PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
UNIVERSITY OF LAGHOUAT

FACULTY OF SCIENCES
DEPARTMENT OF COMPUTER SCIENCE

Field : Mathematics and Computer Science
Option : Computer Science
Specialization : Distributed Networks, Systems, and Applications.

Memoire Submitted in Partial fulfillment of the requirements for the Master degree in Computer Science

Submitted by: SOUFFI Abdelkarim & TALEB Mohammed Ali El Mahdi

THEME

Study of collision avoidance techniques in a fleet of drones

Jury members:

Mr	Tahar Allaoui	(University of Laghouat)	President
Mr	Tahar Bendouma	(University of Laghouat)	Examiner
Ms	Sara Benkouider	(University of Laghouat)	Advisor
Mr	Nasreddine Lagraa	(University of Laghouat)	Co-Advisor

2022

الملخص

يعرف المجال الجوي حضورا بارزا لطائرات الدرون، حضورا ألهم الباحثين و المطورين حتى أصبح هدا النوع من الطائرات يقتحم الجو في المجالين العسكري و المدني فأصبحت تؤدي المهمات باحترافية. تركيزا على مهمات الدرون وأنه خلال العملية لا يخلو مجال المهمة من العوائق بأنواعها الثابتة و المتحركة التي بالإصطدام بها ستفشل المهمة فهذا الوضع يستوجب طرقا و خوارزميات تمكن الدرون من إتخاذ قرار عن كيفية تجنب الدخول في تصادم مع هذه العوائق فنظام تجنب العوائق هو المسؤول عن كشف العوائق أولا و تجنب التصادم بها ثانيا و هو ما ألهمنا على البحث فيه و تقديمه في هذا العمل.

من خلال هذا العمل سنقوم بإلقاء نظرة عن مكونات الدرون ، تصنيفاته و مجالات تطبيقاته في الشطر الأول، مرورا إلى الشطر الثاني الذي من خلاله سنطرح نظام الكشف عن العوائق ثم طرق و كيفية تجنب التصادمات أما ختاما لهذا العمل سنطرح طريقة جديدة لتجنب التصادمات اعتمادا على الطرق المطروحة سابقا و تركيزا على ماتحتويه من نقائص و نقاط ضعف

Résumé

L'espace aérien connaît une présence prédominante des Unmanned Aerial Vehicles (UAVs), une présence qui a inspiré les chercheurs s dans les domaines militaire et civil. En se concentrant sur les missions des UAVs, les UAVs effectuent des tâches de manière professionnelle et que pendant le processus le champ de mission n'est pas exempt d'obstacles de toutes sortes fixes et mobiles en cas de collision, la mission échouera.

Cette situation nécessite des méthodes et des algorithmes qui permettent au Unmanned Aerial Vehicle (UAV) pour prendre une décision sur la façon d'éviter d'entrer en collision avec ces obstacles d'abord et d'éviter la collision avec eux, deuxièmement, ce qui nous a inspiré à rechercher et à le présenter dans ce travail.

A travers ce travail, nous aborderons les composants des UAVs, ses classifications et domaines d'applications dans une première partie, en passant à la seconde partie, dans laquelle nous présenterons le système de détection d'obstacles puis les méthodes et comment éviter les collisions.

A la fin de ce travail, nous présenterons une nouvelle méthode pour éviter les collisions en fonction des méthodes présentées précédement en concentrant sur ses lacunes et ses faiblesses. **Keywords : UAVs, UAV Swarm ,Collision Avoidance, Procedure of escape.**

Abstract

The airspace has a predominant presence of UAVs, a presence that has inspired researchers and developers in the military and civilian fields. Focusing on the missions of the UAVs, it performs tasks in a professional manner and during the process the mission field is not free from obstacles of all kinds fixed and moving in the event of a collision, the mission will fail. This situation requires methods and

algorithms that allow the UAV to make a decision on how to avoid colliding with these obstacles at first and avoid colliding with them secondly, which inspired us to research and present it in this work. Through this work, in the first part, we will

describe the components of the drone, its classifications and fields of application. Moving on to the second part, in which we will present the obstacle detection system then the methods and how to avoid collisions.

At the end of this work, we will present a new method to avoid collisions based on the methods presented previously, focusing on its shortcomings and weaknesses.

Keywords : **UAVs, UAV Swarm ,Collision Avoidance, Obstacles.**

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ADS-B Automatic Dependent Surveillance Broadcast. 24

CAS Collision Avoidance Systems. 11, 37

CC Collision Cone. 28

COD Cylindrical Obstacle Diagram. 35

GUI Graphical User Interface. 44

OVO Optimized Velocity Obstacle. 5, 40, 45, 49, 50

PF Potential Field meethods. 50

UAV Unmanned Aerial Vehicle. 2, 3, 4, 6, 8, 11, 14, 15, 16, 17, 18, 19, 20, 21, 23, 27, 28, 29, 30, 31, 32, 35, 37, 38, 39, 40, 41, 43, 44, 46, 51

UAVs Unmanned Aerial Vehicles. 2, 3, 4, 11, 12, 13, 16, 18, 19, 21, 23, 24, 25, 28, 32, 33, 35, 36, 37, 38, 39, 43, 45, 46, 47, 50, 51

VO Velocity Obstacle. 28, 29, 40, 49

Acknowledgments

After praise be to Allah, we would like to thank who helped us in realizing our work, we also extend our sincere thanks and appreciations to our virtues, Mr. Nasredinne Lagraa and Ms. Sarah Benkouider, who accompanied us in all stages of evaluating this project and providing us with their knowledge and experience in this field as well. also, for being good listeners to our ideas and allocating enough time to us despite their preoccupation. .

We extend our sincere and warm thanks to our honorable teachers, and all the teaching staff at the Computer Science department who accompanied us in our long journey, and from whom we got several skills and teachings that were a prominent connection in our projects. Finally, we thank our dear parents and families and also the virtuous friends who were in support of us and not to forget their merit and their prayers to us for success to finalize our work and reach this important stage in our lives.

CHAPTER 1

INTRODUCTION

1.1 Context and Problem Statement

With the great advancement of UAV technologies and the mass production of UAVs in the last decade, skies are getting crowded with flying objects. And further as UAVs have been recognized as applications accelerators for the emergence of new domains such as civilian uses which includes crop monitoring, load carrying, professional photography, telecommunications and many other tasks.

However, the growing number of flying objects in the sky poses a real threat to civilian flight airspace due to the deployment of diverse collision avoidance systems which could result in disasters. Generally the current Collision Avoidance Systems (CAS) work following a set of steps which are sensing, detecting and avoiding obstacles. We note that pre existing solutions are either based on using individual sensing, communication, simulation of paths ...etc in order to avoid obstacles.

Thus, the existing solutions can rather be too costly in processing performance overview or too restrictive for the UAV which could result in mission success degradation especially in dense networks (UAV Swarm). In our work we aim to study further more pre existing solutions and discover their limits in order to build a new approach that aims to be effective, low cost and compatible with UAV Swarms.

1.2 Organization of the Dissertation

The structure of this work is as follows:

- **Chapter 2** discusses the different aspects of the UAVs from its components to its different application fields.
- **Chapter 3** presents the state-of-art concerning the collision avoidance systems and the pre-existing methods
- **Chapter 4** we present our approach, simulation environment and discuss our simulation results.
- Finally we conclude with a general conclusion that summarizes what was discussed in all the previous chapters

CHAPTER 2

UNMANNED AERIAL VEHICLES

2.1 Introduction

In literature, a drone is an aircraft that can hover without carrying a pilot on-board, it floats autonomously using the flight controller or can be remotely guided through instructions coming from a ground base station.

Drones are built by combining a set of several hardware and software components, In this chapter, we present first the components and the types of UAVs. Then, we detail the communication architectures before presenting the applications of UAVs

2.2 Technical view of UAVs: Components

Drones, as a flying system is a set of hardware modules and software modules, like figure 2.1 shows [2] that work in coordination with each other to assure the safe and reliable operational movements, where each module executes a specific task, In what follow, we detail the task of each module.

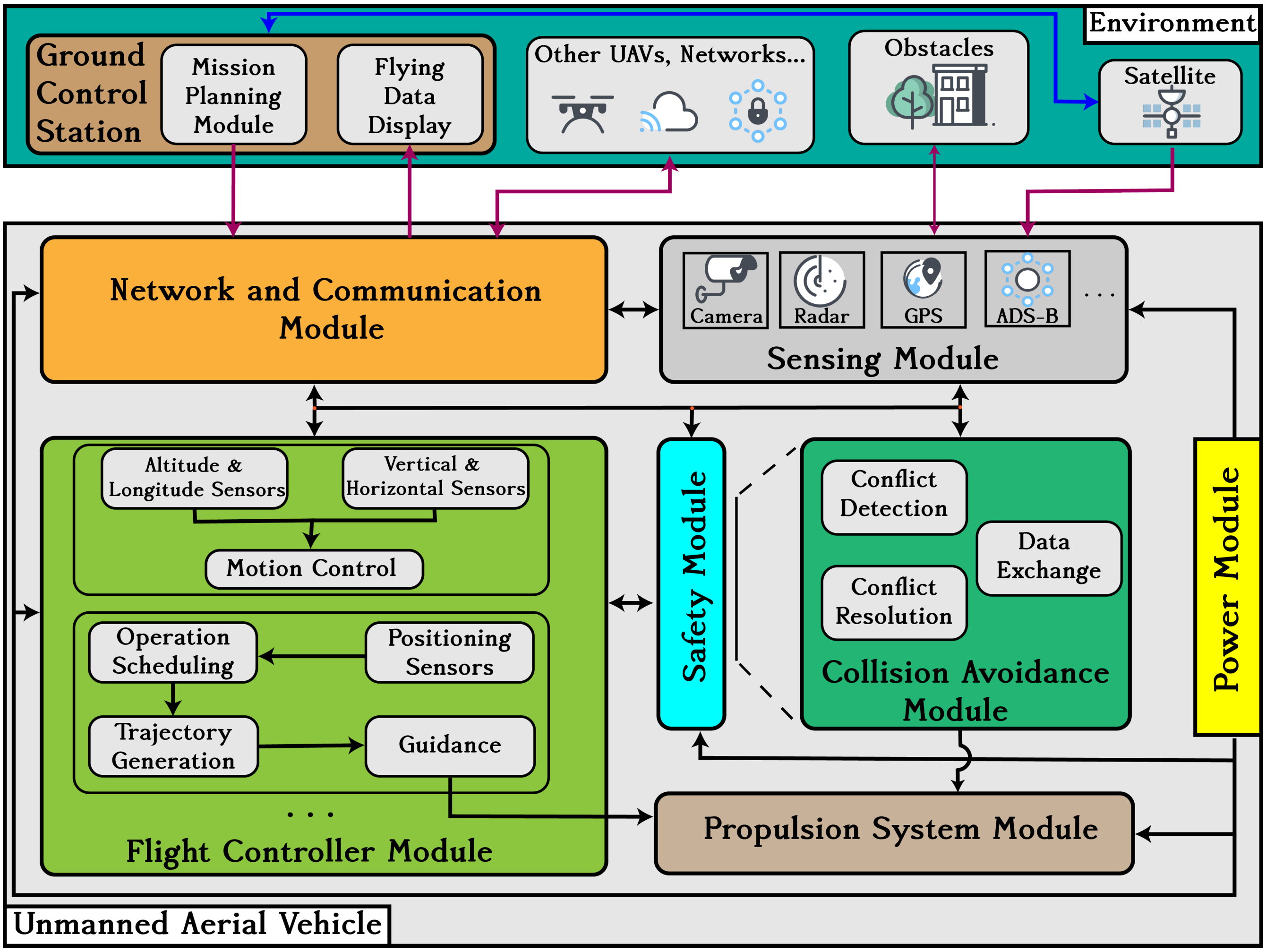


Figure 2.1: UAV modules

2.2.1 Power Module

It represents the power source of the drone that supplies energy to the different modules. It is the key factor to determine the flight time, speed and endurance distances, we distinguish two types of energy sources (i) fuel for medium and large air crafts and (ii) batteries for small pilot-less air crafts.

