abbreviations

WPAN	Wireless Personal Area Network.
WLAN	Wireless Local Area Network.
WMAN	Wireless Metropolitan Area Network.
WWAN	Wireless Wide Area Network.
UAV	Unmanned Aerial Vehicles.
MANET	Mobile Ad hoc Network.
VANET	Vehicular Ad hoc Network.
FANET	Flying Ad hoc Network.
RWP	Random WayPoint.
GM	Gauss Markov.
GCS	Ground Control Station.
MN	Mobile Node.
PDA	Personal Digital Assistant.
IEEE	Institute of Electrical and Electronics Engineers.
ADS-B	Automatic Dependent Surveillance Broadcast.
CAS	Collision Avoidance Systems.
CC	Collision Cone.
COD	Cylindrical Obstacle Diagram
VO	Velocity Obstacle.
MVO	Modified Velocity Obstacle.
RPV	Remotely Piloted Vehicle.
RPA	Remotely Piloted Aircraft.
ROA	Remotely Operated Aircraft.
UAS	Unmanned Aircraft Systems.
VC	Vehicular communication.

Chapter 1

Introduction

The rapid advancements in Unmanned Aerial Vehicle (UAV) technologies over the past decade have led to a significant increase in their deployment across various sectors. UAVs are increasingly recognized for their versatility in applications ranging from civilian uses, such as crop monitoring, logistics, professional photography, and telecommunications, to more critical missions like surveillance and disaster management. This widespread adoption has been facilitated by the self-organizing, self-configuring, and self-managing capabilities of UAVs within ad-hoc networks, which allow for quick deployment without the need for centralized infrastructure.

A key challenge that arises from the growing number of UAVs is the potential for collisions, particularly in dense networks such as UAV swarms. Traditional Collision Avoidance Systems (CAS) typically rely on a sequence of sensing, detecting, and avoiding obstacles. However, these systems can often be too resource-intensive or restrictive, leading to reduced mission effectiveness, especially in environments where many UAVs are operating simultaneously.

In this thesis, we propose a novel method for collision avoidance that integrates principles from existing CAS with an emphasis on efficiency, cost-effectiveness, and compatibility with UAV swarms. Our approach builds upon two widely studied mobility models : the Random Waypoint (RWP) and the Gauss-Markov (GM) models, which are crucial for evaluating the performance of UAV networks. By enhancing these models, we aim to improve surveillance operations while minimizing the risk of collisions.

The structure of this thesis is organized as follows : Chapter 1 provides an overview of UAVs, their characteristics, communication modes, and the significance of surveillance using drones. Chapter 2 delves into the individual mobility models and collision avoidance existing methods for UAVs, analyzing their importance and comparing different existing models and methods. In Chapter 3, we introduce our new surveillance method, which improves upon the RWP and GM mobility models in parallel with the new collision avoidance method based on VO. Finally, in Chapter 4, we simulate the proposed models using the NS-3 simulator to perform a comparative study and evaluate the performance of these methods including the simulation of the proposed collision avoidance method.

This work seeks to contribute to the growing field of UAV technology by addressing the critical issue of collision avoidance in dense UAV networks, ensuring safer and more efficient operations in various applications.

Chapter 2

Fundamentals of Wireless Networks

2.1 Introduction

Wireless networks use radio frequency channels as the physical medium for communication (1). This type of communication between devices facilitates innovative services, but it is also considered complex, adding significant intricacies to modern systems. These complexities make networking challenging and restrict its flexibility. Over the past several years, numerous wireless connectivity standards and technologies have emerged. These advancements enable users to connect a wide variety of computing and telecommunications devices without the need for cables. These technologies support quick and automatic ad hoc connections between devices, with each device supporting multiple standards to ensure interoperability. Wireless networks are particularly useful in providing network services in areas where laying cables for wired networks would be very difficult or prohibitively expensive (1).

2.2 Historical Background

In 1897, Guglielmo Marconi invented the first wireless radio communication system. By 1901, he successfully demonstrated his wireless telegraphy system to the world by transmitting radio signals across the Atlantic Ocean, from England to America, over a distance exceeding 1,700 miles (approximately 2,736 kilometers) (1).

Wireless networks have become an essential component of communication over the past century. The initial users of wireless technology were military and emergency services. For example, World War II films often depict soldiers equipped with wireless communication devices carried in backpacks and vehicles. The first radiotelephone service for customers was introduced by the Bell Telephone Company in the United States in 1950, though it could only accommodate a few subscribers. In 1964, the concept of shared resources was introduced, allowing for dynamic allocation of radio resources, thereby supporting a larger number of subscribers (49).

2.3 Characteristics of Wireless Channels

Wireless networks have several key characteristics that define their performance and capabilities :

- **Bandwidth**

  The bandwidth of a wireless network determines the amount of data that can be transmitted over the network at any given time. Higher bandwidth allows for faster data transfer rates.

— **Range**
The range of a wireless network refers to the maximum distance over which it can transmit data. Factors such as obstacles, interference, and signal strength can affect the range of a wireless network.

— **Mobility**
Wireless networks allow users to move freely while maintaining a connection. This characteristic is particularly important for mobile devices like smartphones and tablets.

— **Security**
Wireless networks are susceptible to security threats such as hacking and eavesdropping. Encryption protocols and other security measures are implemented to protect wireless networks from these threats.

— **Roaming**
Roaming refers to the ability of a wireless device to move seamlessly between different access points without losing connectivity.

— **Scalability**
Wireless networks must be designed to accommodate an increasing number of devices and users. The network should be able to handle the additional traffic without performance degradation.

— **Energy Efficiency**
Wireless networks should be designed to minimize energy consumption and reduce environmental impact.

2.4 Types of Wireless Networks

— **Wireless Personal Area Networks (WPAN)**
These are short-range wireless networks that connect devices within a small area. The range of a WPAN can be up to approximately 30 feet (about 9 meters), with Bluetooth being the common technology used for communication in this type of network. The necessity for personal devices to communicate wirelessly without an established infrastructure has led to the emergence of personal area networks (PAN) (1).

— **Wireless Local Area Networks (WLAN)**
These networks use radio waves for communication. Typically, there is at least one cable that provides internet access to the router, which then broadcasts the wireless signal to other devices. WLANs are used to connect to local resources and the internet. The range can be limited to a single room or house, or it can extend across an entire building or campus (50). WLANs offer low-cost transmission with greater bandwidth (2).

— **Wireless Metropolitan Area Networks (WMAN)**
A group of networks providing wireless connectivity to a metropolitan area. The goal of a WMAN is to extend the coverage area of a LAN in a cost-effective manner that supports high-speed connections without the need for extending wired connections within a network (2).

- **Wireless Wide Area Networks (WWAN)**
  These networks can cover large areas, such as cities or countries, using various systems like satellites, antennas, or mobile phone signals. With extensive coverage areas, WWANs allow users to stay connected even when other forms of wireless network access are unavailable (50).

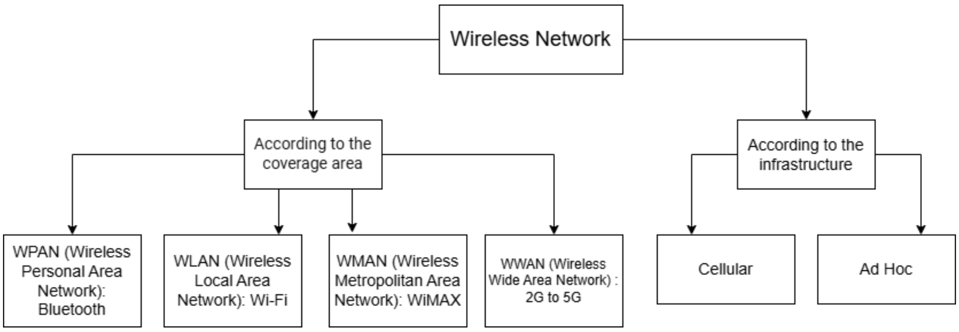


FIGURE 2.1 – types of wireless network.

2.4.1 Types of Networks by Infrastructure

- **Ad hoc Networks**
  An ad hoc network is a collection of wireless mobile nodes that dynamically form a temporary network without using any pre-existing network infrastructure or centralized base stations (51).

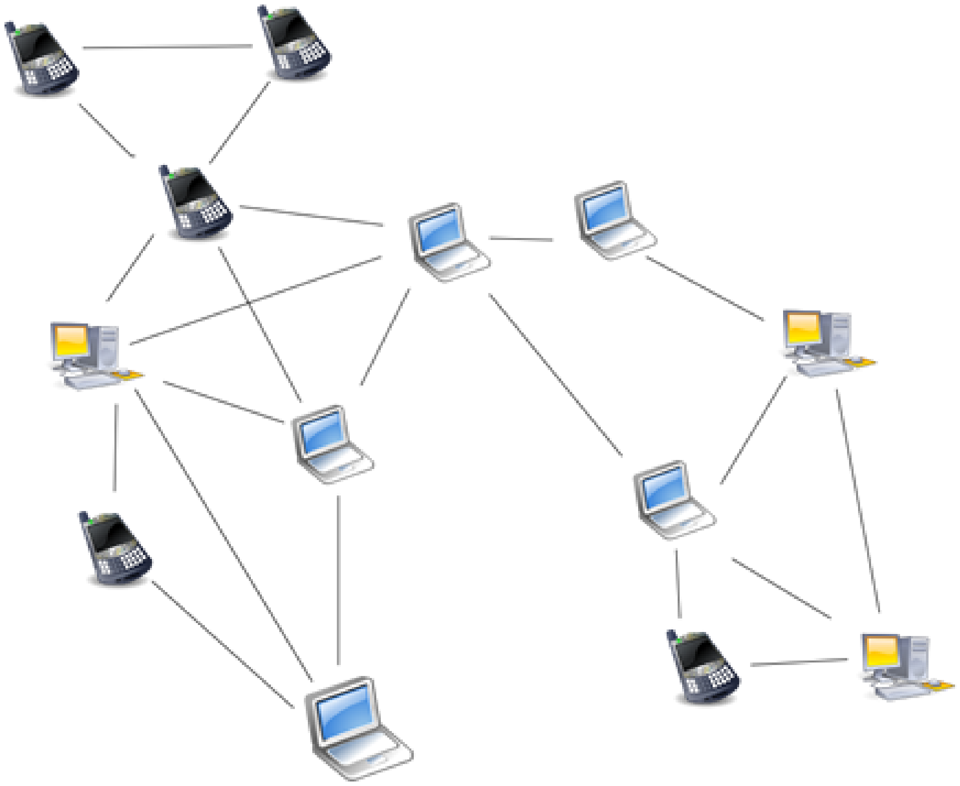


FIGURE 2.2 – Ad Hoc Network.(38)

Wireless ad hoc networks can be rapidly deployed anywhere and at any time because they eliminate the need for an established infrastructure. These networks have applications in various domains such as military communications (e.g., setting up communication among a group of soldiers for tactical operations) and emergency systems (e.g., establishing communication among rescue personnel during earthquakes. An ad hoc wireless network consists of mobile computing devices that use wireless transmission to communicate without a fixed infrastructure (such as a central administration like a base station in a cellular network or an access point in a local area network) (1).

- **Cellular Networks**
  Cellular networks are based on a centralized topology. This technology involves dividing the total area into cells, with each cell being equipped with a base station.

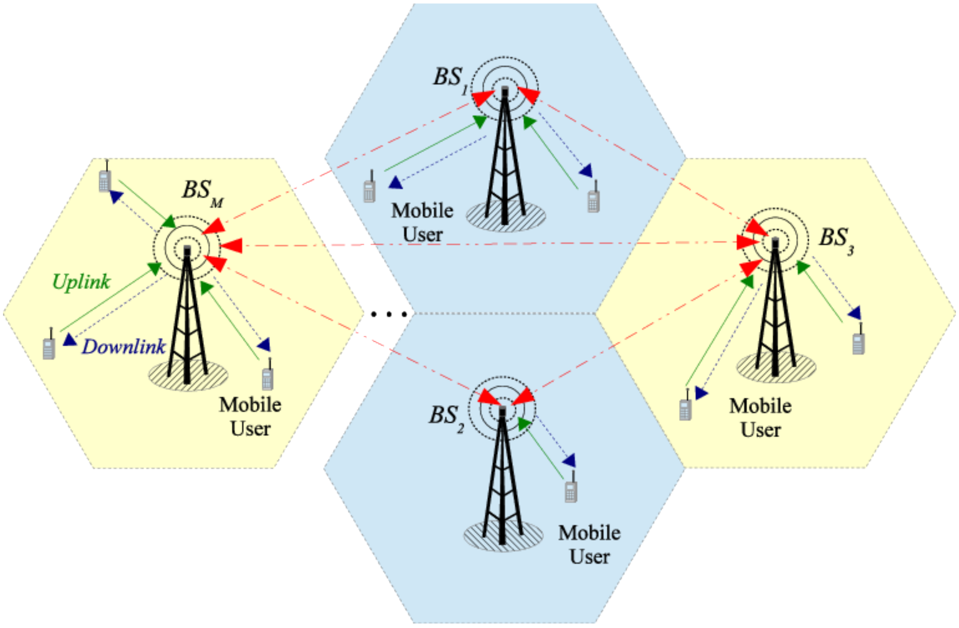


FIGURE 2.3 – cellular network.(39)

2.4.2 Ad hoc Network

Applications of Wireless Ad hoc Networks

Wireless ad hoc networks, due to their rapid deployment and cost-effective nature, find applications in various domains. Here are a few examples :

- **Military Applications**
  Wireless ad hoc networks can be extremely useful for establishing communication among a group of soldiers during tactical operations. Setting up a fixed infrastructure for communication in enemy territory or inhospitable terrains may be impossible. Ad hoc wireless networks quickly provide the required communication mechanism (1).
- **Collaborative and Distributed Computing**
  Collaborative and distributed computing is another area where wireless ad hoc networks are applied. For instance, a group of researchers sharing their research findings or presentation documents during a conference, or a lecturer distributing notes to the class on the fly (1).

- **Emergency Operations**
  Wireless ad hoc networks are very useful in emergency operations such as search and rescue missions. The primary factors that favor ad hoc wireless networks for such tasks are their ability to self-configure with minimal cost (1).

Below is a comparison between cellular networks and ad hoc networks :

Cellular Network	**Ad hoc Network**
Based on fixed infrastructure	No infrastructure
Single-hop wireless links	Multi-hop wireless links
Centralized routing	Distributed routing
High deployment cost and time	Rapid and cost-effective deployment
Application domains primarily include civil and commercial sectors	Application domains include battlefields, emergency search and rescue operations, and collaborative computing
Mobile hosts are relatively less complex	Mobile hosts require more intelligence (they need a transceiver and routing/switching capabilities)

Table 2.1 – Differences Between Cellular Networks and Ad hoc Networks

Types of Wireless Ad Hoc Networks

There are primarily three types of ad hoc networks :

Mobile Ad Hoc Networks (MANETs)

Mobile Ad Hoc Networks (MANETs) have rapidly become a burgeoning area of research. This self-organizing network type combines wireless communication with high node mobility, lacking infrastructure such as access points or base stations (3). Key applications of MANETs include :

- **Defense applications**

- **Disaster relief applications**

- **Civil applications (environment, transportation, surveillance)**

- **Research applications**

Flying Ad Hoc Networks (FANETs)

FANETs are a type of MANET where the network consists of unmanned aerial vehicles (UAVs) as nodes. These UAVs can be remotely piloted by a ground-based operator or autonomously controlled by onboard computers (3).