2.2.2 Flight Controller

After turning on the aircraft it starts flying , during the flight comes the role of the flight controller which is used to stabilize the attitude of a the airplane and achieve a desired speed, position, and direction.

2.2.3 Propulsion System

It is the main UAV direction controller which it intakes directions from the flight controller for propellers to instruct them where to rotate in order to change the direction according to the mission planning module [3]. Propellers depend on the UAV type (Propellers for multi-rotor UAV and wings for fixed wing UAV), We distinguish two types of propellers.

- **Standard Propellers :** Which manipulate the direction of UAV (Right, Left).

- **Pushed Propellers:** Which manipulate the backward and forward direction of the UAV.

2.2.4 Mission Planning Module

It is a software-based module where the mission type, routes, checkpoints and flight parameters are programmed by an operator into the flight controller. The flight controller uses information provided by this module to determine current flight variables such as altitude, current position, distance travelled... etc. The flowchart of figure 2.2 describes the main steps of mission planning

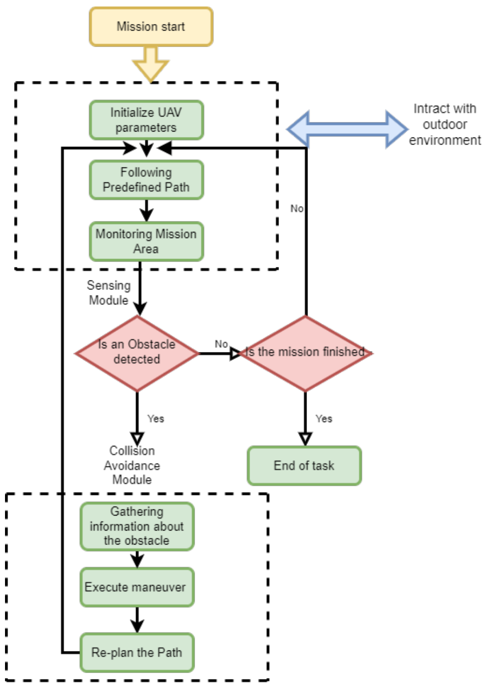


Figure 2.2: Mission planning module organizational chart

2.2.5 Networking and Communication module

It is a set of a communication hardware, programs and protocols that ensure the sent and receive of data [4] from/to UAVs and helps flying in coordination in case of swarms. The communication module [5] is generally equipped with a radio interface dedicated to control the UAV air movement, and a long range transmitter/receiver interface that connects multiple UAVs. Figure 2.3 presents the following types of communications.

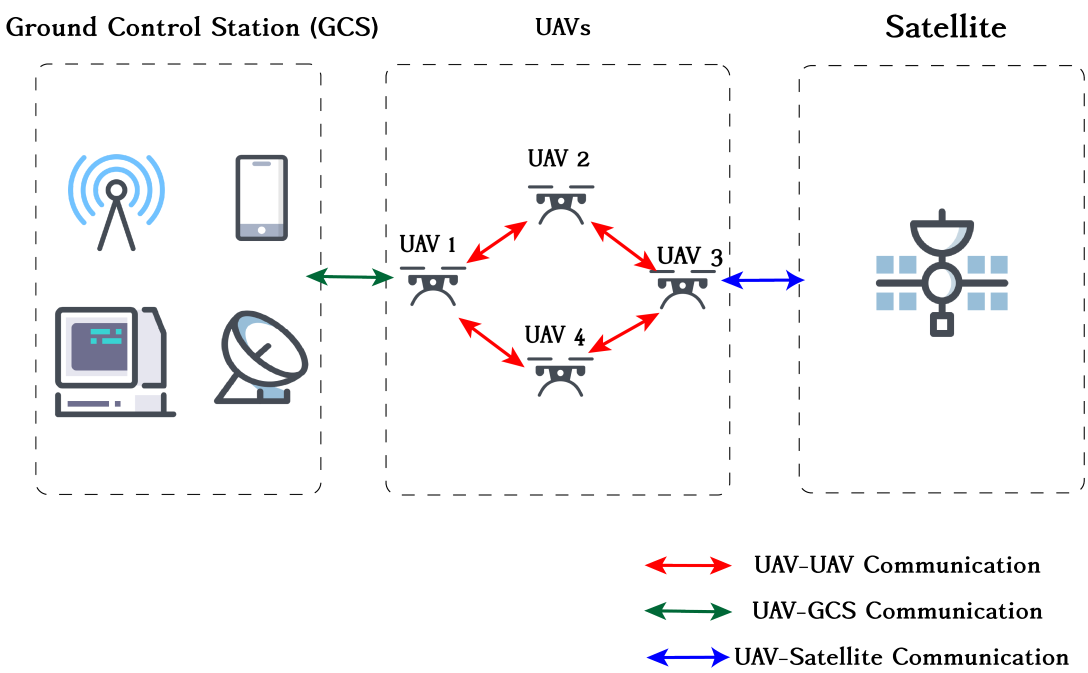


Figure 2.3: UAV communication links

UAV to Ground Control Station communication : This type of communication is also called "network-connected UAVs communication", allows transmitting control between UAV-GBS using 3G/4G/5G technology.

UAV to UAV communication: In this type of communication, each UAV plays the role of Receiver/Transmitter at the same time. It allows by using WiFi, Bluetooth or Zigbee [5].

UAV to Satellite Communication: UAVs are often deployed in complex environments, where it is difficult to install GCSs or when a group of UAVs requires continuous connectivity and the network is severely partitioned. For this purpose, there is a need for a centralized entity ensuring permanent connectivity like using satellites as an adequate option to serve as relays [4].

2.2.6 Sensing Module

This module consists of on-board camera sensors like RADAR, LIDAR, SONAR ...etc. (table 2.1), where it offers the view of the flight area field in order for gathering information or identifying targets [6]. It Plays an important role due the constant and obligatory interaction with collision avoidance module for obstacle detection and avoidance. We differentiate different types of sensors that can be classified as:

- **Active Sensors :** These sensors interact with objects by emitting signal in direction of the object. The reflected signal is recorded by the sensor [1].

- **Passive Sensors :** These sensors do not need to get another source to read the received signal from the object like sun rays on earth [1]..

Sensor	Mode	Accuracy	Weather Condition	Light Sensitivity	Range	Sensor Size	Processing Requirement	Power Required
LiDAR	Active	High	Low Dependency	No	Medium	Small	Low	Medium
Radar μ-wave	Active	High	Not dependant	No	Long	Large	Low	High
MMW	Active	High	Dependant	No	Long	Small	Low	Medium
Ultrasonic	Active	Medium	Partial Dependency	No	Short	Small	Low	Medium
Thermal or IR	Passive	Medium	High Dependency	No	Medium	Small	High	Low
Camera	Passive	Medium	High dependency	Yes	Short	Small	High	Low

Table 2.1: UAV Sensor types comparison [1]

2.2.7 Collision Avoidance Module

after the acquisition of information about the obstacle via sensing module and current localization of UAV, here comes the role of the Collision Avoidance Module. It is a software based solution that allows the aircraft to make an avoidance maneuver to prevent an accident between the UAV and the external environment objects. This module will be more detailed and explained in next Chapter.

2.3 UAVs Classification

The great demand for drones has led to their development and emergence in many different forms and shapes from micro and nano to large UAVs [7], different technologies on hardware and software components like communication and sensing, as well as various flight mode. Drones can also be divided into two other classes based on their weight, flight range and endurance cf. figure 1.5 We generally distinguish UAVs based on their propellers structure which can be either multi rotor or fixed wing drones, but a classification based on this element only can be incomplete [8] which can be recapitulated in figure 2.4.