Vehicular Ad Hoc Networks (VANETs)

VANETs can be considered a subset of MANETs. With the increasing number of vehicles on roads, automotive manufacturers are seeking value-added services to enhance customer safety and information. Vehicular communication (VC) plays a pivotal role in this regard, utilizing short-range radios in each vehicle for communication among vehicles and with roadside infrastructure. These vehicles thus form ad hoc networks within vehicles, commonly known as Vehicular Ad Hoc Networks (VANETs) (3).

The FANET Network

UAVs communicate among themselves to form a self-organizing network without pre-existing infrastructure such as a base station or centralized controller. Here are some drone acronym names :

- RPV Remotely Piloted Vehicle
- RPA Remotely Piloted Aircraft
- ROA Remotely Operated Aircraft
- UAS Unmanned Aircraft Systems

Characteristics of FANETs

- **Node Mobility**
  The mobility degree of drones in FANETs is significantly higher compared to MANETs and VANETs. Drones can change positions much more rapidly, which can lead to communication issues among them (5).
- **Node Density**
  In FANETs, nodes must be dispersed in the sky and separated by large distances due to the nature of flight. Therefore, node density in FANETs is much lower than in MANETs and VANETs.
- **Network Topology**
  In FANETs, the network topology changes frequently due to the higher mobility of drones.
- **Localization**
  Determining the precise location of drones in FANETs is challenging due to their high mobility. Location data needs to be updated at very short intervals.
- **Power Consumption and Network Lifetime**
  Network lifetime is a critical concern for networks composed of battery-powered devices. In FANETs, the communication hardware relies on the UAV's own energy source. While FANET designs may not be as power-sensitive as MANET applications, power consumption remains a significant issue, particularly for mini UAVs.
- **Radio Propagation Model**
  Due to the nature of the environment in FANETs and the considerable distances between UAVs, line-of-sight communication is typically used between UAVs and the ground base. Unlike MANETs, FANETs do not rely on radio signals between nodes.
- **Mobility Models**
  In many mobility models, the flight path is predetermined, and recalculations are made at each step to update the map. Other models employ random speeds and directions for the UAVs, adding variability to their movement patterns.

2.5 Technical view of UAVs

Drones, as a flying system, consist of both hardware and software modules(6). These modules work together to ensure safe and reliable operational movements. Each module has a specific task, which we will delve into further.

2.5.1 Power Module

The power module serves as the drone's energy source, supplying power to various modules. It significantly impacts flight time, speed, and endurance. Energy sources for drones fall into two categories : fuel for medium and large aircraft, and batteries for small pilot-less crafts.

2.5.2 Flight Controller

Once the aircraft is powered on and in flight, the flight controller plays a crucial role. It stabilizes the aircraft's attitude and ensures it achieves the desired speed, position, and direction.

2.5.3 Propulsion System

The propulsion system acts as the primary UAV direction controller. It receives instructions from the flight controller to adjust propellers, determining the aircraft's direction based on the mission planning module (7). Propellers vary depending on the UAV type :

- **Standard Propellers** : Manipulate UAV direction (right or left).
- **Pushed Propellers** : Control backward and forward movement of the UAV.

2.5.4 Mission Planning Module

This software-based module allows operators to program mission details into the flight controller. It includes mission type, routes, checkpoints, and flight parameters. The flight controller relies on this information to determine current flight variables, such as altitude, position, and distance traveled. Refer to the flowchart in Figure 2.4 for an overview of mission planning.

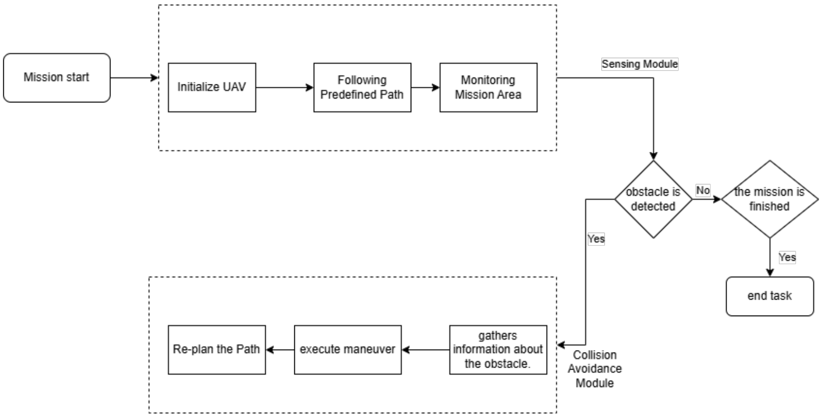


Figure 2.4 – Mission planning .

2.5.5 Sensing Module

The sensing module includes onboard sensors such as RADAR, LIDAR, and SONAR (refer to Table 2.1), which offer visual information about the flight area for data collection or target identification (8). This module plays a vital role due to its interaction with the collision avoidance module for obstacle detection and avoidance. Sensors are classified as :

- **Active Sensors** : These sensors emit signals towards objects and record the reflected signals (18).
- **Passive Sensors** : These sensors do not emit signals but instead read signals received from objects, such as sunlight reflecting off surfaces (18).

Sensors	**Advantages**	**Disadvantages**
	Passive	
Visible Spectrum Camera	— Very rich in content — Easy to interpret — Low price — No interference with the environment	— Not well suited for darkness conditions
Infrared Camera	— Ability to measure the temperature — Independent of the light source	— Sensitive to weather conditions
	Active	
Sonar	— Possibility to measure distance and speed of the target objects	— Difficulties in interpreting the output signal returned by themselves — Acquisition price — Sensitive to weather conditions
Laser	— High accuracy in lateral and longitudinal direction	— Acquisition price
Radar	— Images can be acquired day or night — Can operate in different environmental conditions without any strong limitations	— High price

Table 2.2 – Comparison of Different Sensors (42).

2.5.6 Collision Avoidance Module

After gathering information about obstacles through the sensing module and determining the current location of the UAV, the Collision Avoidance Module comes into play. This software-based solution enables the aircraft to perform avoidance maneuvers, preventing collisions with external objects. A more detailed explanation of this module will be provided in the next chapter.

2.5.7 Communication Modes Among Drones

The communication architecture specifies the rules and mechanisms governing how information flows between the Ground Control Station (GCS) and multiple UAVs or among UAVs. We distinguish four (4) types of communication in FANET (5) :

Direct Communication between Drones

Direct communication links can be established between the GCS and each drone. This is the simplest architecture where the GCS acts as a central node to which all drones or UAVs are connected. However, the GCS represents a vulnerability in FANET ; if the GCS encounters issues, the entire drone network may fail. Hence, this communication system lacks robustness.

Communication between Drones via Satellite Networks

For communicating between distant points where fixed infrastructure is impractical, satellite communication offers the best solution. Satellites can facilitate communication between the GCS and UAVs. Similarly, UAV-to-UAV communications can also leverage satellite links. However, this approach has drawbacks such as high satellite leasing costs and the requirement for drones and the GCS to be within the satellite's line of sight.

Communication between Drones via Cellular Networks

This type of communication relies on a centralized topology where territories are divided into cells, each served by a base station (the central point). All communications must pass through this central point, which routes them to their destinations. Unlike satellite networks, cellular networks use low-power transmitters. Utilizing existing cellular infrastructure from telecom operators can potentially reduce deployment costs.

Communication between Drones via Ad-Hoc Networks

This network architecture is part of MANET, where nodes communicate with each other without a central infrastructure. Each drone acts as an independent system. All drones must collaborate and self-organize to relay information effectively.

2.6 Ground Control Station

A Ground Control Station (GCS) consists of several components that together create an independent system to oversee UAV operations. The GCS enables the operator to modify waypoints, adjust flight trajectories, manage altitude, control airspeed, and designate landing areas. Communication between the GCS and UAVs is facilitated via an uplink to send commands and a downlink to receive status updates. Typically, a GCS is made up of the following key components (52) :

1. **GCS Desktop Software :** This is a critical element of the UAV system, allowing the operator to manage UAVs throughout their flight. The software provides the capability to analyze surrounding areas, offering a predictive map of signal strength. Additionally, it enables the monitoring and adjustment of sensor payloads during UAV missions.

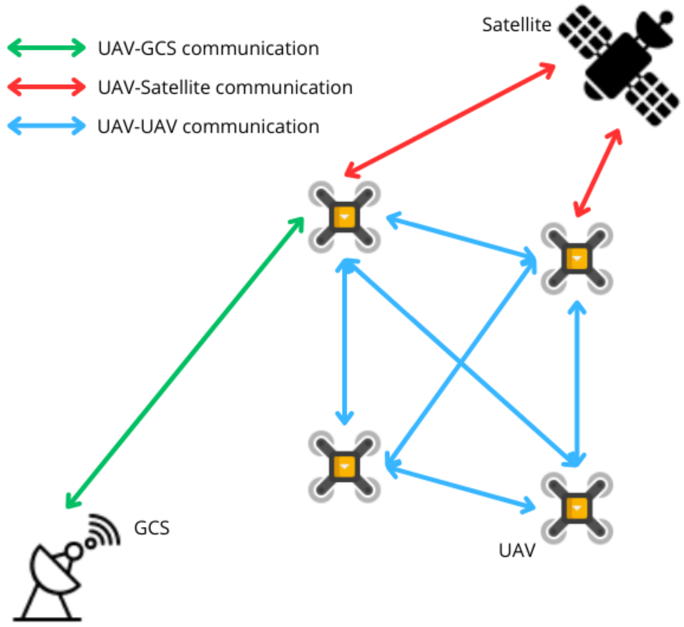


FIGURE 2.5 – UAV Communication modes.

2. **GCS Infrastructure :** This refers to the physical hardware of the GCS, including transmitters and receivers for data communication. The infrastructure supports two-way communication between the GCS and the closest UAV : the uplink is used for controlling the UAV's flight and managing its payload, while the downlink is used to transmit UAV status information (such as altitude, speed, and direction) back to the operator. To ensure mission success, it is essential that the data link includes anti-interference features.

2.7 FANET Challenges

FANETs (Flying Ad-Hoc Networks) inherit several challenges from their MANET (Mobile Ad-Hoc Network) counterparts while also introducing additional difficulties due to the unique characteristics of UAVs, such as their high velocity, rapidly changing topology, and mobility patterns (10).

1. **Routing :** Unlike traditional ad-hoc networks, routing in FANETs is complicated by the swift movement of UAVs, leading to constant and unpredictable changes in network topology. Developing a routing protocol that can efficiently handle these dynamics and quickly adapt to frequent topology shifts remains a major challenge.
2. **Security :** Ensuring secure communication in FANETs is crucial, especially considering the frequent exchanges between UAVs and between UAVs and ground control stations. The vulnerability to node compromise, due to the lack of physical protection, and the difficulty in managing trust among nodes due to their constant mobility are significant security concerns.
3. **Quality of Service (QoS) :** FANETs must support the transmission of various types of data, such as audio, video, images, text, and GPS coordinates. Achieving high Quality of Service

(QoS), characterized by minimal delays, low error rates, and reliable network performance, is essential for effective communication in FANETs.

4. **UAV Mobility and Placement :** The strategic placement and movement of UAVs are key to optimizing network performance in FANETs. Different UAVs, depending on their size and capabilities, are used for specific tasks, such as surveillance or data collection. Efficiently positioning these UAVs to reduce energy consumption while ensuring timely data retrieval is an ongoing research challenge.

2.8 Applications of Ad Hoc Networks

While wireless network projects in general, and Ad Hoc networks in particular, initially started in purely military contexts, their applications extend beyond military settings. Mobile Ad Hoc networks are easy to deploy in buildings, especially old buildings or heritage sites (castles and historical monuments). In general, Ad Hoc networks are used in any application where deploying a wired network infrastructure is challenging or where the installation time for cabling is significant. There are numerous applications for drone surveillance :

2.8.1 Military Applications

- **Border Security**
  Drones can be deployed to detect unauthorized movements or activities.
- **Attack and Defense**
  Military and defense organizations commonly use drones for surveillance missions, as well as for targeting and attack purposes.

FIGURE 2.6 – Military use of drones.(48)

2.8.2 Civilian Applications

- **Agriculture**
  Farmers can utilize drones to monitor crop health and detect diseases in their fields.

FIGURE 2.7 – Using drones in agriculture.(47)

- **Search and Rescue**
  Drones are valuable for locating missing individuals in hard-to-access areas.
- **Forest Fire Detection**
  Applications for detecting forest fires involve monitoring heat signatures and fire risk to prevent disasters.

FIGURE 2.8 – Using drones for fire detection.(46)

These applications highlight the versatility and utility of drones in enhancing surveillance capabilities across various sectors.

2.9 Conclusion

Ad hoc networks are autonomous systems that consist of a group of mobile nodes using wireless transmission for communication. They are self-organized, self-configured, and self-controlled. This type of network can be set up or deployed anywhere and at any time because it requires only a very simple infrastructure and no central administration. These networks are primarily used by various users, including the military, researchers, and students (51). In this chapter, we discussed the fundamental principles of wireless networks, followed by their characteristics, then we discussed a classification of wireless networks. After that we focuse on FANET networks by discussing the applications and challenges of Ad Hoc networks.

Chapter 3

Comparative Study of Mobility Models and Collision Avoidance

3.1 Introduction

In the domain of wireless networks, node mobility is a fundamental characteristic that directly influences the behavior and performance of the network. In various scenarios, such as WLANs, Ad hoc networks, and wireless sensor networks, the mobility of nodes is critical. For instance, in WLANs, mobile devices like laptops and PDAs are the primary nodes, while in Ad hoc networks, mobility is inherent as nodes may represent soldiers on the battlefield, rescue teams in disaster areas, or swarms of drones on surveillance missions. In specific cases, even wireless sensors exhibit mobility, such as those mounted on animals for tracking purposes.

Understanding mobility is particularly important in the context of UAVs (Unmanned Aerial Vehicles), as it significantly affects the network's performance. This chapter begins by discussing individual mobility models, highlighting their relevance in evaluating network performance. It then explores various existing mobility models, followed by a comparative analysis to discern their strengths and weaknesses.

In parallel, this chapter addresses the critical issue of collision avoidance, which is vital for the safe and efficient operation of UAVs and other mobile nodes. Obstacles, whether static (e.g., buildings, towers) or dynamic (e.g., vehicles, birds), can impede the movement of nodes and pose significant challenges in navigation. The chapter delves into the concept of collision and reviews the approaches utilized to mitigate these risks, ensuring that mobile nodes can navigate their environments safely and effectively (11).

By integrating the study of mobility models with collision avoidance strategies, this chapter provides a comprehensive understanding of how these two aspects are interrelated and essential for the optimal functioning of wireless networks, particularly in scenarios involving UAVs.

3.2 Mobility Models

3.2.1 Classification of Mobility Models

Mobility models aim to mimic certain types of mobility (human, vehicular, animal, etc.). There are several classifications of mobility models, the most important of which are as follows :

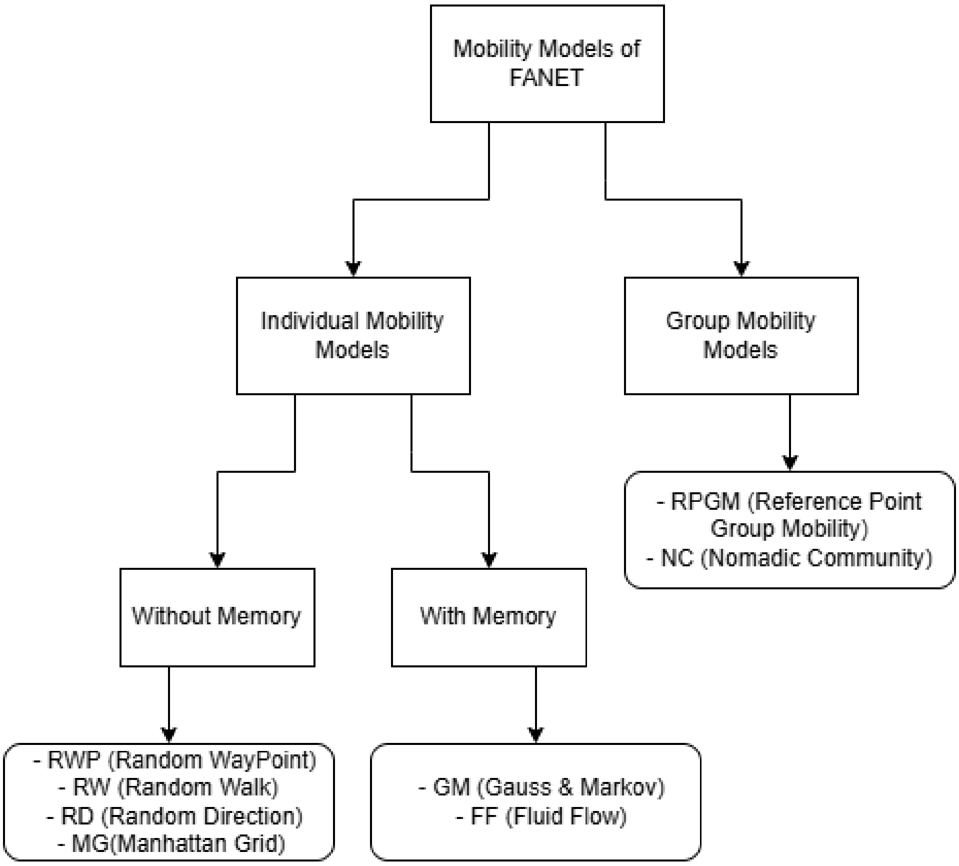


FIGURE 3.1 – 1st classification of mobility models.

Individual Mobility Models

This type focuses on the movement and behavior of a single UAV, taking into account factors such as flight altitude, flight trajectory, flight speed, and obstacle avoidance.

Group Mobility Models

This model focuses on the behavior of a group of UAVs, considering factors such as communication, coordination, and collision avoidance.

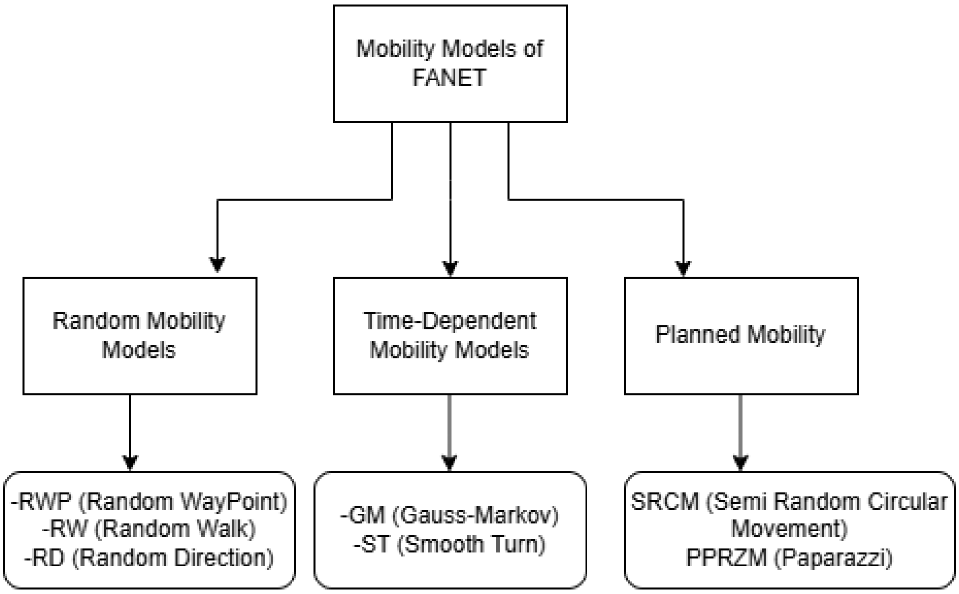


FIGURE 3.2 – 2nd classification of mobility models.

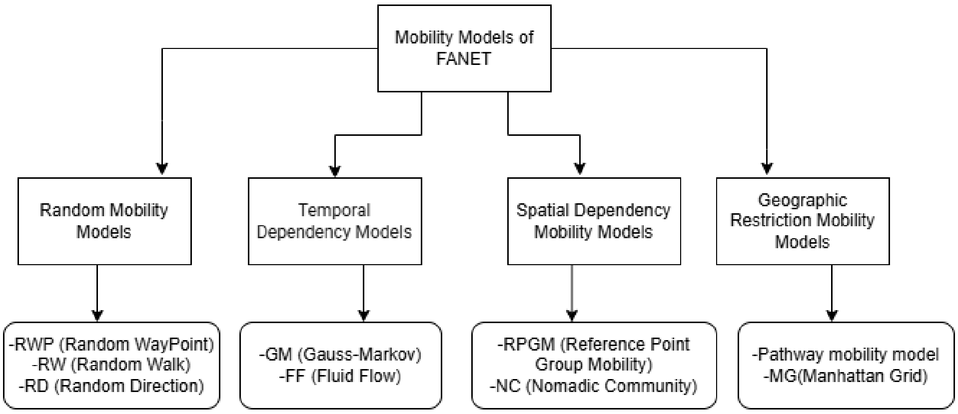


FIGURE 3.3 – 3rd classification of mobility models.

3.2.2 Random Mobility Models

Many entities in nature move in extremely unpredictable ways. In mobility models based on randomness, mobile nodes move freely without restriction and randomly. This means that the destination, speed, and direction are all chosen at random. We have chosen the Random Waypoint model, which is commonly used in simulation studies. Before explaining it, we provide some important definitions(51).

Definitions

In this section, we present the basic definitions and terminology that will be used to describe different random mobility models(53).

— **A spatial domain in which the nodes move** :
The spatial domain is usually a region R of one, two, or three-dimensional space. An informal definition (for example, a set of roads is defined, and the nodes are constrained to move only along the roads)(53).

- **The initial position of the nodes** :
  The position of the nodes at the beginning must be determined. Generally, this is done by randomly selecting the positions of the nodes according to a certain spatial probability distribution, with the uniform distribution of nodes being the most common choice(53).
- **How to perform a movement** :
  A movement can be defined in several ways : for example, by specifying a destination point and a geographic path—the trajectory—connecting the current position of the node to the destination point. Note that the destination point and the trajectory must be entirely contained within the spatial domain R. It is also possible to define the direction of movement and the duration of the journey(53).
- **How to choose the speed** :
  The speed of a trip is usually chosen at random. A common choice is to select the speed uniformly at random within an interval $[v_{\min}, v_{\max}]$, where $v_{\min}$ and $v_{\max}$ represent the minimum and maximum possible speeds, respectively(53).
- **The transition from one trip to another** :
  A common transition rule is based on the notion of pause time, that is, a node is supposed to remain stationary at the destination point for a certain time before starting the next trip(53).
- **The boundary rule** :
  In some mobility models, it is possible for a node to reach the boundary of the spatial domain R during a movement. In this case, since nodes are not allowed to exit R, a boundary rule must be defined to describe how to handle this situation. A typical boundary rule is reflection(53).

The Random Waypoint (RWP) Model

Introduction

The Random Waypoint model was first proposed by Johnson and Maltz. It quickly became a "reference" mobility model for evaluating MANET routing protocols. The success of this mobility model is due to the fact that it can be considered a first attempt to define a simple mobility model aimed at modeling intentional human movement, which is now part of the IEEE 802.11 standard. The RWP model belongs to the class of individual mobility models. In particular, this means that the mobility of different nodes is modeled by independent stochastic processes(50).

Operating Principle

The RWP mobility model in a d-dimensional spatial domain R is defined by the initial selection of the node's position uniformly and randomly within R. After a predefined pause time t_p, randomly chosen by the simulation software according to a probability distribution (uniform distribution or exponential distribution, etc.), the node selects a destination—called a Waypoint—uniformly at random within R, and starts moving along a straight trajectory towards the waypoint with a constant speed v chosen uniformly at random within an interval

$[v_{\min}, v_{\max}]$, where $v_{\min}$ and $v_{\max}$ represent the minimum and maximum speeds, respectively. Once the waypoint is reached, the node pauses at the waypoint for the time t_p. Then, it begins a new trip according to the same rules. More formally, a mobile node in the RWP model is defined by the following stochastic process (53) :

$$\{(D_i, T_i, V_i),\ \text{for } i = 1, 2, \ldots\}$$

Where D_i is a d-dimensional random variable corresponding to the coordinates of the i-th waypoint (the destination point must be included in R), T_i is the pause time at the i-th waypoint, and V_i is a variable corresponding to the node's speed (velocity) randomly chosen within $[v_{\min}, v_{\max}]$ during the trip to the i-th waypoint. The initial node position D_0 is also uniformly and randomly chosen within R. An example of RWP mobility in the unit square $R = [0, 1]^2$ is illustrated in the following Figure 3.4, with the starting point and waypoints being the black dots.

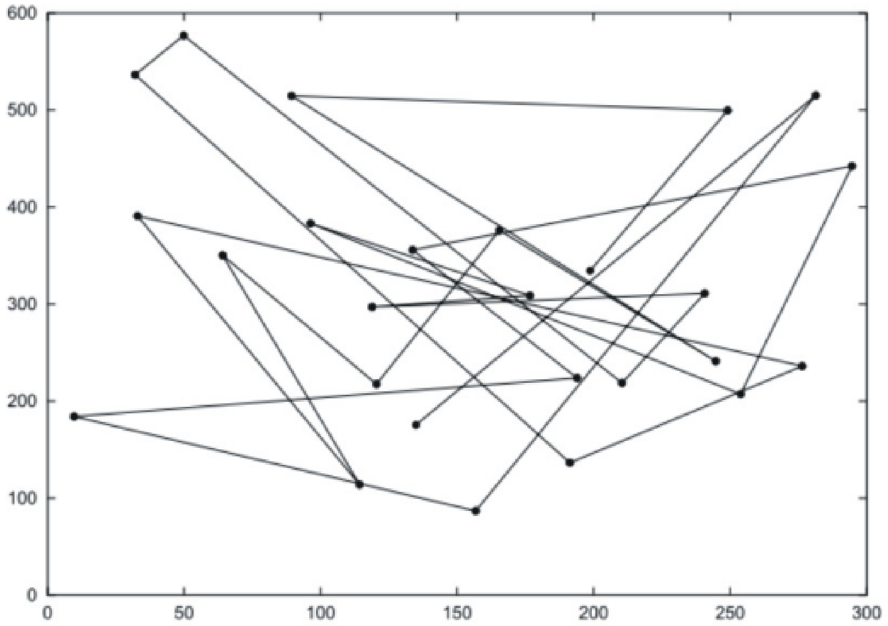


FIGURE 3.4 – example of RWP mobility.(40)

In this model, we have two key parameters, $V_{\max}$ and T_{pause}, which determine the mobility behavior of the nodes. If $V_{\max}$ is small and T_{pause} is long, the ad hoc network topology becomes relatively stable. Conversely, if the node moves quickly (i.e., if $V_{\max}$ is large) and T_{pause} is short, the topology is expected to be very dynamic(51). The random choice of pause time is intended to simulate the unpredictable behavior of mobility models in the real world.

Johansson proposed the mobility metric to capture and quantify this notion of node speed. The measurement of the relative speed between nodes i and j at time t is as follows :

$$RS(i, j, t) = |V_i(t) - V_j(t)|$$

Properties of the RWP Model

We will present a characterization of the average nodal speed for an RWP mobile network.

- **The average nodal speed of the RWP model** :
  The stationary average nodal speed, which is formally defined as follows. Suppose n nodes move independently in a spatial domain R according to the RWP mobility model, and let $v_i(t)$ denote the instantaneous speed of the i-th node at time t. The stationary average nodal speed V_{rwp} is defined as follows(53) :

$$\lim_{x \to \infty} \sum_{i=1}^{n} \frac{v_i(t)}{n}$$

Limitations of the Random Waypoint (RWP) Model

The two main limitations of the RWP mobility model are as follows :

- **Unrealistic model** :
  In this type of mobility model, sudden stops and starts can occur. Moreover, excessive changes in direction can occur due to the random control of speed and direction. This is one of the reasons why the Random Waypoint is considered an unrealistic mobility model.
- **Boundary effect** :
  Reveals that the trajectories of an RWP mobile node moving in a bounded region are more likely to pass through the center than the boundary of the movement domain R. In other words, the spatial distribution of stationary RWP nodes in a bounded domain is not uniform, an RWP mobile node is relatively more likely to be positioned at the center than at the boundary of R. The fact that the spatial density of nodes at the boundary is relatively low is known as the boundary effect. Consequently, the boundary rule is rarely applied (reflection or other rule)(50).

3.2.3 Temporal Dependency Models

In the RWP model, the speed of a mobile node is a memoryless random mechanism, that is, the speed at the current epoch is independent of the previous epoch. Therefore, some extreme mobility behaviors, such as sudden stops or sudden accelerations, can frequently occur in the Random Waypoint model. However, in many real-world scenarios, the speed of vehicles gradually accelerates. This is what interests this type of model, in addition to the fact that the movement of a mobile node is likely to be affected by its movement history. To explain how this class works, we have chosen the Gauss-Markov mobility model(51).