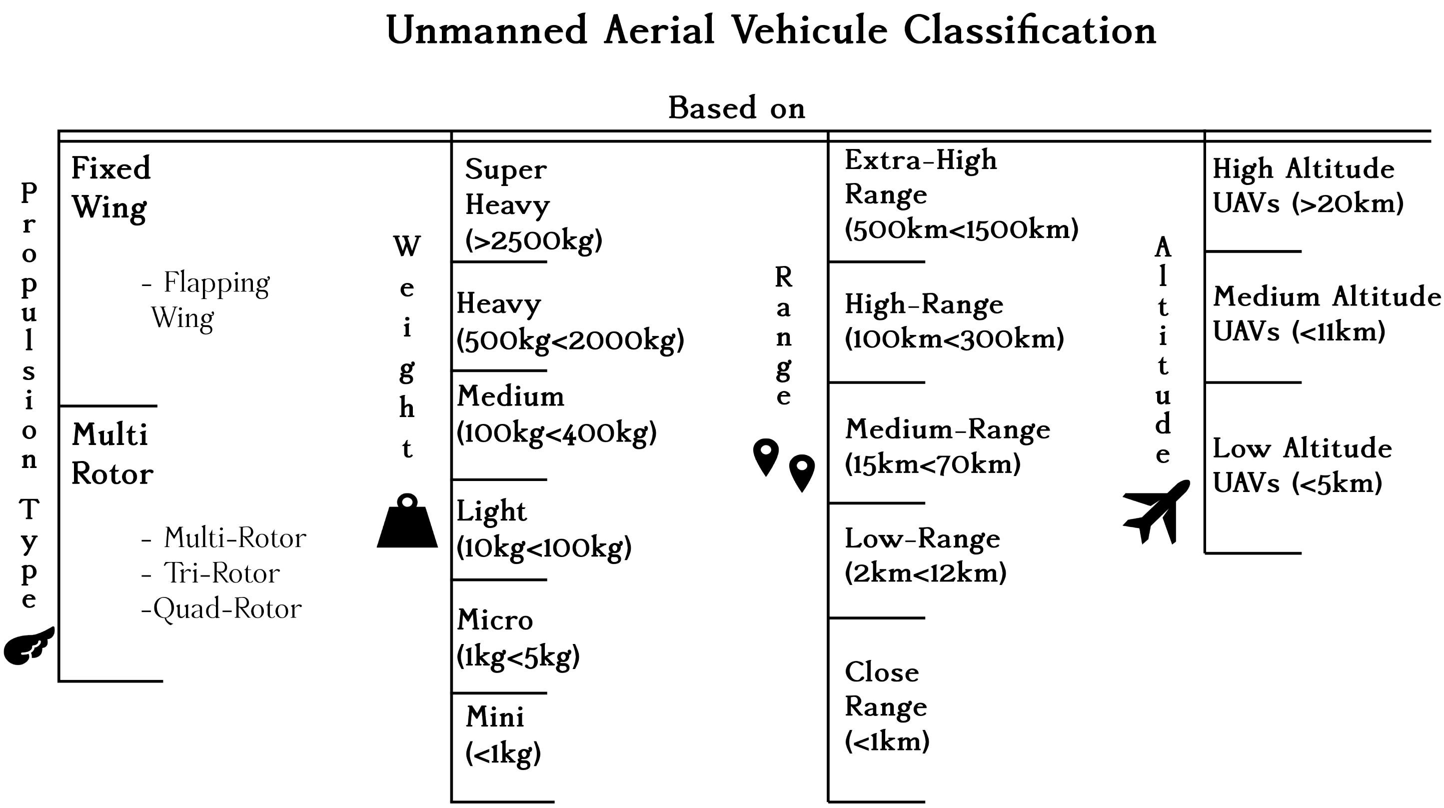


Figure 2.4: UAV classification

2.4 UAV Swarm Control Strategies

A swarm of UAVs is a set of UAVs that are flying following topology (mesh network, follower-leader topology, star topology ... etc); They are used to increase the efficiency of executing a task and get a better and accurate results like monitoring a land or capturing high-quality images by making a coordination and communication links between UAVs [9, 10]. As in [11] UAV networks architecture can be classified as :

2.4.1 Centralized Architecture

- A single aircraft monitors all the swarm and assures the coordination between the UAV network members and the base station.
- UAV current state exchange is necessary throughout the mission with a certain UAV that organizes the movement of UAVs as in follower-leader approach as in the figure 2.5(A).

2.4.2 Decentralized Architecture

- Every member in the swarm flies independently from the other UAVs.
- Each member executes its own task, without common point of coordination with others.
- Each member can share information and coordinate with another members [12] but it isn't necessary and each member of the swarm can communicate directly with the base station as in the figure 2.5(B).

Example : *behavior-Based approach*

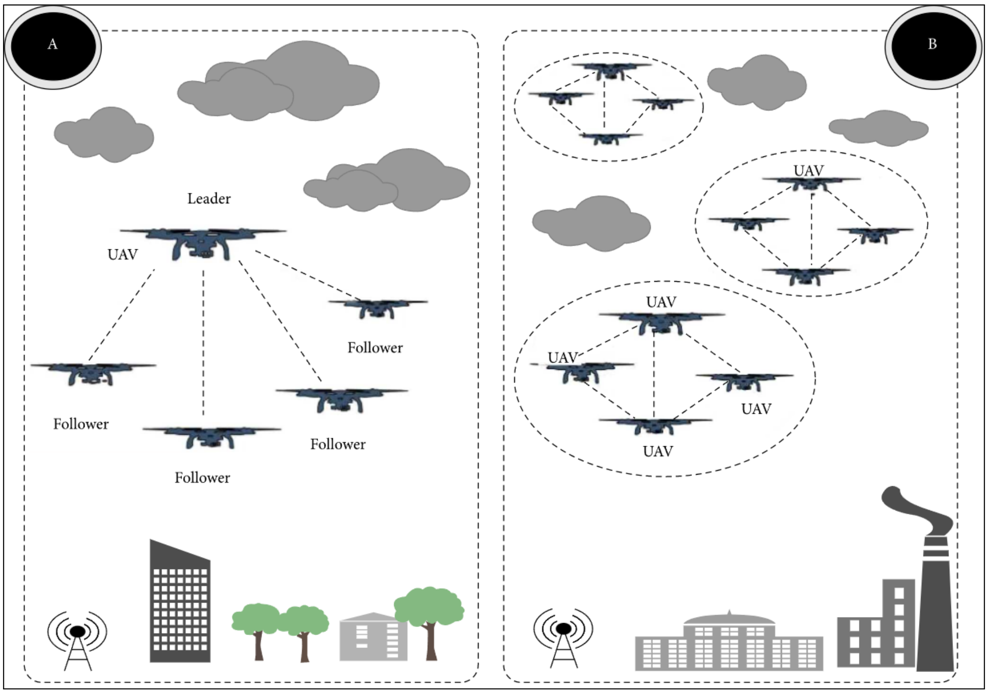


Figure 2.5: UAV control strategies

2.5 UAV Applications

As in [7] drones may be used in a wide range of applications (as figure 2.6 shows) such as :

- **Cinematography :** Drones are mostly used to make movies, film stunts, and record television news. Drone journalism allows for low-cost local news coverage and weather forecasting without putting people at danger on other modes of transportation.
- **Medical/Emergency :** It includes any process that necessitates a large-area search or information collection for health, police, or firefighting personnel. Many challenges are dealt here, including the distribution of medical supplies and humanitarian relief in natural disasters, the evaluation and mitigation of hazardous materials and wildfires, missing people response and protests monitoring.
- **Land Planning Mapping :** Land planning requires mapping information that is reliable and does not exceed budget. An inexpensive drone mapping solution eliminates the risk of outdated or obscure map/data sources. In many cases, drones can provide data that fits planned budget.

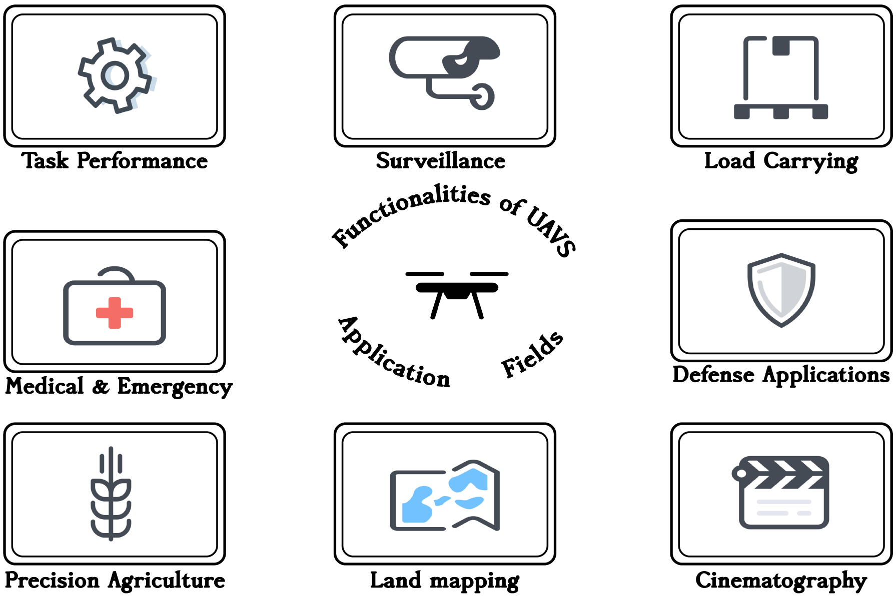


Figure 2.6: UAV Functionalities and Applications

- **Precision agriculture :** Includes the examination of crop health or the surveying of land for agricultural and food items. Monitoring livestock, measuring crop fields, estimating crop production, evaluating the requirement for chemical and pesticide application, and identifying plant illnesses are all part of these activities. Tractors, field sprayers, and sprinklers are examples of technology that might be superseded by the use of drones in this industry.
- **Defense Applications :** Used by military's around the world for surveillance, reconnaissance, electronic warfare and strike missions. They eliminate the risk to the life of the pilot and navigation abilities such as endurance are not limited by human limitations.

2.6 Conclusion

This chapter introduced the basic concepts behind the UAVs, such as types, components, and application fields. In the next chapter, we will discuss more UAVs and how they avoid the risks concerning collision and how they asses the different scenarios if either a collision will happen in the future.

CHAPTER 3

COLLISION AVOIDANCE

3.1 Introduction

In literature, an obstacle is something that blocks you so that the movement toward a destination is prevented or made more difficult.

Obstacles can be classified in two main classes static obstacles or dynamic obstacles. Static like buildings, towers or simply objects that rarely or never move, dynamic such as vehicles, birds, persons or any objects that have a higher mobility [13]. In this chapter, we represent the concept of collision and approaches used to avoid it.

3.2 Concept of a collision

By definition, a collision is an event that happens when two or more vehicles hit each other with force, this event can lead to issues on the frame like breaking , separation, or chassis clinging to each other which clearly fails the mission [14].

The methods used to avoid colliding with other objects whatever their type are called Collision Avoidance Methods [15]. Where in the literature, this is referred as obstacle avoidance, and it incorporates surrounding elements and their overall purpose is to move safely.

In the next section, we concentrate our study on collision avoidance in UAVs.

3.3 Collision avoidance systems

A collision avoidance system can realize many functions, from simple conflict detection and warning to completely autonomous conflict detection and resolution as detailed in [16]. UAV roles totally depend on the autonomy level of the UAV and its components. Collision avoidance system can be outlined as a set of cooperative actions between different UAV modules. Figure 3.1 represents the different phases running in the collision avoidance process.