The Gauss-Markov Mobility Model

The Gauss-Markov (GM) mobility model is a widely used mobility model known for its memory that allows smooth node movement, where the speed and direction at a given time step probabilistically depend on the speed and direction at the previous time step. Moreover, mobile nodes are forced to move away from the simulation boundaries to avoid unnatural movements such as bouncing off the simulation boundaries. This is done using a buffer zone defined as the region between the simulation boundaries and the inner area. Initially, each mobile node is assigned a position, speed, and direction angle. The speed and direction are updated at each step using the following equations :

$$S_n = \alpha S_{n-1} + (1-\alpha)\bar{S} + \sqrt{(1-\alpha)S_{n-1}}$$
$$d_n = \alpha d_{n-1} + (1-\alpha)\bar{d} + \sqrt{(1-\alpha)d_{n-1}}$$

Where s_n is the speed and d_n is the direction at time step n. The memory of the model is controlled by the parameter α, which varies between 0 and 1, s_{n-1} and d_{n-1}
represent its previous speed and direction at time step $n-1$. The terms $(1-\alpha)\bar{s}$ and $(1-\alpha)\bar{d}$ represent the average speed and direction of all mobile nodes in the network at time step $n-1$. Meanwhile, $s_{x_{n-1}}$ and $d_{x_{n-1}}$ are random variables drawn from a Gaussian distribution (normal distribution).

When α is close to zero, the user's mobility tends to follow a highly random behavior. If α increases, the uncertainty of the movement will be lower, and the speeds and directions during previous time intervals will have a greater impact on the selection of future values, making the mobility model more time-dependent. These terms $(1-\alpha)\bar{s}$ and $(1-\alpha)\bar{d}$ are added to the equation to provide a reference value for speed and direction for the node, preventing its speed and direction from deviating too much from the speed and direction of all the nodes in the network(13).

It is important to note that this is a two-dimensional mobility model in which the positions of the mobile nodes are updated by the equations :

$$X_n = X_{n-1} + S_{n-1} \cdot \cos(d_{n-1}) \tag{3.1}$$

$$Y_n = Y_{n-1} + S_{n-1} \cdot \sin(d_{n-1}) \tag{3.2}$$

Where (x_n, y_n) is the position on the xy-plane. When a mobile node is near a border, it is moved away by modifying the average direction $\bar{d}$ according to the sectors of the buffer zone indicated in the following figure. The buffer zone has 8 distinct sectors. When a node enters the buffer zone, the sector in which it resides must be determined to move it away from the boundaries. For example, when the mobile node is near the right edge of the simulation grid, the value $\bar{d}$ is changed to 180 degrees. Thus, the new direction of the Mobile Node (MN) moves away from the right edge of the simulation grid(12).

In the Gauss-Markov mobility model in 3D (3D-GMMM), the nodes move inside a three-dimensional simulation box. The movement in the z-direction is controlled by the angle ϕ_n given by

$$P_n = \alpha P_{n-1} + (1-\alpha)\bar{P} + \sqrt{(1-\alpha)Px_{n-1}}$$

Where Pn ∈ [-π/2, +π/2]. The sectorization of the buffer zone in 3D-GMMM would result in 26 sectors due to the third dimension. The principle of sectorization in the Gauss-Markov model in 2D is depicted as follows :

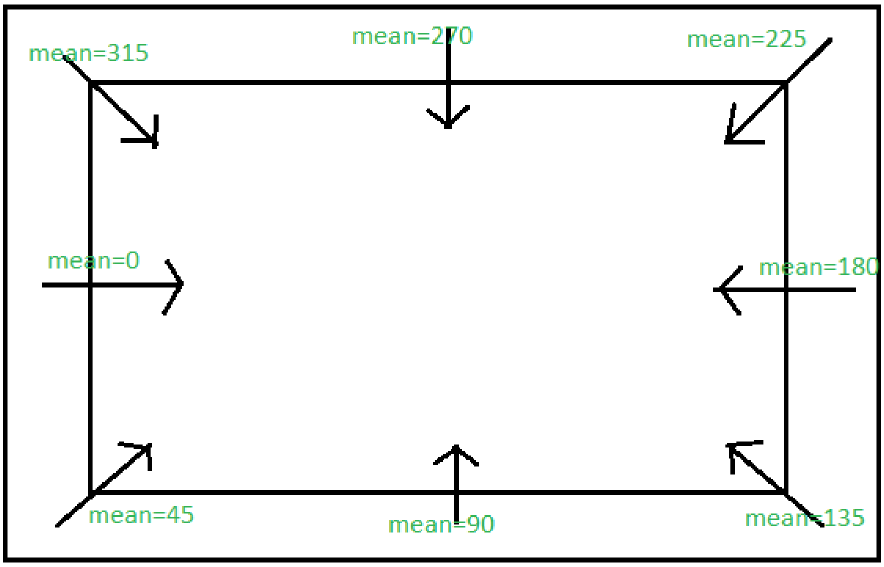


FIGURE 3.5 – The sectorized buffer zone of the Gauss-Markov mobility model.(41)

Advantages of the Gauss-Markov Model

- **Realistic Movement :** The Gauss-Markov model is based on real observations of human mobility patterns. Having memory in the GMMM reduces the possibility of abrupt movements of mobile nodes, as observed with other mobility models such as random-based mobility models.
- **Simplicity :** The Gauss-Markov model is relatively simple to implement and requires only a few input parameters, making it more accessible to researchers with limited programming experience.
- **Flexibility :** The Gauss-Markov model can be adapted to different scenarios. For example, researchers can use it to simulate mobility patterns for pedestrians, vehicles, or drones.

Limitations of the Gauss-Markov Mobility Model

- **Lack of Diversity :** The Gauss-Markov model generates mobility patterns based on a few statistical assumptions about user movements, such as average speed and maximum speed. However, these assumptions may not reflect the diversity of human mobility patterns in real scenarios. Moreover, real-world mobility patterns can be very diverse and complex, depending on factors such as the user's age, gender, and social status, as well as the environment in which they move. For example, residents of urban areas may have different mobility patterns from those in rural areas.
- **Absence of Dynamic Interactions :** The Gauss-Markov model does not account for dynamic interactions between users or with the environment. For instance, it does not consider the impact of congestion or obstacles on user mobility patterns.
- **Limited Temporal Accuracy :** The Gauss-Markov model assumes that user mobility patterns are homogeneous over time, meaning that the same mobility statistics apply at all times. However, in real scenarios, user mobility patterns can change over time due to

factors such as weather conditions, peak hours, or events.

All these points can limit the realism of the generated mobility models and affect the accuracy of simulation results.

3.3 Difference between Random and Realistic Models

The work of Wang et al(4) presents several reasons for using realistic mobility models rather than simple random models :

- Random models can be very different from real movement models found in the real world.
- The distribution of node locations impacts many network characteristics such as network connectivity, average path length, and network capacity.
- The mobility model is an important factor affecting the performance of a FANET, so it is important to establish a realistic movement model.
- Finally, random mobility models are almost always based on simple linear patterns that differ from many real scenarios. Drones typically mimic the movement of bird flocks or fish flocks. In this case, they must move along continuous and curved trajectories rather than a simple straight line.

3.4 Influence of Mobility Models on Drones

Mobility models play an important role in the design, development, and deployment of drones. A mobility model can be used to predict the drone's trajectory, speed, and other parameters. One of the main uses of mobility models in drones is route planning and optimization. By using a mobility model, it is possible to calculate the optimal trajectory that a drone should take to reach its destination as efficiently as possible. This helps reduce energy consumption, increase flight time, and improve overall performance. Mobility models can also be used to simulate the behavior of drones in different environments. This can be useful for testing and validating drone design, as well as predicting the impact of environmental factors such as weather conditions.

3.5 Collision Avoidance

3.5.1 Concept of a Collision

A collision occurs when two or more vehicles collide with considerable force, leading to potential damage such as frame fractures, separation, or the chassis becoming entangled, all of which can compromise the success of a mission (14). The techniques developed to prevent collisions with various types of objects are known as Collision Avoidance Methods (15). These methods, often referred to in literature as obstacle avoidance, focus on the identification and avoidance of surrounding elements, ensuring safe navigation.

The following section delves into the study of collision avoidance systems specifically within the context of UAVs.

3.5.2 Collision Avoidance Systems

A collision avoidance system can serve multiple purposes, ranging from basic conflict detection and alerting to fully autonomous conflict detection and resolution, as described in (16). The role of UAVs in such systems is determined by their level of autonomy and the capabilities of their individual components. Generally, a collision avoidance system is the result of cooperative interactions between various UAV modules. Figure 3.6 illustrates the different stages involved in the collision avoidance process.

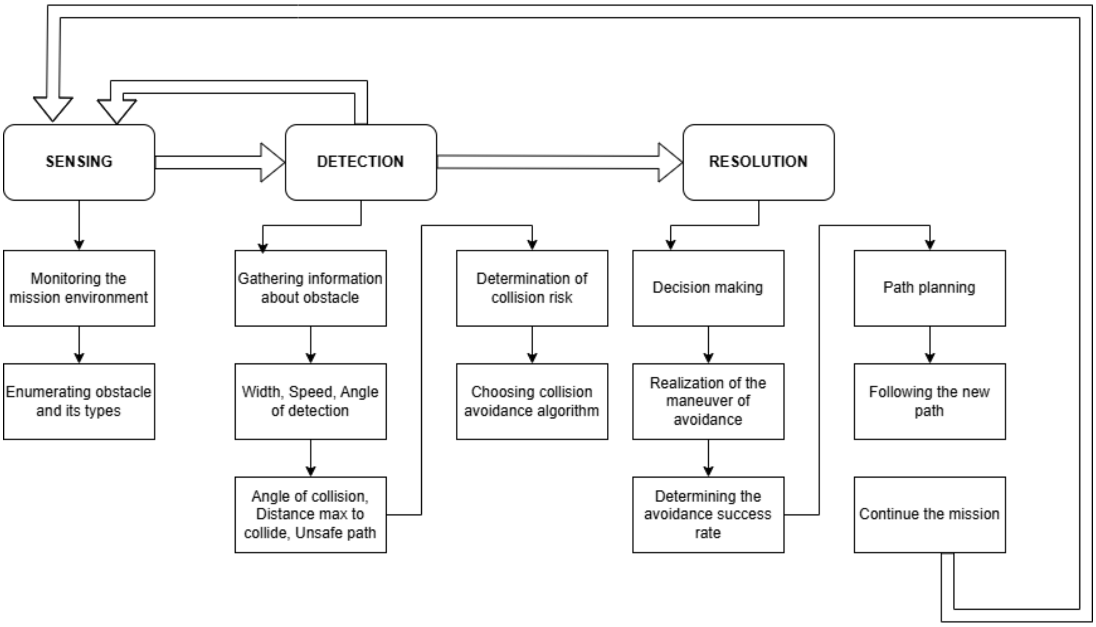


Figure 3.6 – UAV collision avoidance modules.

3.5.3 Sensing Phase

The sensing task in a UAV system can be executed using two types of sensors, as illustrated in Figure 3.7 :

Cooperative Sensors : These sensors function by receiving radio signals from another aircraft equipped with identical onboard systems (17). They are designed to sense the surrounding environment and share the collected data with other aircraft. A prominent example of a cooperative sensor is the Automatic Dependent Surveillance-Broadcast (ADS-B), which is capable of transmitting comprehensive flight plan data.

Non-Cooperative Sensors : Unlike cooperative sensors, non-cooperative sensors can detect obstacles independently, without requiring communication with other UAVs or obstacles (17). Non-cooperative sensors are classified into two categories : active and passive sensors. Active sensors operate by emitting signals to identify obstacles, whereas passive sensors detect obstacles by analyzing signals emitted by the obstacles themselves (18).

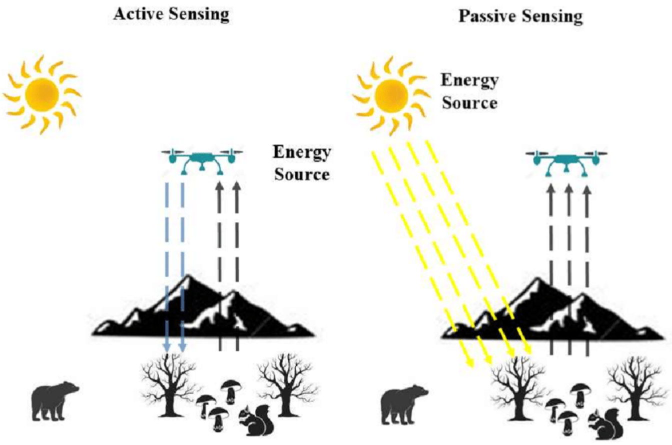


FIGURE 3.7 – Types of sensors.(45)

3.5.4 Detection Phase

In the detection phase, potential future conflicts in the air traffic are identified (19) through the use of current state projections. Any intrusion into a UAV's protective zone triggers conflict alerts, which enables timely execution of avoidance maneuvers. There are three types of state projections commonly used : nominal, worst-case, and probabilistic projections (20).

Nominal Projection : This method involves projecting the current state of the UAV along a single, most likely trajectory (e.g., a straight path) into the future.

Worst-Case Projection : This projection considers a broad range of possible maneuvers for the aircraft. If any of these maneuvers result in a conflict, an alert is issued.

Probabilistic Projection : Instead of projecting all possible maneuvers for an obstacle, only a select set of trajectories with associated probabilities are projected. This is typically done by developing a complete set of future trajectories weighted by their likelihood of occurring (e.g., using probability density functions). These probable trajectories are then used for future conflict detection.

3.5.5 Resolution Phase

When a potential conflict is identified for the near future, the system initiates the resolution maneuver process. Resolution maneuvers involve determining the necessary actions to avoid an impending collision.

3.3.8.1 Resolution Maneuvers

Resolution maneuvers are the set of actions required to avert a conflict. These maneuvers include altering speed (accelerating or decelerating), horizontal movements (turning left or right), and vertical adjustments (climbing or descending). In some scenarios, a single basic maneuver might suffice to avoid a collision (21). However, in more complex situations, a combination of these basic maneuvers may be necessary. These combined maneuvers can be executed either simultaneously or sequentially, particularly when dealing with a swarm of drones.

3.3.8.1 Management of Multiple Aircraft Conflicts

When multiple aircraft are involved in a conflict, the resolution system can manage the situation in two ways : pairwise or global-wise.

Pairwise : In this approach, conflicts are addressed sequentially, dealing with each pair of aircraft individually.

Global-wise : In this method, the entire conflict is assessed simultaneously, and a global resolution is achieved. This typically involves a centralized approach where all aircraft involved in the conflict are grouped, and the issue is resolved collectively.

3.4 Collision Avoidance Approaches

Collision avoidance strategies for UAVs can be categorized into various classes (20; 22; 15; 23). The most commonly referenced categories in the literature are illustrated in Figure 3.8.

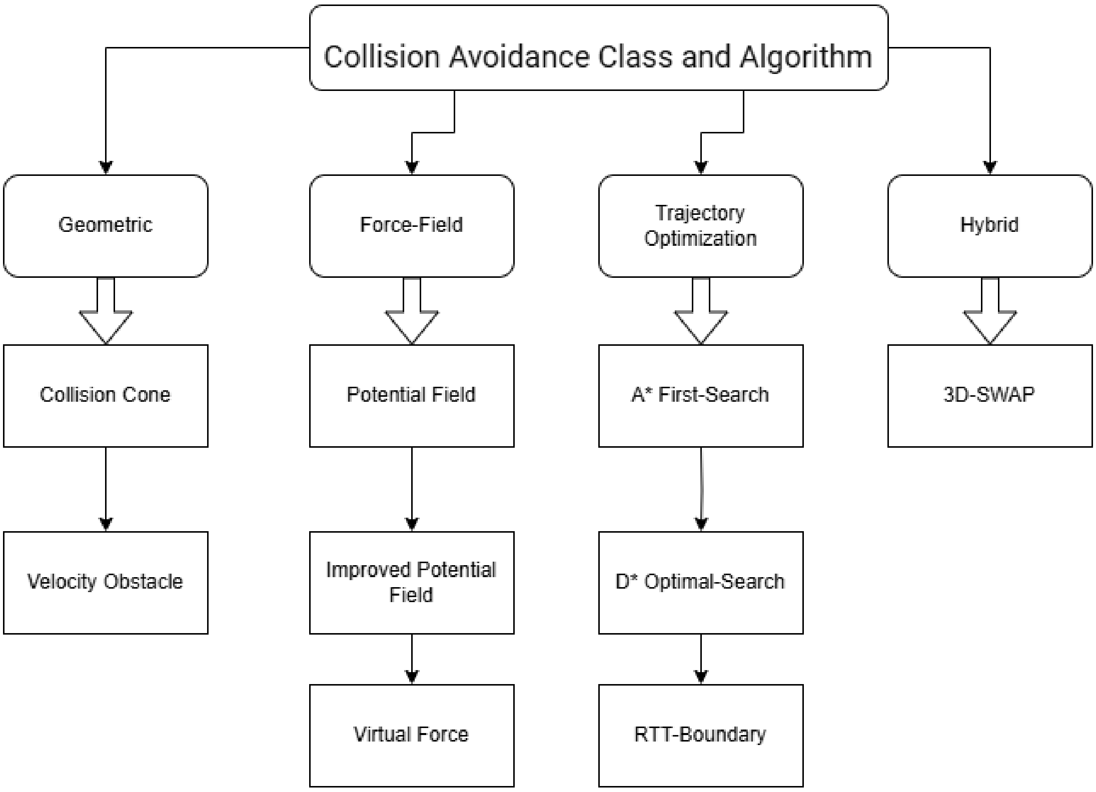


FIGURE 3.8 – Collision Avoidance Methods Classification.

3.5.6 Geometric Approaches

Geometric approaches represent UAVs as point masses characterized by a velocity vector (V_x, V_y) (24). These approaches typically assume that UAVs share their velocity data to facilitate cooperative collision avoidance maneuvers (25). Two prominent algorithms based on geometric methods are the Velocity Obstacle and the Collision Cone algorithms.

Velocity Obstacle and Collision Cone

The Collision Cone (CC) concept is a fundamental part of this approach. It defines a set of velocities that would inevitably lead the UAV into a collision with an obstacle (26). The CC can be mathematically represented as :

$$CC_{uo} = \{\forall V_{uo} \exists \lambda_{uo} | \lambda_{uo} \cdot V_{uo} \cap \text{Obstacle} \neq \emptyset\} \tag{3.3}$$

Where :

- V_u is the velocity of the UAV,
- V_o is the velocity of the obstacle,
- $V_{uo} = V_u - V_o$ represents the relative velocity of the UAV with respect to the obstacle,
- λ_{uo} is the line of the relative velocity vector V_{uo}.

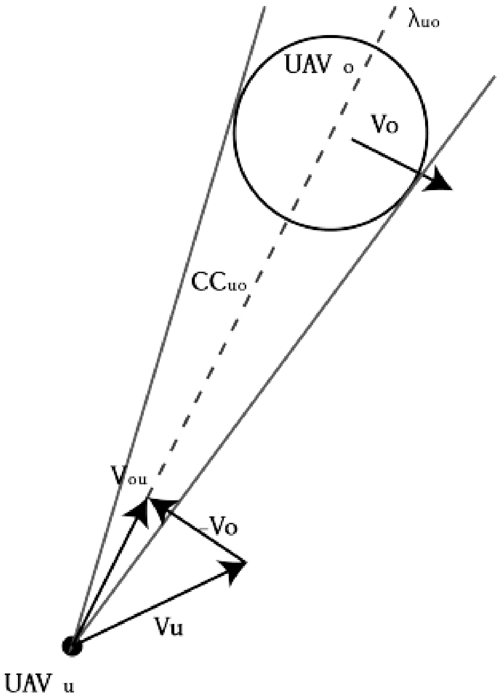


FIGURE 3.9 – collision cone.

Another critical concept is the Velocity Obstacle (VO), which is particularly useful for dynamic obstacles. The VO is derived by adding the set of collision cone velocities to the velocity of the obstacle using the Minkowski sum, resulting in another cone known as the Velocity Obstacle (illustrated in Figure 3.10) (23). The VO can be described by the following equation :

$$V_{O_{uo}} = CC_{uo} \oplus V_o$$

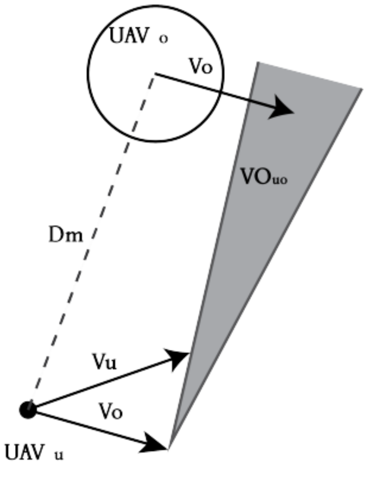


FIGURE 3.10 – Velocity Obstacle.

When a UAV faces a potential collision, it must select a velocity V_u that lies outside the calculated velocity obstacle (VO) to ensure it avoids the obstacle. In scenarios where multiple obstacles are present, the velocity obstacle is defined as the union of the individual velocity obstacles :

$$VO_{\text{total}} = \bigcup_{i=1}^{m} VO_i$$

Velocity Obstacle Limitations

While the velocity obstacle method is widely employed in geometric approaches, it does have its limitations. For example, if a UAV is encircled by multiple VO cones, it may not find a feasible path to evade the obstacles, rendering collision avoidance impossible.

Force Field-Based Approaches

Force field-based approaches calculate a safe trajectory by considering various potential forces exerted on the UAV by obstacles and the intended goal (27). The Potential Field method, specifically used in selective avoidance strategies, is a prime example of this approach (28; 29; 30).

3.5.7 Selective Avoidance Approaches

The Selective Avoidance algorithm operates by calculating the total force acting on a UAV when an obstacle is detected (31; 15). The total force is given by :

$$F_{\text{total}}(x) = F_{\text{rep}}(x) + F_{\text{att}}(x)$$

Where :

$F_{\text{rep}}(x)$ represents the repulsive force, which pushes the UAV away from the obstacle. It is defined as :

$$\mathrm{F}_{\text{rep}}(x) = \begin{cases} -\Delta \cdot \frac{1}{2} \cdot \mu \left(\frac{1}{\rho_o} - \frac{1}{\rho_{\text{safe}}} \right) \cdot \rho_d^2, & \text{if } \rho_x \leq \rho_0 \\ 0, & \text{otherwise} \end{cases}$$

Where Δ represents the gradient of potential, μ is a positive constant specific to an obstacle, ρ_o represents the distance to the obstacle, ρ_{safe} represents the safety distance, and ρ_d represents the distance between the UAV and the destination. In the case of multiple obstacles, F_{Rep} is calculated by the equation :

$$F_{Rep} = \sum_{i=1}^{n} F_{rep,i}$$

F_{Att} represents the attractive force generated by the goal that pulls the UAV toward it, and it is defined by :

$$F_{Att(x)} = -\epsilon \cdot \rho_d \Delta \rho_d$$

Where ϵ is an attractive constant. Figure 3.11 illustrates the different forces acting on a UAV.

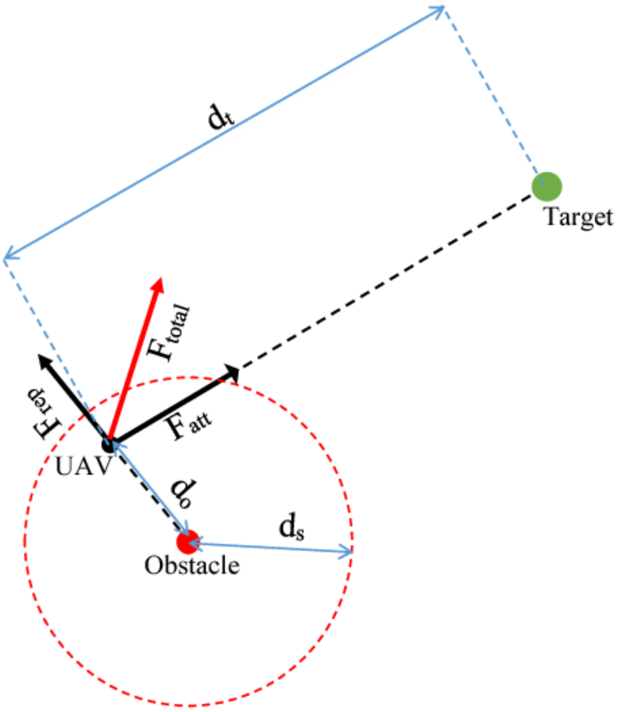


FIGURE 3.11 – Different Forces applied by the obstacle and the goal.(43)

Selective Avoidance Algorithm

The Selective Avoidance Algorithm, as depicted in Figure 3.12 and detailed in (43), involves selecting the UAV that has traveled a shorter distance to adjust its trajectory to avoid a collision, while allowing the other UAV to proceed towards its destination.

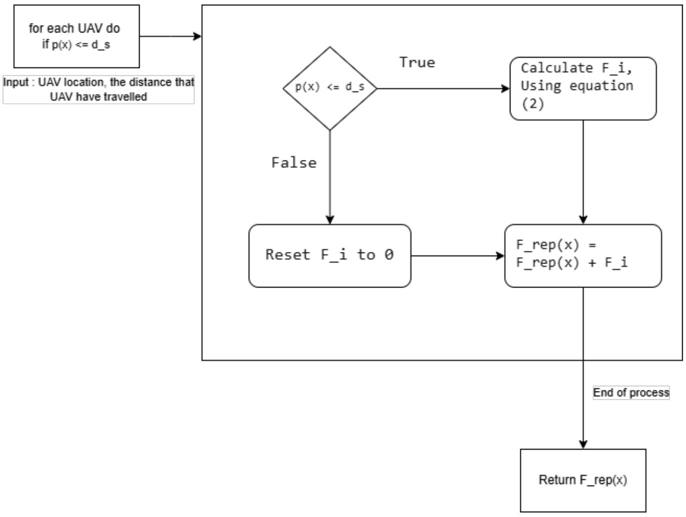


FIGURE 3.12 – Flowchart for Selective Avoidance algorithm.

Limitations of Selective Avoidance

In certain scenarios, the repulsive force required for the UAV to maneuver can become unrealistic when considering conceptual constraints. This limitation means that the approach might not be applicable to all UAV types. For instance, when used with fixed-wing UAVs, the resulting repulsive force might be excessively large, resulting in a backward total force that cannot be immediately executed, unlike multi-rotor drones.

3.5.8 Optimized Trajectory Approaches

Optimized trajectory methods (32; 33; 34) require each UAV to compute a path with the lowest cost using a cost function F, similar to the A* algorithm , which closely resembles UAV routing algorithms.

A* Algorithm

The A* algorithm operates by treating the environment as a weighted 2D grid and handles obstacles as follows :

- It computes the most efficient route to the goal using the total cost function :

  $$F = G + H$$

  where G denotes the cost incurred from the starting point to the current location, and H represents the heuristic function that estimates the remaining cost to the destination.
- The algorithm evaluates paths close to obstacles using two distinct heuristic strategies : conservative and aggressive.

In the conservative heuristic, the algorithm prioritizes safety by assigning lower costs to paths that keep a safe distance from obstacles, thereby promoting safer route choices. On the other hand, the aggressive heuristic aims for paths that may involve greater risk but offer quicker routes to the destination, with a focus on maintaining a minimal safety distance between UAVs (35).

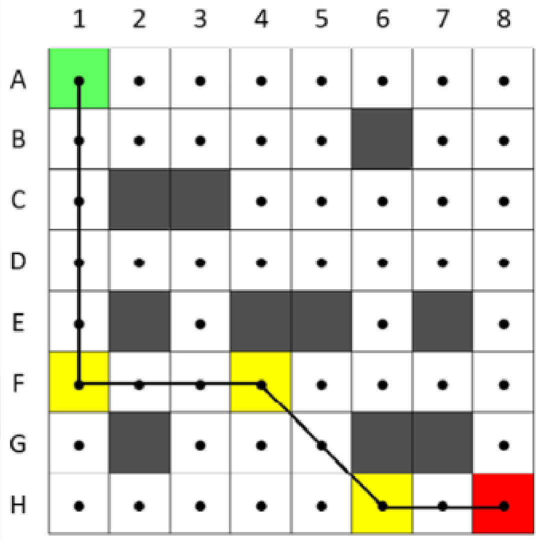


Figure 3.13 – A* approach (44).

A* Algorithm Limitations

The A* algorithm requires significant computational resources and is primarily effective in avoiding fixed obstacles. Its ability to generate efficient avoidance maneuvers diminishes in more dynamic environments.

Hybrid Approaches

Hybrid approaches combine elements from geometric methods, force field strategies, and optimized trajectory techniques, creating unique and effective collision avoidance methods.

3D SWAP

3D SWAP is a decentralized, reactive collision avoidance algorithm that employs the concept of safety cylinders, to ensure safe navigation (36). It is classified as a reactive approach because it responds to real-time situations, allowing for highly efficient avoidance maneuvers. While deliberative approaches rely on pre-planned actions and generally perform well in tasks, their slower reaction times and inability to adapt quickly to changing environments can be a limitation.

The 3D SWAP algorithm uses three types of safety cylinders :

- **Collision Cylinder :** This cylinder encases each UAV and is used to determine whether a collision has occurred.
- **Reserved Cylinder :** This cylinder surrounds the collision cylinder and is used to detect potential xy-plane conflicts.
- **Blocking Cylinder :** This outermost cylinder encapsulates the previous two and is responsible for detecting conflicts in the z-plane.

The Cylindrical Obstacle Diagram (COD) is a data structure utilized by 3D SWAP for the cylindrical representation of obstacles around the UAV, By defining these distinct cylinders around each UAV, the system can identify two types of conflicts :

- **XY-Conflicts :** When an xy-plane conflict is detected, an avoidance direction $\phi_{\text{avoidance}}$ is calculated based on the direction of the obstacle $\phi_{\text{collision}}$. 3D SWAP then prevents UAVs from moving toward the obstacle.
- **Z-Conflicts :** If a z-plane conflict is identified, the UAV's altitude is restricted, and only horizontal movement toward the goal is permitted.

3.6 Conclusion

In this chapter, we have undertaken a comparative study of mobility models and collision avoidance systems, emphasizing their significance in the domain of drone-based applications. Mobility models play a critical role in simulating the movement patterns of mobile nodes, particularly drones, which must be carefully selected to match the specific requirements of each mission. The mobility model not only influences the performance of network protocols but also impacts the effectiveness of collision avoidance strategies, which are integral to ensuring the safety and reliability of drone operations.