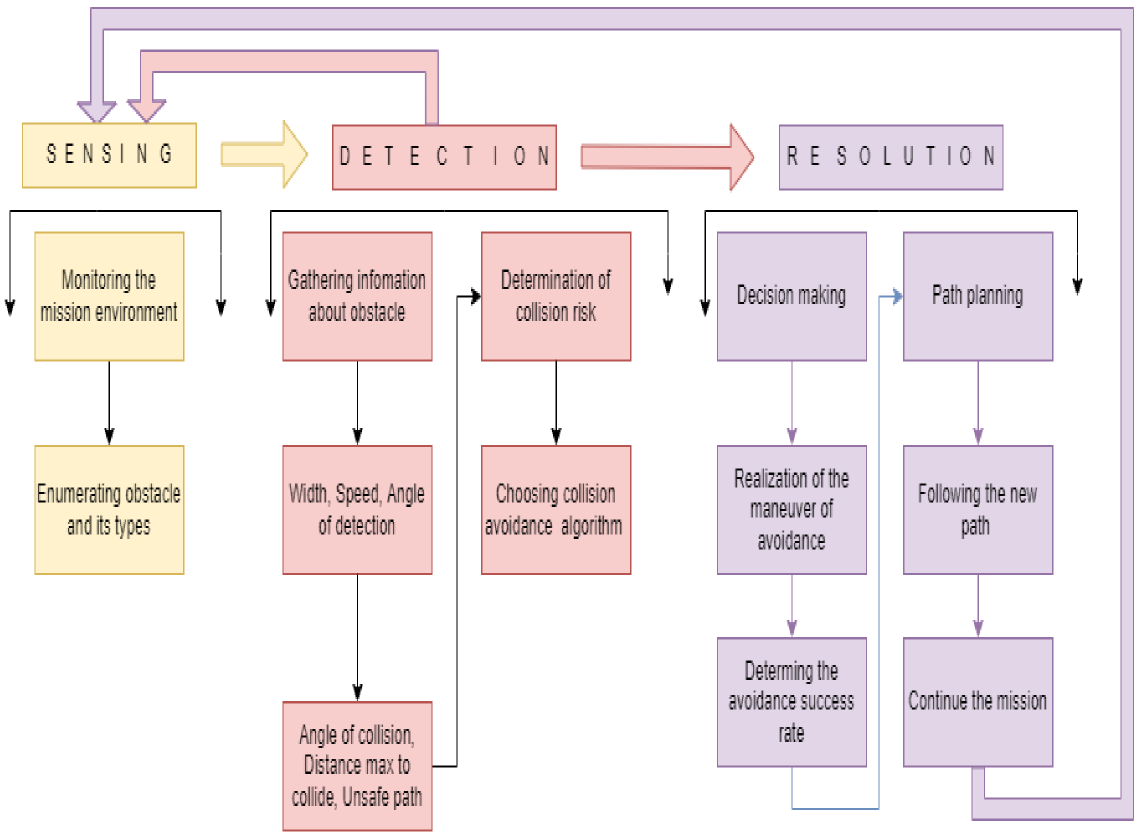


Figure 3.1: UAV collision avoidance modules

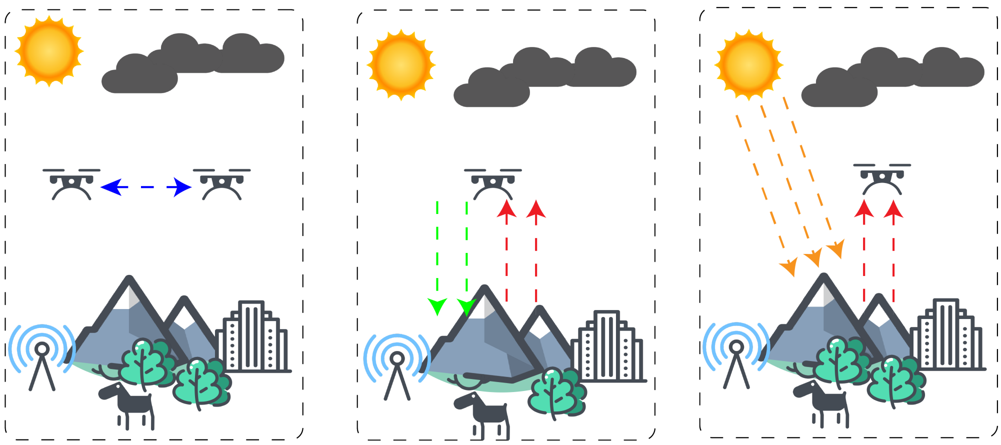
3.3.1 Sensing phase

The task of sensing may be accomplished with two types of sensors (see figure 3.2):

- **Cooperative Sensors :** It is a type of sensors that receive a radio signal from another aircraft equipped with the same onboard equipment [17], and it has the ability to sense the environment and communicate their data with other air crafts.

  Example : *Automatic Dependent Surveillance Broadcast (ADS-B)* can send the entire flight plan data.

- **Non-Cooperative Sensors:** : They are able to sense all types of obstacles without the need of a communication link between other UAVs or obstacles [17]. We differentiate two types of non-cooperative sensors: active and passive sensors. Active sensors [1] diffuse signals to discover obstacles, while passive sensors rely on the signals emitted by the obstacles themselves.



(a) Cooperative Sensing (b) Non-Cooperative Sensing (Active) (b) Non-Cooperative Sensing (Passive)

Figure 3.2: Types of sensors

3.3.2 Detection phase

In this phase future conflicting traffic are identified [18] using current state projections. Therefore, any incursion into UAVs protection zones will generate an conflict alerts. This allows for for avoidance maneuvers in the right interval of time. Three types of projections exist which are Nominal, worst-case, and probabilistic projections [19] as presented in the table 3.1.

- **Nominal Projection :** It projects the current state into the future along a single trajectory which is the most commonly used (e.g., straight trajectory).
- **Worst case projection :** A wide range of maneuvers are projected for the aircraft, and if any one of them leads to a conflict an alert is issued.
- **Probabilistic projection :** For each obstacle, not all possible maneuvers are projected but only a set of them with a probability (P), this is generally done by developing a complete set of future trajectories that are weighted by a probability of occurring (eg., using probability density functions), the occurred trajectories are then propagated into the future to use them for later to check for possible conflicts.

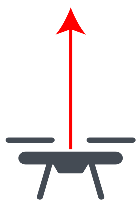
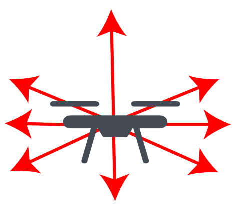
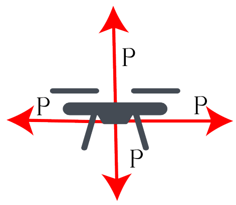
	Nominal Projection	Worst case Projection	Probabilstic Projection
	 - Project a one path only	 - Project all possible paths	 - Project only a few ways with a certain possibility
A D V	- Easy to implement	- Less false negatives	- feasable and widely applied
D I S	- More false negatives	- Requires more processing	- Cant predict all conflicts

Table 3.1: Projection approaches

3.3.3 Resolution phase

When a conflict in the near future is detected, the resolution maneuver function should be triggered. We describe resolution maneuver as the act of determining how to resolve a specific conflicting circumstance in order to avoid possible an impending collision.

3.3.3.1 Resolution Maneuvers

The collection of maneuvers needed to avoid a conflict are referred as the resolution maneuvers,are speed changes (speeding up or slowing down), horizontal movements (turning left or right) and vertical movements (climb or descend). In certain circumstances, a single fundamental maneuver is all what is required to escape a collision [20]. But in other cases, a mix of fundamental movements is necessary. The combined movements can be done concurrently or sequentially for a set of drone swarm.

3.3.3.2 Management of Multiple Aircraft Conflicts

A conflict resolution system can manage conflicts between more than two aircraft in two ways: pairwise or globally.

- **Pairwise:** In pairings, issues are addressed sequentially.
- **Global-wise:** The entire issue is evaluated at the same time, and the conflict is resolved at the same time. This is normally accomplished in a centralized way by forming a cluster of all the planes participating in the conflict.

3.4 Collision Avoidance Approaches

UAV collision avoidance approaches can be classified on various classes[19, 21, 15, 22]. The commonly classes used in the literature are presented in figure 3.3.

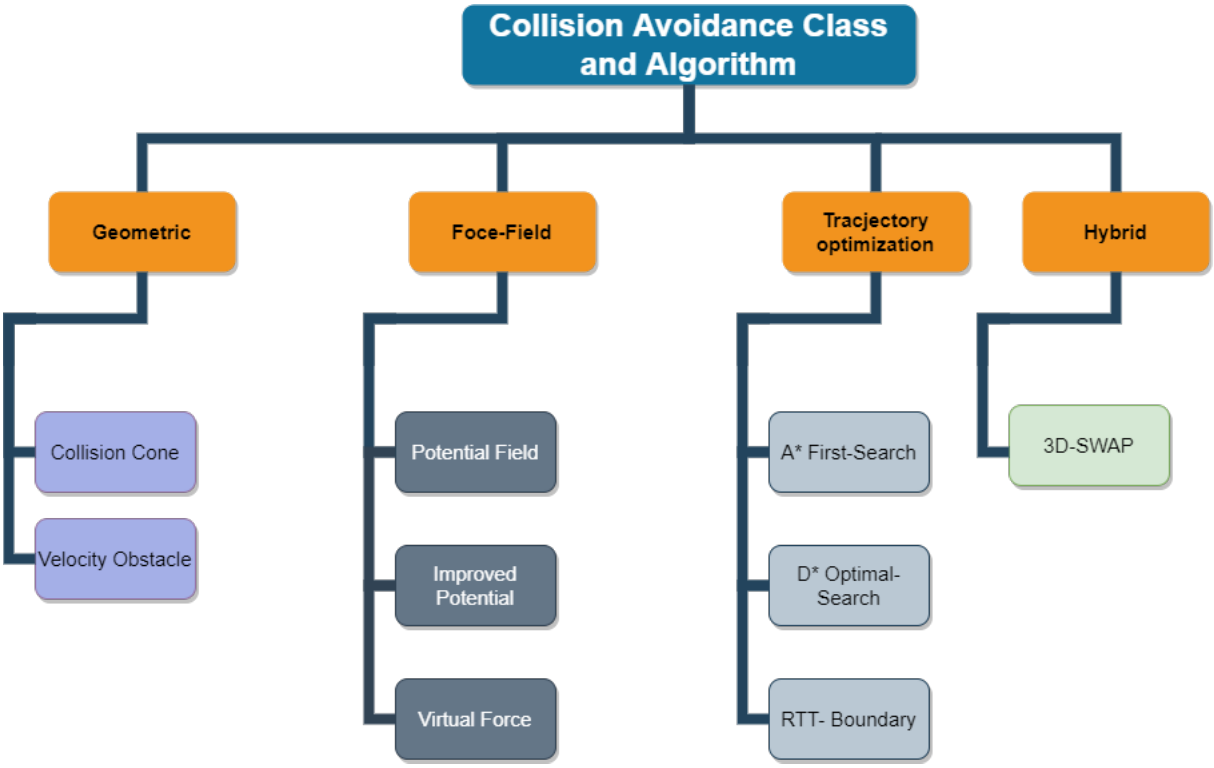


Figure 3.3: Collision Avoidance Methods Classification

3.4.1 Geometric approaches

In this type of approaches, UAVs are presented as a mass of points defined by velocity vector (V_x, V_y) [23]. Geometric approaches assume that the drones share their velocities in order to achieve a cooperative collision avoidance maneuver [24].