The exploration of collision avoidance systems in this chapter has highlighted the various methods available, each with its strengths and limitations. The choice of an appropriate collision avoidance strategy is, therefore, just as crucial as the selection of a mobility model. Both must be considered in tandem to achieve optimal performance in drone networks.

As we move forward, the next chapter will propose a new method that synthesizes the insights gained from the study of mobility models and collision avoidance techniques. This approach will be grounded in the foundational concepts discussed in Chapter 2 and will adhere to the general structure of collision avoidance strategies, with the goal of enhancing both mobility modeling and collision prevention in drone networks.

Chapter 4

A new surveillance method with intergration of collision avoidance mechanism

4.1 Introduction

Surveillance drones have become an essential technological system for ensuring the safety of property and people. In our work, we are particularly interested in the surveillance of forests, specifically for detecting fires. The UAV sends a report or an alert only when a fire is detected by the sensor equipped in the drone. One of the key technical characteristics of drones, crucial for maintaining continuous surveillance missions, is their energy consumption. This chapter focuses on this aspect. We aim to propose a new surveillance method using drones, which can also be considered an improvement of the two mobility models, RWP and GM. However, one limitation of this method is the absence of a collision avoidance mechanism. To overcome some of the shortcomings of other techniques, we have tried to develop a new collision avoidance technique that addresses some of the limitations discussed in the previous Chapter. After briefly discussing these limitations, we present our technique and the simulation concept.

4.2 Proposition for a Drone Surveillance Method

In a drone-based surveillance system, energy consumption is a critical factor that significantly influences the accuracy and overall quality of the system. Our primary goal is to develop a surveillance method utilizing drones that aims to minimize energy usage.

In this approach, we incorporate the concept of "clustering," which involves grouping similar objects. Among the various types of clustering, we have selected a well-known method called "Hierarchical Clustering (top-down)." The number of levels in our approach can vary from one 1 to three 3

The key parameters in our method include the surveillance area (x, y) and the total number of drones. The method is structured into the following three (03) phases :

4.2.1 Assignment of Tasks at Each Level

The surveillance drones are organized into three distinct levels :

1. **Level 1 (Master Level) :** This highest level consists of a single drone, referred to as the Master, responsible for the following tasks :

   (a) Dividing the entire surveillance area into four sub-zones and assigning the coordinates (x_i, y_i) for these sub-zones to the four drones at Level 2.
   (b) Sent to the four (04) drones contains in the second level the number of drones of the third level which belong to them (i.e., the number of drones of each sub-zone which does the surveillance).
   (c) Gathering data from the four drones at Level 2.
2. **Level 2 (Leader Level) :** This level consists of four drones, each acting as the leader for one of the sub-zones. The tasks for these drones include :
   (a) Receiving the coordinates (x_i, y_i) and the number of surveillance drones allocated to their sub-zone from the Master drone.
   (b) Distributing the assigned coordinates to each Level 3 surveillance drone within their sub-zone.
   (c) Collecting data from their respective Level 3 surveillance drones.
   (d) Follow a strategy in the event of the presence of difficulties linked to weak batteries or unexpected breakdowns ; the aim of this last task is to ensure the continuity of the monitoring mission.
3. **Level 3 (Surveillance Level) :** This level comprises the drones tasked with patrolling the sub-zones. The primary responsibilities include :
   (a) Reporting any significant changes to the sub-zone conditions or the drone's status to the leader.
   (b) Notifying the leader in the event of a low battery level.

Selection Methods for the Master and Leaders

the method to select the Master and the leaders is :

— our method is to designate the drone with index 0 (Host[0]) as the Master, with the leaders being the drones indexed from 1 to 4 (Host[1..4]). This method is used in the pseudocode algorithms presented below.(37)

Algorithm 1 Partitioning area to subzones

```
Require: nbrDrones, ConstraintMaxX, ConstraintMaxY
Host[0].isMaster := true;
if 1 $\leq$ nbrDrones $\leq$ 4 then
    nbrLevel := 1;
    for i = 0 to (nbrDrones - 1) do
        Host[i].isSurv := true;          // All drones perform surveillance.
    end for
else if 5 $\leq$ nbrDrones $\leq$ 12 then
    Host[0].isSurv := false;
    nbrLevel := 2;
    for i = 1 to (nbrDrones - 1) do
        Host[i].isSurv := true;          // All drones survey except the master.
    end for
else
    Host[0].isSurv := false;
    nbrLevel := 3;
    nbrSubzones := 4;
    for i = 1 to 4 do
        Host[i].isLeader := true;        // The leaders of the subzones.
        Host[i].leaderOf := Host[i] mod 4;
    end for
    for i = 5 to (nbrDrones - 1) do
        Host[i].isSurv := true;          // The drones perform surveillance.
    end for
end if
Assignment of nodes to zones (nbrDrones, ConstraintMaxX, ConstraintMaxY,
    nbrLevel);
```

4.2.2 Assignment of Drones to Sub-Zones

The principle behind assigning drones to sub-zones is to allocate drones with successive identification numbers to different sub-zones. In other words, at each iteration, the current drone is assigned to a different sub-zone than in the previous iteration. This process is repeated until all drones have been assigned.

The calculation of coordinates (x, y) is performed as follows :

The Master drone is conventionally allowed to move throughout the entire area designated for surveillance(37).

Algorithm 2 Assignment of UAVs to Zones

```
Require: nbrDrones, ConstraintMaxX, ConstraintMaxY, nbrLevel
if nbrLevel = 1 then
  for i = 0 to (nbrDrones - 1) do
    Host[i].minX := Host[i] * (ConstraintMaxX / nbrDrones);
    Host[i].minY := 0;
    Host[i].maxX := (Host[i] + 1) * (ConstraintMaxX / nbrDrones);
    Host[i].maxY := ConstraintMaxY;
  end for
else
  Host[0].minX := ConstraintMinX;
  Host[0].minY := ConstraintMinY;
  Host[0].maxX := ConstraintMaxX;
  Host[0].maxY := ConstraintMaxY;
  for i = 1 to (nbrDrones - 1) do
    includeIn := Host[i] mod 4;
    if includeIn = 1 then
      Host[i].minX := 0;
      Host[i].minY := 0;
      Host[i].maxX := ConstraintMaxX / 2;
      Host[i].maxY := ConstraintMaxY / 2;
    else if includeIn = 2 then
      Host[i].minX := ConstraintMaxX / 2;
      Host[i].minY := 0;
      Host[i].maxX := ConstraintMaxX;
      Host[i].maxY := ConstraintMaxY / 2;
    else if includeIn = 3 then
      Host[i].minX := 0;
      Host[i].minY := ConstraintMaxY / 2;
      Host[i].maxX := ConstraintMaxX / 2;
      Host[i].maxY := ConstraintMaxY;
    else
      Host[i].minX := ConstraintMaxX / 2;
      Host[i].minY := ConstraintMaxY / 2;
      Host[i].maxX := ConstraintMaxX;
      Host[i].maxY := ConstraintMaxY;
    end if
  end for
end if
```

4.2.3 Selecting a Mobility Model

The third phase involves selecting a mobility model to ensure comprehensive coverage of the area. This phase can be considered as an enhancement of the GM and RWP mobility models. In these models, as previously discussed in Chapter 3, the drone traverses the entire area, leading to significant energy consumption.

Our approach aims to reduce the mobility of each drone through the concept of clustering. The mobility of a drone is directly proportional to its energy consumption. Therefore, by reducing the mobility of each drone, we achieve a corresponding reduction in energy consumption.

4.2.4 Expected Benefits

Our method offers several anticipated advantages :

1. **Load Balancing :** The use of a hierarchical model allows tasks to be distributed across different levels within the system (the Master initiates the mission and performs calculations, the leaders receive data, and the slave drones carry out the surveillance).
2. **Extended Surveillance Time :** Reducing drone mobility conserves battery energy, which in turn extends the overall surveillance duration.
3. **Battery Preservation :** By optimizing energy usage, the lifespan of the drone batteries is prolonged.
4. **Minimized Message Exchanges :** Predefining the Master and leaders by their identification numbers, instead of using an election algorithm, reduces the number of message exchanges, thereby increasing both the surveillance time and battery life.
5. **Flexibility :** The system allows for the easy addition of drones if the initial number is found to be insufficient, or reduction if fewer drones are needed.

4.2.5 Limitations

While our method provides several advantages, it also has some limitations :

1. **Single Point of Failure :** The **Chief Controller** (formerly Master) acts as a central point for initiating and managing the mission. If this drone fails or encounters issues, it could impact the entire operation.
2. **Collision Risk :** Despite hierarchical management, the risk of collisions among drones remains. Limited collision avoidance mechanisms may not fully address scenarios with high drone density or dynamic obstacles, potentially leading to conflicts or crashes.
   This highlights the need for more robust collision avoidance strategies to ensure safe and efficient operations, then we will propose a new collision avoidance method to ensure a safe surveillance.

4.3 Collision Avoidance Methods : Overview

After examining the techniques presented in the previous chapter, we can summarize the following key points :

- **Velocity Obstacles and Collision Cone :** While these methods are computationally efficient, they may be insufficient in densely populated networks, such as UAV swarms.
- **Selective Algorithm :** This algorithm is tailored for vehicles, such as quadrotor UAVs, that can rapidly change direction. However, its application is limited to such agile systems.
- **A* Algorithm :** The primary limitation of this method lies in its high computational demands, especially due to the extensive future state projections required.

4.4 Modified Velocity Obstacle : Our Approach

Our approach builds upon the velocity obstacle methods, with the following enhancements :

- **Reduced Prohibited Angles :** We introduce the concept of future UAV positions and facilitate the exchange of these positions between drones, thereby reducing the range of prohibited angles.

To formalize our approach, we structured our collision avoidance system into three main steps : **Sensing**, **Detecting**, and **Avoiding** collisions, as depicted in Figure 4.1.

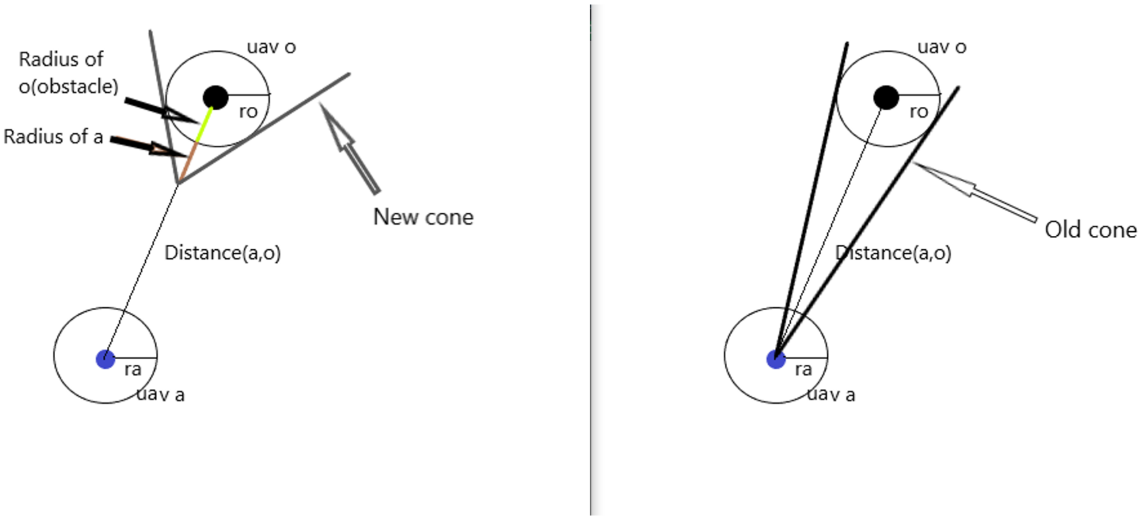


FIGURE 4.1 – New vs old approach.

4.4.1 Modified Velocity Obstacle Phases

Sensing : Gathering Parameters

This phase is crucial in our Collision Avoidance System (CAS) approach. To ensure the efficiency of our method, each UAV must collect and maintain a set of parameters that are necessary for the protocol to function effectively.

Sensing : Communication and Data Exchange

When UAVs enter each other's influence zones, they exchange their (velocity,timeStep,angle)information. This data exchange significantly reduces processing costs and improves performance compared to methods like the A* algorithm, which relies on extensive future state projections.

The future position of a UAV can be calculated using the following equation :

$$\text{FuturePos(x, y)} = \begin{cases} \text{future}(x) = \text{current}(x) + \text{velocity} \times \text{time} \times \cos(\text{angle}) \\ \text{future}(y) = \text{current}(y) + \text{velocity} \times \text{time} \times \sin(\text{angle}) \end{cases}$$

Here, *velocity* represents the UAV's speed, *time* (Δt) is a parameter defined within the swarm that represents the projection into the future, and *angle* is the current directional angle of the UAV.

Detection : Projection

Once the future positions of neighboring UAVs are gathered, a projection is conducted to predict potential collisions and issue alerts in the event of hazards.

- It is observed that when $\Delta t >$ maneuver_time, the system's accuracy is high. Conversely, when this is not the case, UAVs tend to perform avoidance maneuvers closer to the obstacle.

4.4.2 Modified Velocity Obstacle : Key Idea

The core of our optimization stems from the traditional velocity obstacle approach. However, instead of attempting to avoid a wide range of potential velocities—a method that proves to be both impractical and computationally expensive, as previously discussed in Chapter 3—our Modified Velocity Obstacle (MVO) method adopts a more communication-centric strategy.
our new method for optimizing the Velocity Obstacle (VO) concept by modifying the calculation of the cone angle indeed addresses some limitations of the traditional VO approach. By using $\frac{r_o}{r_o+r_a}$ instead of $\frac{r_o}{d}$, our method focuses on the relative sizes of the UAV and the obstacle rather than just the distance, which can lead to more efficient and realistic collision avoidance. This can particularly reduce the likelihood of unnecessary evasive maneuvers, thereby potentially improving the energy efficiency and overall performance of the UAVs.

In the Velocity Obstacle (VO) approach, the initialization point typically corresponds to the current position (x, y) of the UAV (e.g., UAV a).
However, in our new idea, the initialization point has shifted, as indicated as below. Calculation of the New Initialization Point

1. **Determine the Direction Vector** - Calculate the unit direction vector $\vec{d}$ from UAV a to the dynamic obstacle (UAV o). This vector is given by :

   $$\vec{d} = \frac{(x_o - x_a, y_o - y_a)}{\sqrt{(x_o - x_a)^2 + (y_o - y_a)^2}}$$

   - Here, (x_a, y_a) and (x_o, y_o) are the coordinates of UAV a and UAV o, respectively.
2. **Calculate the Offset Distance** - The offset distance, which represents the distance from

the center of UAV a to the new initialization point, can be calculated as :

$$\text{offset} = \frac{r_a}{r_o + r_a} \times \text{Distance}(a, o)$$

Where :
- r_a is the radius of UAV a.
- r_o is the radius of the dynamic obstacle (UAV o).
- Distance(a, o) is the Euclidean distance between UAV a and the dynamic obstacle, calculated as :

$$\text{Distance}(a, o) = \sqrt{(x_o - x_a)^2 + (y_o - y_a)^2}$$

3. **Compute the New Initialization Point** - The new initialization point (x', y') can be calculated by moving from the original position of UAV a along the direction vector $\vec{d}$ by the calculated offset distance :

$$x' = x_a + \text{offset} \times \vec{d_x}$$

$$y' = y_a + \text{offset} \times \vec{d_y}$$

- Where $\vec{d_x}$ and $\vec{d_y}$ are the components of the direction vector $\vec{d}$.

This is the pseudocode of the Modified Velocity Obstacle.

Algorithm 3 Modified Velocity Obstacle (MVO) Calculation for each UAV_i

```
Require: Positions and radius of UAV $a$ and obstacle UAV $o$ : $(x_a, y_a)$, $(x_o, y_o)$, $r_a$, $r_o$
Require: Velocities of UAV $a$ and UAV $o$ : $\vec{v}_a$, $\vec{v}_o$
Calculate the Direction Vector
$\vec{d} \leftarrow \frac{(x_o - x_a, y_o - y_a)}{\sqrt{(x_o - x_a)^2 + (y_o - y_a)^2}}$
$D \leftarrow \sqrt{(x_o - x_a)^2 + (y_o - y_a)^2}$
Calculate Offset Distance
offset $\leftarrow \frac{r_a}{r_o + r_a} \times D$
Compute the New Initialization Point $(x', y')$
$x' \leftarrow x_a + \text{offset} \times \vec{d_x}$
$y' \leftarrow y_a + \text{offset} \times \vec{d_y}$
Calculate Relative Velocity
$\vec{v}_{rel} \leftarrow \vec{v}_a - \vec{v}_o$
Construct the VO Cone
Calculate VO Cone Boundaries : $\vec{v}_{left}, \vec{v}_{right} \leftarrow$ angles derived from $r_a, r_o,$ and $D$
Define VO Cone : VO cone $\leftarrow$ Region bounded by $\vec{v}_{left}$ and $\vec{v}_{right}$
Check for Collision
if $\vec{v}_{rel}$ lies within the VO cone then
    Collision predicted, adjust velocity.
else
    No collision.
end if
```

4.4.3 Avoidance Maneuver

This phase is activated solely when an alert is issued by the detection system. At this point, all previously calculated paths are analyzed, with non-viable (dead) paths being identified and excluded. The objective is to ensure that the remaining paths will guide the UAV to a safe movement trajectory. When two UAVs detect an imminent collision, the solution involves adjusting the trajectory of the UAV that has traveled a shorter distance, allowing it to avoid the collision, while the other UAV continues on its path toward its destination.

Modified Velocity Obstacle : Path Filtering

From the set of safe paths, the UAV must select the optimal avoidance route that allows it to continue toward its target. This selection is guided by a cost function, which is determined by the following equation :

$$F = \arg\min\left(Path_i \in AvoidancePaths \,|\text{distance}(Path_i, Goal_{uav})\right)$$

Modified Velocity Obstacle : Multiple Obstacles

When confronted with multiple obstacles, the avoidance maneuver is calculated and executed on a pairwise basis.

Advantages of our Method

(a) **Reduced Conservatism** The traditional VO method might be overly conservative because the cone can be quite large when the distance d is small, leading to unnecessary avoidance maneuvers. Our method adjusts the cone size based on the actual sizes of the UAV and the obstacle, reducing unnecessary maneuvers.

(b) **Better Scalability** In scenarios with multiple UAVs, the reduced cone size means that the algorithm scales better, as it is less likely to interpret safe situations as potential collisions.

(c) **Energy Efficiency** By minimizing unnecessary maneuvers, the UAVs can follow more direct paths, conserving energy.

4.5 Conclusion

In this chapter, we have presented our “Clustering based” system which is a surveillance system using drones. It also contains a set of pseudo algorithms that helped us to program this system. We have also talked about the advantages that concern this system. As well as some limitations such as absence of collision avoidance mechanism that we have also improved. In the next chapter, we will present a comparative simulation between the mobility models mentioned in the third chapter and our new model that contains the proposed collision avoidance method.

Chapter 5

Simulation and performance analysis

5.1 Introduction

Technological advancements have enabled the evolution and increasing complexity of computer systems and networks. To address issues related to a specific system, we rely on protocols or develop new ones. These protocols require thorough testing and evaluation to ensure their validity, which can be achieved through the use of simulation tools. The objective of this chapter is to simulate the mobility models and collision avoidance techniques discussed in Chapters 3 and 4 using the NS-3 simulator. This will allow for a comparative analysis to assess the performance of these methods. In Section 5.2, we will explore various performance evaluation techniques, presenting the potential metrics for testing and evaluating the protocols. Section 5.3 will provide a brief overview of the simulator to be used. Lastly, Section 5.4 will detail the Simulation Parameters and the results.

5.2 Performance Evaluation Techniques

There are several methods available for evaluating the performance of a system :

5.2.1 Real-World Implementation

This technique involves directly measuring and analyzing the performance of a system in a real-world setting. While this approach provides an accurate understanding of the system's true behavior, it also presents certain challenges :

i. **High Cost :** Implementing an algorithm in a real-world environment may require expensive resources, such as specialized equipment, sensors, monitoring devices, or measurement tools.

ii. **Control Challenges :** It can be difficult to manage all variables in a real-world environment, making it hard to replicate the same conditions for each experiment. Environmental factors, external interferences, and other uncontrolled variables may influence the results, complicating the precise analysis of the algorithm.

iii. **Risks and Safety :** In some cases, executing an algorithm in the real world may involve safety risks. For instance, in the field of drones, errors during execution could lead to potentially dangerous accidents. Additionally, there may be concerns regarding data security when handling sensitive real-world data.

iv. **Time :** Conducting experiments in real-world conditions can be time-consuming, especially when strict time constraints are present. Some experiments may require extended observation periods to collect sufficient data.

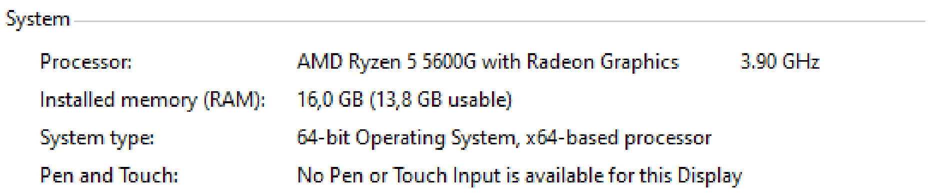
5.2.2 Simulation

This technique involves implementing a simplified model of the system using an appropriate simulation program. This method realistically represents the behavior of the system under evaluation. Moreover, simulation allows for the visualization of results in the form of graphs, which are easy to analyze and interpret.

To evaluate the performance of the mobility models under study, it is necessary to simulate them to present results that enable a comparative analysis between these models and to test their functionality.

5.3 Simulation tool and work environment

ns-3 is an open-source, discrete-event network simulator widely used for research and educational purposes in the field of network communication. Written in C++ with optional Python bindings, ns-3 allows for the modeling, simulation, and analysis of various network protocols and systems. It is particularly well-suited for simulating internet protocols, wireless networks, and large-scale network topologies. ns-3 provides a realistic and scalable simulation environment that includes various models for IP-based protocols (TCP, UDP, IPv4, IPv6, etc.), link-layer protocols (Wi-Fi, Ethernet, LTE, etc.), and mobility models such as Random Waypoint (RWP) and Gauss-Markov (GM). Researchers and developers can extend ns-3 by creating custom modules or integrating external software, making it a flexible tool for studying the performance of communication networks and algorithms.
We realize the simulation under Windows 10. The Desktop used has the following configuration :



System

Processor:	AMD Ryzen 5 5600G with Radeon Graphics 3.90 GHz
Installed memory (RAM):	16,0 GB (13,8 GB usable)
System type:	64-bit Operating System, x64-based processor
Pen and Touch:	No Pen or Touch Input is available for this Display

FIGURE 5.1 – hardware environment.

5.4 Simulation and Results

Clustering simulation

Before initiating the simulation and analyzing the results, it is essential to specify the simulation parameters, as well as the mobility models that will be compared. We identify two types of parameters : (A) variable parameters, which change throughout the scenarios, and (B) fixed parameters, which remain constant. The following table presents the parameters used in all the scenarios discussed below.

Variable Parameters	**Fixed Parameters**
Number of nodes [10,40]	Routing protocol : AODV
Speed [60, 120] km/h	Communication range = 250 m
Pause time [30, 80] ms	Transmission rate = 1 Mb/s
	Energy production = 1 mW
	Minimum stop capacity of a node = 0.1 J
	Alpha = 0.5
	Node startup capacity = 1000 J
	Surface = (10000*10000) m^2

Table 5.1 – Simulation Parameters

Routing protocol AODV The routing protocol employed is AODV (Ad hoc On-Demand Distance Vector), which is a reactive protocol belonging to the On-Demand family. It operates using two main mechanisms : route discovery and route maintenance. The choice of AODV is due to its ability to minimize packet header overhead.

Collision Avoidance simulation

The parameters for the collision avoidance method are presented in the table below.

Parameter	**Value**
Radius of Vehicles	3
Radius of Obstacles	3
Direction Angle	50
Safety Distance	10
Time steps	1

Table 5.2 – Simulation Parameters Values

We compare both GM standard model and RWP standard model with GM Clustering and RWP Clustering models with addition of a collision avoidance method in term of energy consumption, The results highlight the differences in performance and behavior under various conditions.

Mobility models in comparison

i. RWP.
ii. GM.
iii. RWP clustering.
iv. GM clustering.
v. RWP clustering using collision avoidance.
vi. GM clustering using collision avoidance.

Scenario 1 :

Our goal is to compare the GM model with the GM Clustering method with GM Collision method to analyze energy consumption based on the variation in the number of nodes, and to identify which method is more efficient.

Density	GM	GM clustering	GM collision
10	408,4845	404,817	405,932
20	408,7943	405,119	405,885
30	409,1082	405,419	406,38
40	409,4231	405,71925	406,91

TABLE 5.3 – GM vs GM clustering vs GM collision (density/consumed energy)

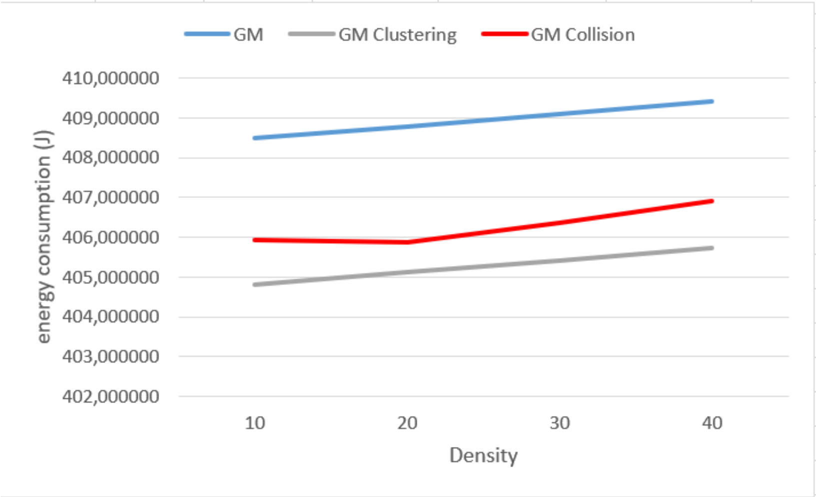


FIGURE 5.2 – GM vs GM Clustering vs GM Collision (density/consumed energy).

The chart reveals that as UAV density increases, the GM standard model consistently consumes the most energy, followed by the GM Clustering model, which reduces energy consumption through minimized UAV mobility. The GM Collision model, while adding energy overhead for collision avoidance, sits between the GM standard and GM Clustering in terms of energy use. Overall, the GM Clustering is the most energy-efficient, while the GM Collision balances efficiency and safety by reducing crash risk without consuming as much energy as the GM standard.

Scenario 2 :

we aim to compare the RWP model and the RWP Clustering method and RWP Collision to observe the energy consumption as a function of the variation in the number of nodes, and to determine which method is more efficient.

Density	RWP	RWP clustering	RWP collision
10	409,706	405,617	406,402
20	409,686	405,919	406,65
30	409,959	406,219	407,18
40	410,305	406,5125	407,71

TABLE 5.4 – RWP vs RWP clustering vs RWP collision (density/consumed energy)

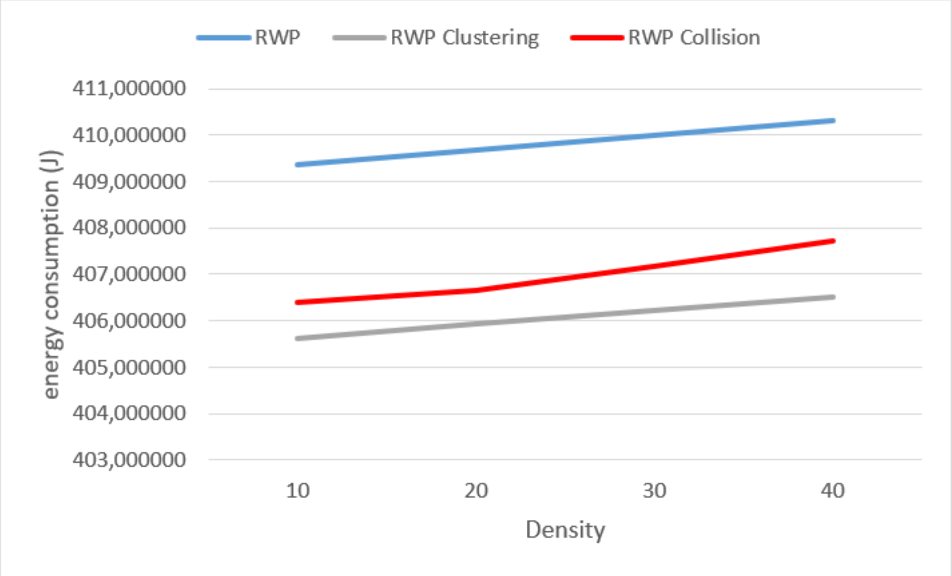


FIGURE 5.3 – RWP vs RWP Clustering vs RWP Clustering(density/consumed energy).

Through the comparative graph which represents Energy Consumed (J) as a function of node density, it is observed that the RWP model has consumed the highest value of energy, reaching 410.305 J when utilizing 40 nodes. On the other hand, the RWP Clustering model shows a more consistent increase in energy consumption with increasing node density. The GM Collision model, while adding energy overhead for collision avoidance, sits between the GM standard and GM Clustering in terms of energy use. notice the same observation with RWP simulation, But with different values in energy consumption, wich shows that the GM results is better than RWP results.

Scenario 3 :

The objective is to compare the energy consumption of the GM model with the GM clustering method and GM collision method by analyzing how energy consumption varies with different velocities.