An example of algorithms that is based on geometric approaches, velocity obstacle and collision cone algorithm.

3.4.1.1 Velocity Obstacle and Collision Cone:

This algorithm uses two main concepts known as Collision Cone (CC) [25]. The CC is a set of velocities that should take the UAV directly to a collision with the obstacle as shown in the figure 3.4. This can be expressed by:

$$CC_{uo} = \{\forall\, V_{uo} \exists \lambda_{uo} | \lambda_{uo}.V_{uo} \cap Obstacle \neq \varnothing\} \tag{3.1}$$

Where V_u: Velocity of the UAV
V_o: Velocity of the obstacle
$V_{uo} = V_u - V_o$: V_{uo} is the relative velocity of U respectively to O.
λ_{uo}: is the line of V_{uo}.

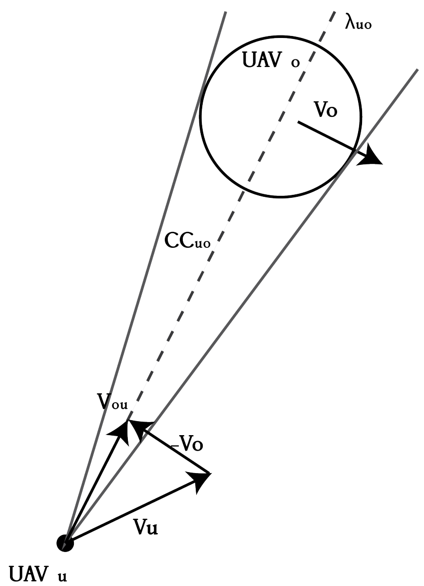


Figure 3.4: collision cone

The other main concept, is Velocity Obstacle (VO) which used for dynamic obstacles. VO is defined as the set of collision cone velocities plus (Minkowski Sum) the velocity of the other obstacle which outputs another cone called Velocity Obstacle (see figure 3.5) [26]. VO is defined by the following equation :

$$VO_{uo} = CC_{uo} \bigoplus V_o \tag{3.2}$$

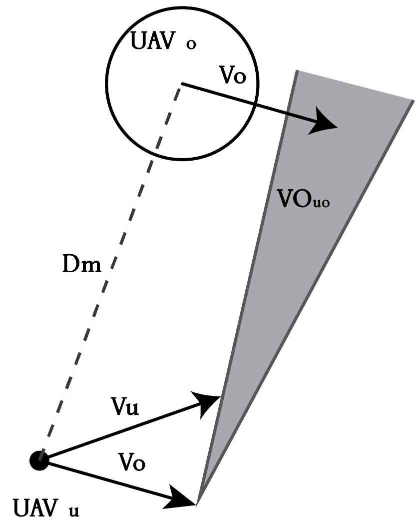


Figure 3.5: Velocity Obstacle

For the avoidance maneuver, each UAV risks a potential collision has to choose any velocity V_u outside the $_{uo}$ that will guarantee a collision avoidance of the obstacle.

In the case of the occurrence of multiple obstacles, the velocity obstacle will be defined as the UNION of individual velocity obstacles and it is defined mathematically as: $\bigcup_{i=1}^{m} VOi$

Velocity Obstacle limits :

Velocity obstacle is largely deployed in the geometric approaches but it also has its limits. For instance, if the UAV is surrounded by VO cones it cannot find a way pass through the obstacle to perform collision avoidance.

3.4.2 Force Field based approaches :

This type of approaches [27] calculates a safe path using different potential forces applied towards the UAV by all obstacles and the goal. The main example of force field based methods is **Potential method in selective avoidance [28, 29, 30]** .

3.4.2.1 Selective Avoidance Algorithm

Selective Avoidance Concept:

In this algorithm, when an obstacle is detected the UAV has to calculate the total force acting on it [31, 15].

$$F_{total(x)} = F_{rep(x)} + F_{att(x)} \tag{3.3}$$

Where F_{Rep} represents the repulsive force that pushes the UAV away from the obstacle, and it is defined by:

$$F_{rep(x)} = \begin{cases} -\Delta.\frac{1}{2}.\mu(\frac{1}{\rho_o} - \frac{1}{\rho_{safe}}).\rho_d^2, & \text{if } \rho_x \leq \rho_0 \\ 0, & \text{otherwise} \end{cases} \tag{3.4}$$

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 safety distance and ρ_d represents the distance between UAV and destination. In case of multiple obstacles F_{Rep} is calculated by the equation:

$$F_{Rep} = \sum_{i=1}^{n} F_{rep} i \tag{3.5}$$

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

$$F_{Att(x)} = -\epsilon.\rho_d.\Delta.\rho_d \tag{3.6}$$

Where ϵ is an attractive constant. The figure 3.6 illustrate different forces acting on an UAV.

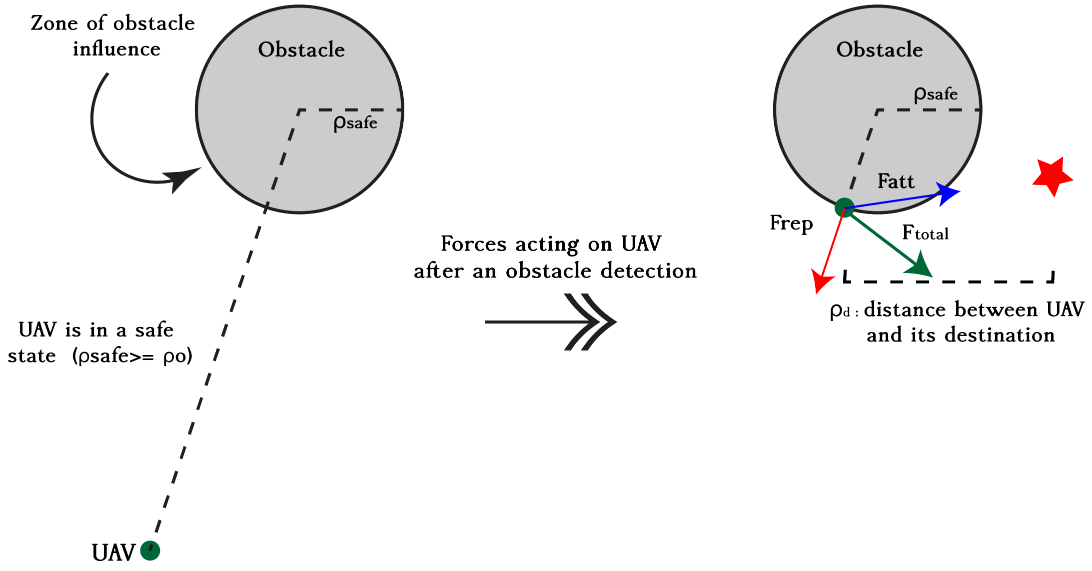


Figure 3.6: Different Forces applied by the obstacle and the goal

Selective Avoidance Algorithm:

The algorithm of selective avoidance detailed in [28] is presented in the figure 3.7.

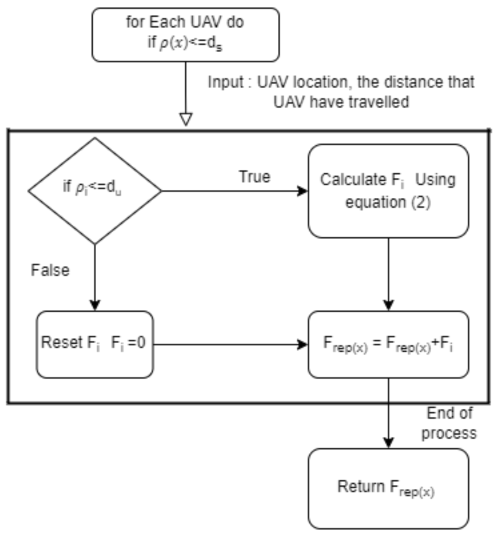


Figure 3.7: Selective Avoidance diagram

- The UAV that has travelled a shorter distance is selected to change its path to avoid , while the other UAV goes through towards its destination.

Selective Avoidance limits :

Sometimes the resulted repulsive force that the UAV has to apply is unrealistic for conceptual limits which means this approach cant be applied to all types of UAVs. For example, when applying this method with fixed wing UAVs sometimes the repulsive force will be too large resulting in a backward total force which cant be done by the UAV immediately like multi rotor drones.

3.4.3 Optimized trajectory approaches:

Optimized trajectory approaches [32, 33, 34] obliges each UAV to calculate a trajectory with lowest cost using a cost function F just like the A* algorithm explained in section 2.4.3.1 which is very similar to UAV routing algorithms.

figure 3.8, shows an example where a UAV tries to avoid an obstacle by calculating a set of weighted paths based on a cost function.

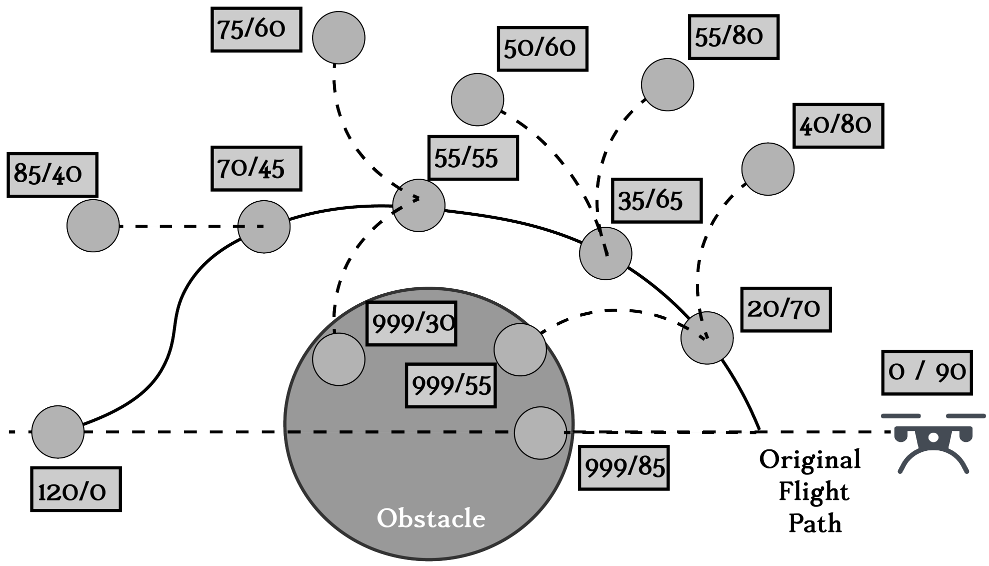


Figure 3.8: Multiple trajectories optimal search

3.4.3.1 A* Algorithm

This algorithm treats the surrounds as a weighted 2D map and upon finding an obstacle it works as follows:

- Finding a preferable route to reach the goal using the total cost function defined by: $F = G + H$

  Where G is to the cost from the starting point to current (visited) one, and H is the heuristic function estimating the cost from the current point to the destination.