Velocity	GM	GM clustering	GM collision
60/80	408,4331	405,218	406,85
80/100	408,6785	406,518	408,452
100/120	408,4363	407,818	409,95

TABLE 5.5 – GM vs GM clustering vs GM collision (velocity/consumed energy)

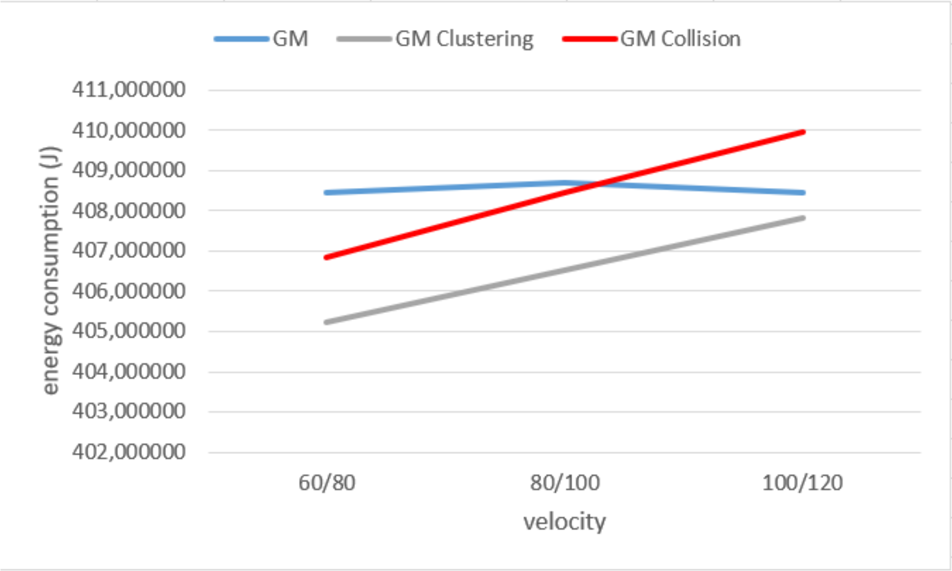


FIGURE 5.4 – GM vs GM Clustering vs GM Collision(Velocity/consumed energy).

In this chart, where velocity is the variable factor, the GM standard model shows relatively stable energy consumption across different velocities. The GM Clustering model remains the most energy-efficient, with a gradual increase as velocity rises. The GM Collision model, however, shows a sharp increase in energy consumption as velocity increases, due to the higher likelihood of performing collision avoidance maneuvers. This demonstrates how higher speeds make collision avoidance more energy-intensive, whereas clustering reduces mobility and helps maintain lower energy consumption even at higher velocities.

Scenario 4 :

The aim is to compare the energy consumption of the RWP model with the RWP clustering method and GM collision method by analyzing how energy consumption varies with different velocities.

Velocity	RWP	RWP clustering	RWP collision
60/80	409,337	406,018	407,65
80/100	409,378	407,318	409,102
100/120	409,361	408,618	410,75

Table 5.6 – RWP vs RWP clustering vs RWP collision (velocity/consumed energy)

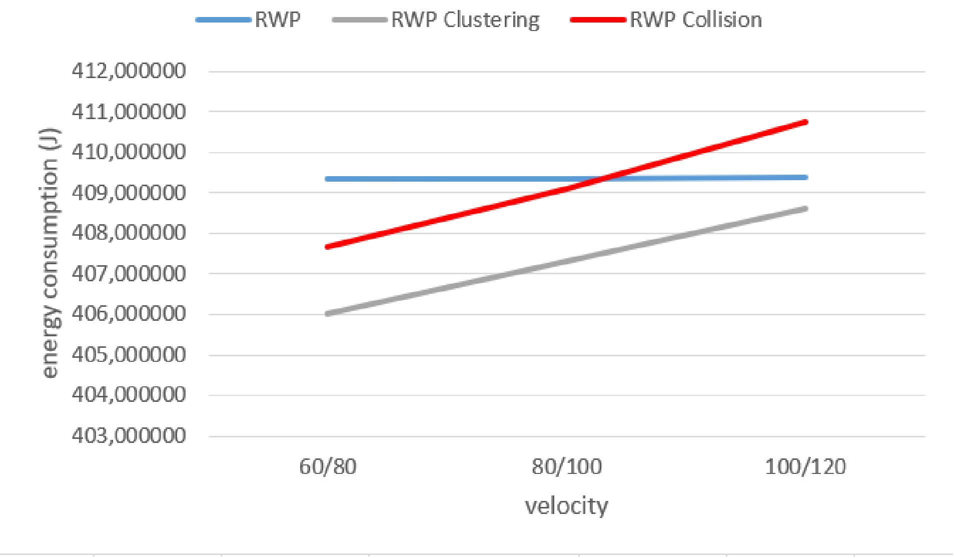


Figure 5.5 – RWP vs RWP Clustering vs RWP Collision(Velocity/consumed energy).

In this chart, where velocity is the variable factor, the RWP standard model exhibits relatively stable energy consumption across various speeds. The RWP Clustering model remains the most energy-efficient, with a gradual increase in energy usage as velocity rises.

On the other hand, the RWP Collision model shows a significant increase in energy consumption with higher velocities, due to the increased likelihood of executing collision avoidance maneuvers. This highlights how higher speeds make collision avoidance more energy-intensive, whereas clustering reduces mobility and helps maintain lower energy consumption even at higher velocities.

The values shows that the GM results are better than the RWP results.

Scenario 5 :

The study aims to evaluate the energy consumption of the GM model compared to the GM clustering method and GM collision by analyzing their performance at different pause times.

Pause Time	GM	GM clustering	GM collision
0.1	408,3967	405,2446667	406,004000
1	408,4331	404,8446667	405,105000
5	408,4068	403,9446667	404,501200

TABLE 5.7 – GM vs GM clustering vs GM collision (pause time/consumed energy)

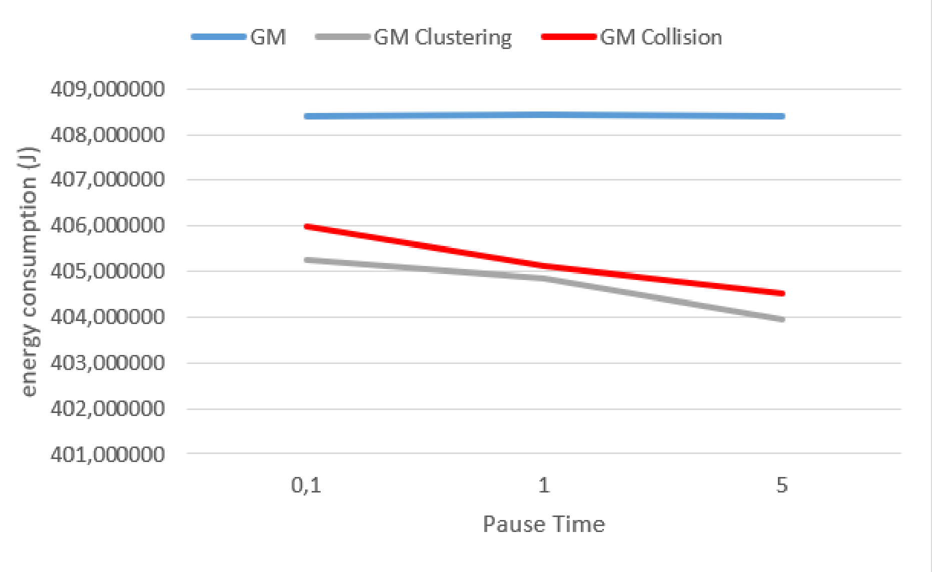


FIGURE 5.6 – GM vs GM Clustering vs GM Collision (Pause time/consumed energy).

The standard GM mobility model shows relatively constant energy consumption across different pause times, indicating minimal adaptation to varying UAV mobility. By contrast, GM Clustering reduces energy consumption as the pause time increases, as limiting UAV mobility within clusters minimizes energy use.

On the other hand, GM Collision, despite incorporating collision avoidance mechanisms, leads to higher energy consumption than clustering but shows a decreasing trend due to the UAVs adjusting their paths less frequently at higher pause times. Thus, clustering optimizes energy, while collision avoidance prioritizes safety at an energy cost.

Scenario 6 :

The objective is to compare the energy consumption of the RWP model with the RWP clustering method and RWP collision method by analyzing their performance at different pause times.

Pause Time	RWP	RWP clustering	RWP collision
0.1	409,337	406,5000967	407.200000
1	409,337	405,7513333	406.233000
5	409,3369	404,3513333	405.800000

Table 5.8 – RWP vs RWP clustering vs RWP collision (pause time/consumed energy)

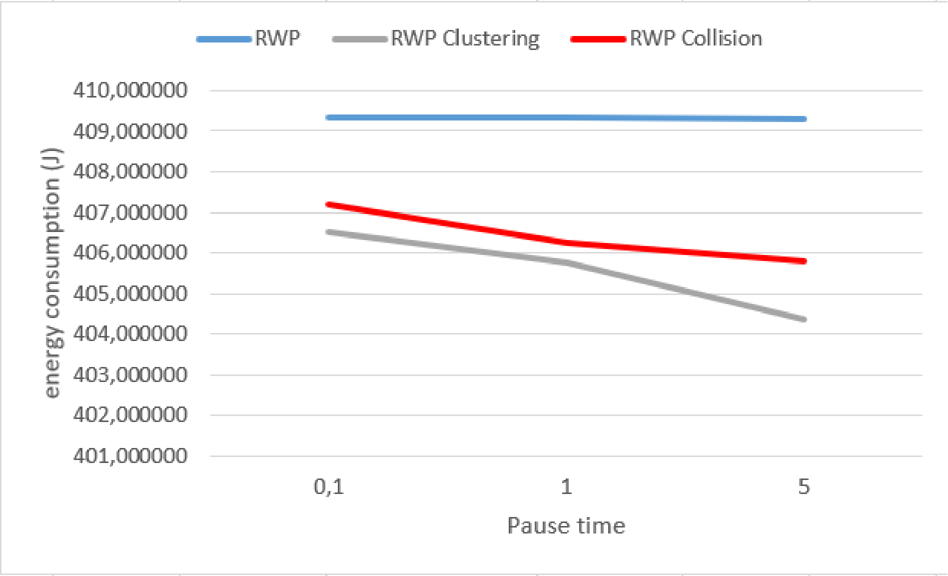


Figure 5.7 – RWP vs RWP Clustering vs RWP Collision (Pause time/consumed energy).

The RWP standard mobility model demonstrates relatively stable energy consumption across various pause times, indicating minimal adaptation to changes in UAV mobility. In contrast, the RWP Clustering model reduces energy consumption as pause time increases, as limiting UAV mobility within clusters minimizes energy use.
Conversely, the RWP Collision model, despite incorporating collision avoidance mechanisms, results in higher energy consumption compared to clustering but shows a decreasing trend as UAVs adjust their paths less frequently at higher pause times. Therefore, clustering optimizes energy efficiency, while collision avoidance prioritizes safety at an energy cost.
the values also indicates that the GM results are better than the RWP results.

5.5 Conclusion

The simulation results presented in this chapter demonstrate the effectiveness of clustering methods in optimizing the energy consumption of UAVs in surveillance applications. Initially, we explored the Gauss-Markov (GM) and Random Waypoint (RWP) mobility models, observing that while each model has its inherent strengths, both suffered from inefficiencies in energy usage due to extensive UAV mobility across the entire surveillance area. By introducing clustering techniques—GM Clustering and RWP Clustering—we successfully minimized UAV mobility by confining their operations to subzones. This approach significantly reduced energy consumption, with GM Clustering outperforming RWP Clustering, likely due to the GM model's more predictable and stable movement patterns within clusters.

In the second phase, a collision avoidance mechanism was integrated into the simulation. While this method effectively reduced the risk of sudden accidents, protecting hardware, humans, animals, and other objects, it did lead to an increase in energy consumption. The primary reasons for this are twofold : first, the need for UAVs to perform additional maneuvers to avoid collisions, which often require changes in velocity and direction, consumes more energy than maintaining a steady path. Second, collision avoidance necessitates more frequent communication between UAVs to share their positions and velocities, further increasing energy consumption.

Despite these trade-offs, the clustering methods still provided superior energy efficiency compared to the collision avoidance strategies in both GM and RWP scenarios. This outcome underscores the effectiveness of clustering in not only minimizing UAV mobility but also in conserving energy more efficiently than the collision avoidance methods, particularly in large-scale UAV networks.

In conclusion, while the introduction of collision avoidance adds a vital layer of safety by protecting against potential accidents, the GM Clustering method remains the most energy-efficient approach. This highlights the potential of clustering techniques in enhancing the sustainability of UAV-based surveillance systems, even when safety measures are considered.

Conclusion and perspectives

Conclusion

In recent years, Flying Ad-hoc Networks (FANETs) have emerged as one of the most promising fields of application due to their versatility and adaptability. Among the various uses of FANETs, UAV-based surveillance has gained significant attention for its potential to enhance the security of assets and individuals. Ensuring effective and resource-efficient surveillance missions hinges on several factors, one of the most critical being the mobility model employed by the UAVs. This work has focused on optimizing resource consumption by evaluating and improving these mobility models.

Ad-hoc networks offer a range of mobility models, each with distinct strengths and weaknesses. This thesis has specifically examined two well-established mobility models, the Random Waypoint (RWP) and Gauss-Markov (GM) models, and proposed a new approach to enhance their effectiveness. The simulations were conducted using the NS-3 simulator to evaluate the performance of these models, particularly in the context of UAV swarm operations.

Additionally, the past decade has witnessed revolutionary advancements in UAV technology, leading to significant enhancements in their capabilities, applications, and hardware. As UAVs are increasingly deployed in swarms to accomplish missions more rapidly and efficiently, the need for robust collision avoidance systems has become critical. In this thesis, we have explored existing collision avoidance systems, identified their limitations, and proposed a novel avoidance technique based on UAV communications. This new method aims to address the shortcomings of current approaches, ensuring safer and more reliable operations in dense UAV networks.

In conclusion, the results of our simulations and analyses demonstrate the potential of the proposed methods to optimize UAV surveillance operations and improve collision avoidance in swarm scenarios. This work contributes to the ongoing development of UAV technologies by providing insights into mobility modeling and proposing solutions for collision avoidance that are both efficient and scalable. Future research could build upon these findings by further refining the proposed models and exploring their applications in even more complex and dynamic environments.

Future Perspectives

Moving forward, enhancing the system's capabilities involves several key developments. First, extending the model to include a z-plane will enable effective operation in 3D environments, allowing UAVs to navigate complex terrains with varying altitudes. Second, implementing a dynamic election process for the Master and Leaders UAVs will ensure uninterrupted surveillance missions by seamlessly assigning leadership roles when failures or low battery issues occur. Lastly, incorporating optimal pathfinding as a cost function will allow UAVs to determine the most efficient and safe maneuvers, balancing energy consumption with effective area coverage and obstacle avoidance. These advancements aim to increase the robustness, efficiency, and adaptability of the UAV-based surveillance system for diverse real-world applications.

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