  - A* assigns costs to paths that are too close to obstacles using two different types of heuristic functions: conservative and aggressive heuristics as shown in figure 3.9.

  In the conservative function safety rules are considered by allocating a lower cost for the paths passing behind the intruders to encourage the UAVs to choose a safer path. But in the aggressive function A* tries to find a path that can be a little more dangerous in order to reach the destination faster, where the distance between UAVs is considered as the minimum requirement of safety [35].

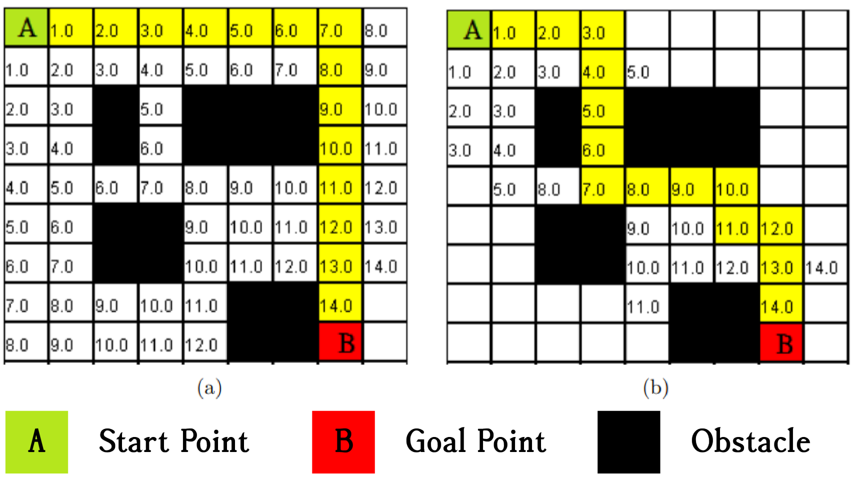


Figure 3.9: (a) Conservative and (b) aggressive heuristic approach

- **A* limits:** A* algorithm requires a really high computational power and it gives a good avoidance maneuvers only for fixed obstacles.

3.4.4 Hybrid approaches

These approaches merge different aspects of geometric, force field and optimized trajectories methods which creates a unique new methods.

3.4.4.1 3D SWAP

3D SWAP is a decentralized and reactive collision avoidance algorithm, it [21] uses the notion of safety cylinders figure 3.10 to ensure a safe trip.

It is classified as reactive approach due to the act depending on the situation that means there is no plan before and due the high efficiency in the avoidance maneuver. Although deliberative approaches are based on a plan search before acting but they exhibit a high performance in tasks, their reaction speed is low, and the deliberative approaches cannot effectively adapt to environmental changes.

- **Collision cylinder**: this cylinder encapsulates each aircraft, this cylinder is used to detect if a collision was produced or not.
- **Reserved cylinder**: encapsulates the previous cylinder, and it is used to check for xy-conflicts.
- **Blocking cylinder**: This cylinder surrounds all previous cylinders, and it is used to check for z-conflicts.

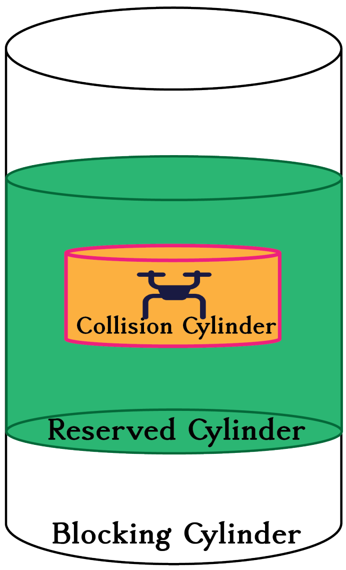


Figure 3.10: 3D SWAP different collision avoidance cylinders

Cylindrical Obstacle Diagram (Cylindrical Obstacle Diagram (COD)) is a data structure used by 3D Swap for cylindrical representation of the obstacles in the close surroundings of the UAV as shown in Figure 3.11.

In this environment ,by establishing distinct cylinders surrounding each UAV, vehicles can identify two forms of conflicts:

- **Xy-conflicts**: If an xy-conflict is identified, an avoidance direction $\phi_{avoidance}$ is determined using the obstacle straight direction $\phi_{collision}$, 3D swap prevents UAVs from going toward $(\phi_{collision} - \frac{\pi}{2}, \phi_{collision} + \frac{\pi}{2})$ directions.
- **Z-conflicts**: If the aircraft has identified a z-conflict, the UAV's altitude is blocked only moving horizontally toward the goal is allowed.

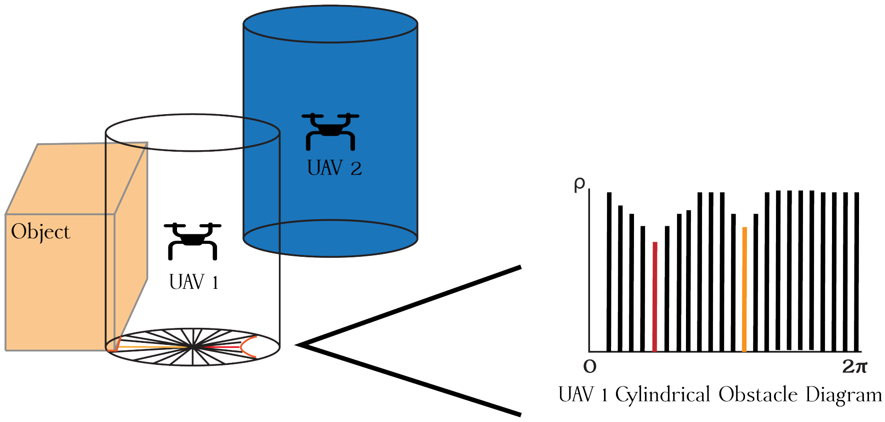


Figure 3.11: 3D SWAP Cylindrical Obstacle Diagram

3.5 Conclusion

This chapter presented and concluded most of the basics relating to collision avoidance systems, the different avoidance methods used and their limits. In the next chapter, we will extract a new method based on the points noted in chapter 2 respecting the general collision avoidance approach structure.

CHAPTER 4

COLLISION AVOIDANCE: OPTIMIZED VELOCITY OBSTACLE (OVO)

4.1 Introduction

In order to overcome some of the shortcomings of other techniques, we tried to extract a new collision avoidance technique that treats some of the limits discussed in chapter 3. Thus, after discussing briefly these limits, we present our technique, the simulation concept and the results. Then, we compare the obtained results with those obtained with other techniques.

4.2 Collision avoidance methods : discussion

After analyzing techniques presented in the previous chapter, we highlight the following points :

- **Velocity Obstacles and Collision Cone :** Although these methods are low computational costs but, they can generally fail in case of dense network (swarm of UAVs).
- **Selective Algorithm :** This algorithm is designed for a set of vehicles that can move towards any direction immediately such as quad rotor UAVs.
- **A* algorithm :** The high computational requirement for this method is the major limit due to the large number of future projections.

4.3 Optimized Velocity Obstacle: our approach

Our approach is an enhancement of 3D Swap and velocity obstacle method where we:

- Reduce the prohibited angles by introducing future positions of UAVs.
- Determine the optimal path by adding a cost function.
- Introduce a mechanism of exchanging future position.
- Develop for this context a basic simulator that can be used for other purposes.

To formulate our approach, we divided our collision avoidance system into three main steps which are Sensing; Detecting; and Avoiding collision as illustrated in figure 4.1.

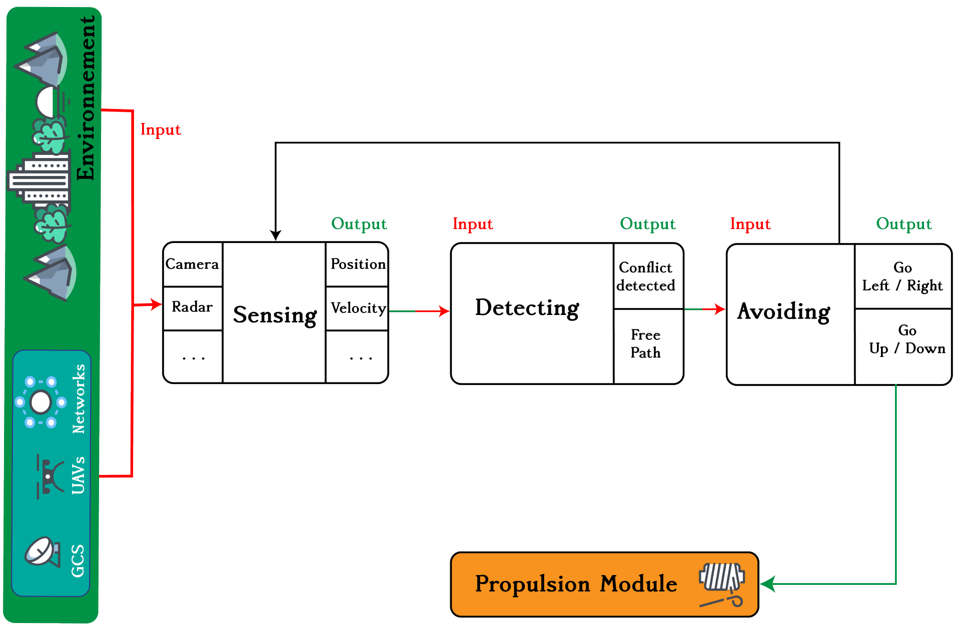


Figure 4.1: Main steps of our avoidance method

4.3.1 Optimized Velocity Obstacle phases

4.3.1.1 Sensing : Gathering Current State Parameters

This phase is considered as the most important in our CAS approach. In order to make our collision avoidance method efficient, a set of parameters is required for each UAV to run the protocol.

4.3.1.2 Sensing : Communication and exchanging data :

When UAVs are entering the influence zone of each other. Each UAV calculates its future position and send it to other UAVs. This operation can significantly help to reduce the processing costs and enhances the performance compared to a* algorithm projection approach for example.

The future position can be obtained using the following equation (4.1):

$$FuturePos_{(x,y)} = \begin{cases} future(x) = current(x) + velocity * time * \cos(angle) \\ future(y) = current(y) + velocity * time * \sin(angle) \end{cases} \tag{4.1}$$

Where velocity represents the UAV speed, time (Δt) is a parameter mutually defined in a swarm which represents projection into the future, angle is the current direction angle of the UAV. Figure 4.2 illustrates a case where two UAVs are entering the influence zone of each other and then share their future positions.

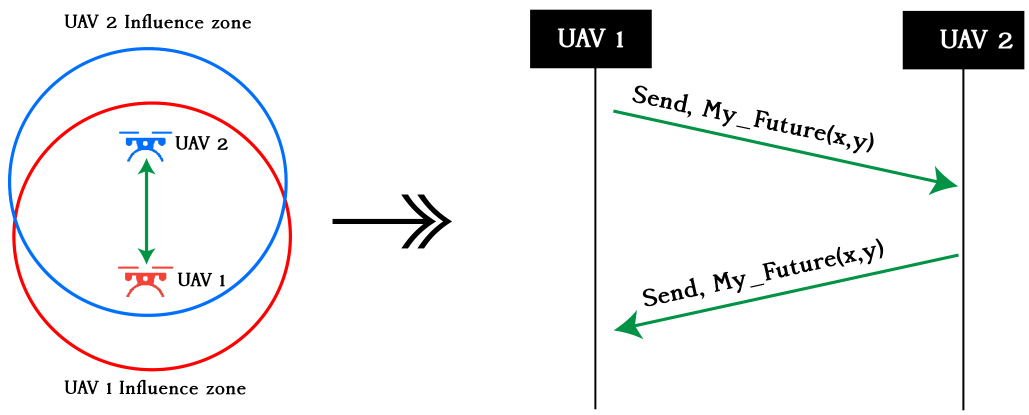


Figure 4.2: Influence zone and exchanged messages in our approach

4.3.1.3 Detection: Projection

After gathering neighbouring UAVs future positions. Projection is needed to predict future collisions and generate alerts in case of hazards.

- We notice that for $\Delta t >$ maneuver_time the system accuracy is high. But, in case of the opposite we note that drones perform avoidance maneuvers relatively closer to the obstacle as the figure 4.3 illustrates.

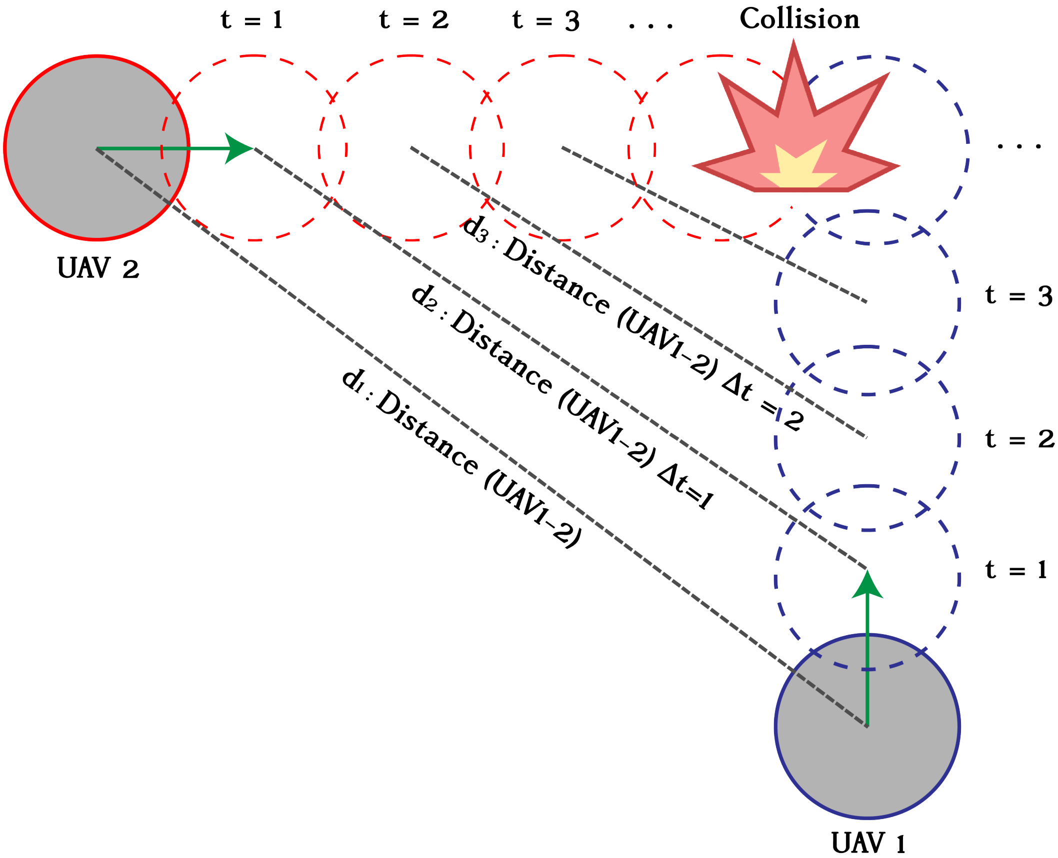


Figure 4.3: UAV-UAV conflict detection with future projection

Conflict detection

– In order to detect if a collision will happen in the future, we need to check if the future position of the other UAVs (obstacles) collide with our position in the future (all possible paths after n* Δt) using the following equation.

$$Conflict = \begin{cases} 1, & \text{if } distance_{(obs,uav)} \leq radius_{(uav)} + radius_{(obstacle)} + safe\_distance \\ 0, & \text{otherwise} \end{cases} \tag{4.2}$$

Optimized Velocity Obstacle : Key idea

Our idea of optimization is adapted from the velocity obstacle method, where instead of avoiding a large set of velocities which is impossible and costly as discussed before in chapter 3. Optimized Velocity Obstacle method is a communication based solution in which it allows to each UAV to send its future positions to its neighbours. Thus, it uses the received data and only the future colliding paths will be avoided. It's worth noting that this idea allows to use an only a small set instead the large one used in velocity obstacle. Figure 4.4 illustrates the restrictions of OVO compared to VO.

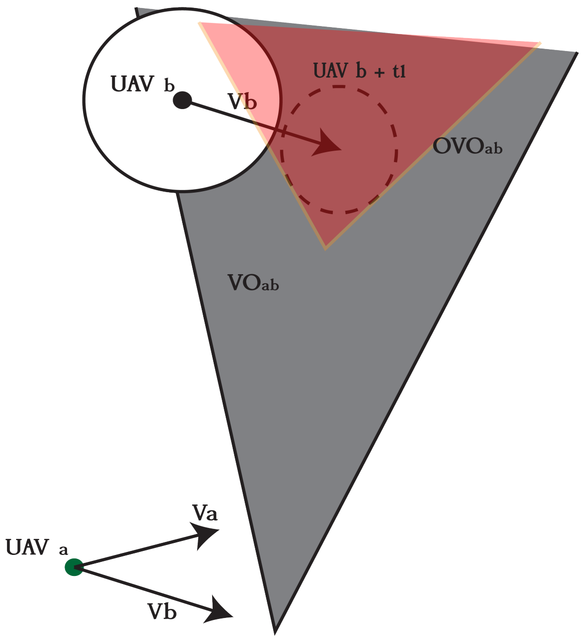


Figure 4.4: Optimized Velocity Obstacle Compared to Velocity Obstacle

4.3.1.4 Avoidance maneuver

This step, is triggered only and if only an alert is sent by the detection unit. All previously calculated paths are filtered and dead paths are extracted in order to be avoided. Moreover, avoidance paths that should lead to a safe movement.

Optimized Velocity Obstacle : Path filtering

- Among all the safe paths, a drone has to determine the optimal avoidance path which allows it to reach the target. For this, it uses the cost function defined by:

$$F = argmin(Path_i \in AvoidancePaths | distance(Path_i, Goal_{uav})) \quad (4.3)$$

Optimized Velocity Obstacle : Multiple Obstacles

In the case of multiple obstacles, the avoidance maneuver is calculated and addressed in a pairwise way as explained in section 3.3.3.2 shows.

The figure 4.5 illustrates our approach steps.

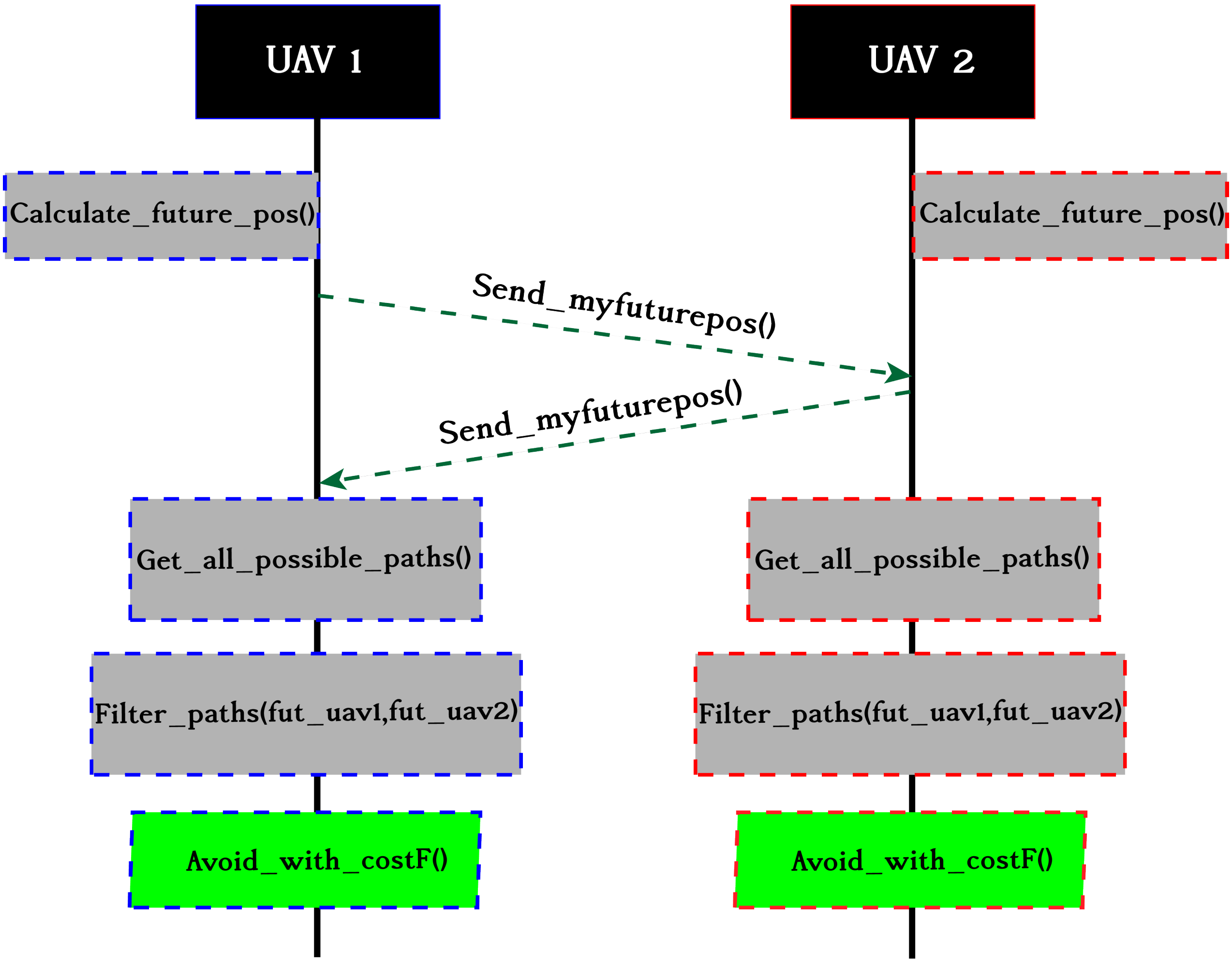


Figure 4.5: UAV-UAV conflict detection with future projection

4.4 Simulation Concept and Results

4.4.1 Simulation design and description

Our protocol is implemented using Pygame game engine. Pygame consists of video, sound and graphic modules used for game development based on python language.

The simulation structure is illustrated in the Figure 4.6.

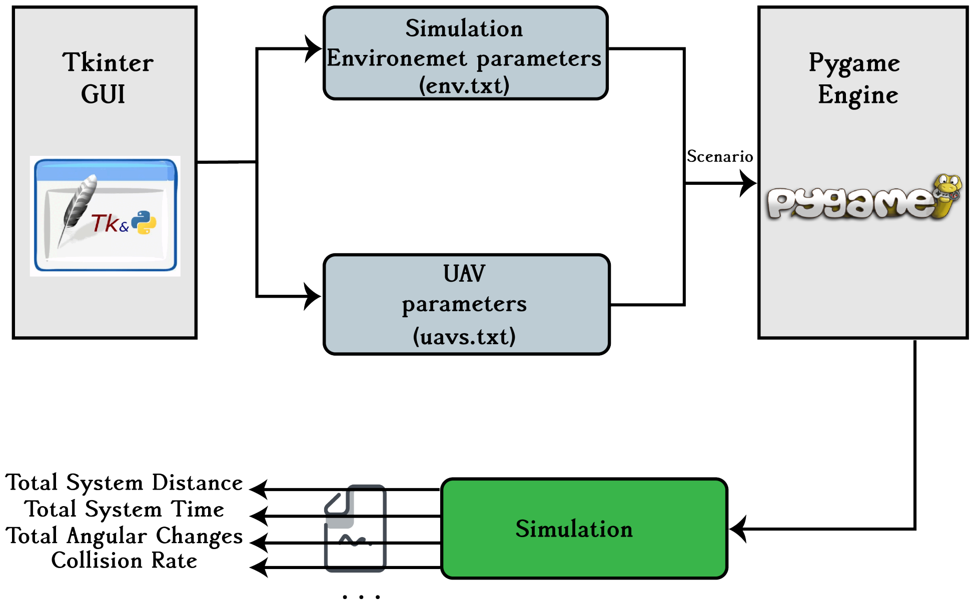
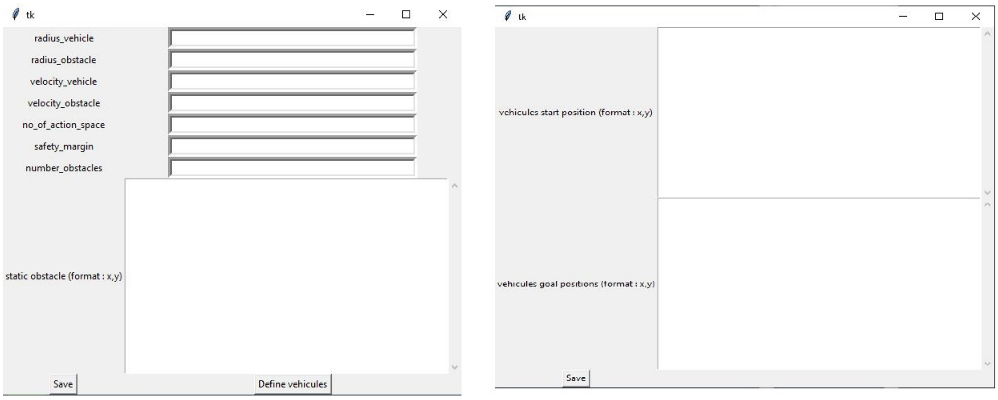


Figure 4.6: The CBCS (Collision Based Communication Simulator) structure

Input module:

First of all, user should define a set of parameters (see table 4.1) to control the UAV via the interface presented in the figure 4.8(a). Then defining the positions of UAVs by the interface presented in the figure 4.8(b).



(a) (b)

Figure 4.7: Interface to introduce parameters

Parameter	Definition
V_obs	Vehicle radius
R_obs	Obstacle radius
V_vehicle	Initial speed of vehicles
V_obstacle	Initial speed of obstacles
Fut_step	Number of angles, Used for smoother motion of the agents
Safe_dist	Safety distance that needs to be checked at all times
Stat_Obs	The coordinates for each stationary obstacle
V_points	The initial spawn point for each vehicle
G_points	The destination points for each vehicle

Table 4.1: Simulation Parameters

Intermediate module:

After entering the simulation parameters into the Graphical User Interface (GUI), two text files are generated in order to be used as input to the game engine module as illustrated in figure 4.6.

Pygame module:

Our approach is programmed from scratch then launched. Algorithm 1 illustrates the main steps executed by the engine.

Algorithm 1: For each UAV_i

```
calculate_my_future_position(velocity,time_step,angle);
if any UAV_j is detected in range then
    send_to(UAV_j)
end
for Path_k(k = 1..n) in all possible paths do
    distance ← distance(fut_position(UAV_i), fut_position(UAV_j)) ;
    if distance ≤ radius(UAV) + radius(Obstacle) + safety_distance
     then
        mark path as dead end path ;
    else
        add_to_avoidance_paths(Path_i);
    end
    filter_min_paths(Avoidance_Paths)
end
```

Simulation module:

From the simulation module we can extract the results of our simulation such as total distance, time, angular changes, success rate and collision rate.

4.4.2 Performance evaluation of OVO using CBCS

We evaluate our protocol using the following metrics:

- Total System Distance: It represents the total distance traveled by UAVs from their starting points toward their targets while avoiding static and dynamic obstacles. The total system distance is calculated by the expression:

$$TotalTripDistance = \sum_{i=1}^{Count\_of\_UAVs} Distance\ of\ UAVi \tag{4.4}$$

- Total System Time: It represents the total airborne time of the UAVs from start to end points while avoiding collisions. It can be calculated by the following equation:

$$TotalTripTime = \sum_{i=1}^{Count\_of\_UAVs} Time\ of\ each\ UAVi\ trip \tag{4.5}$$

- Total Angular Changes: It represents the variations on trajectories of all UAVs while in the air.

  It is calculated using the following equation:

$$TotalAngularchanges = \sum_{i=1}^{Count\_of\_UAVs} Absolute\ angular\ change\ of\ UAVi \tag{4.6}$$

  We can check if an angular change has been made using the following equation:

$$AngleChange(U_1, U_2, PA) = \begin{cases} True, & \text{if } Diff * \frac{180}{\pi} \neq PA \\ & with\ Diff = atan2(U_1.y, U_1.x) - atan2(U_2.y, U_2.x) \\ False, & \text{otherwise} \end{cases} \tag{4.7}$$

- Success Rate : The effectiveness of our approach in case of swarm of UAVs is weighted by the collision rate parameter which is a ratio that intakes the number of collisions, then we can extract the mission success rate. Using the following equation:

$$collision\ rate = \frac{number\ of\ collision}{number\ of\ obstacles} \tag{4.8}$$

$$mission\ success\ rate = (1 - collision\ rate) * 100. \tag{4.9}$$

Simulation Parameters:

In our simulation, a set of parameters were taken to make the scenarios, the following table 4.2 represents the parameters values. Concerning units for the parameters, distances and radius-es are given in pixels, velocity in pixels/system time, direction angles is the number of angles to be used in path generation.

Parameter	**Value**
Radius of Vehicles	10
Radius of Obstacles	10
Velocity of Vehicles	2
Velocity of Obstacles	1
Direction Angles	50
Safety Distance	30
Time steps	1

Table 4.2: Simulation Parameters Values

Simulation Results

To evaluate our approach, we conducted many simulations using the following scenario and we variate many parameters.

First Scenario : We tested the performance of our approach in a scenario with one UAV, where we performed the test multiple times giving fixed start and end points to the UAV. Each time, we increase the number of random dynamic obstacles. The following results were obtained for the previously discussed metrics.

Total Trip Distance:

Table 4.3 and figure 4.8 show the results of this scenario.

UAVs/Obstacles	0	1	2	3	4	5
1 UAV Scenario	806.56	855.999	865.11	861.78	868.23	878.11

Table 4.3: Total Trip Distance Values

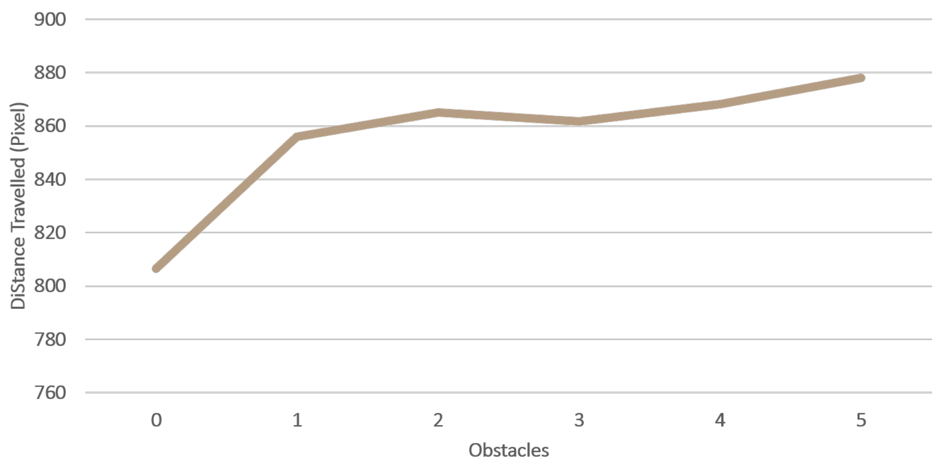


Figure 4.8: Total trip distance

Total Angular changes :

Table 4.4 and figure 4.9 show the total angular changes of this scenario.

UAVs/Obstacle	0	1	2	3	4	5
Angular Changes	268	288	279	285	328	311

Table 4.4: Total Angular Changes

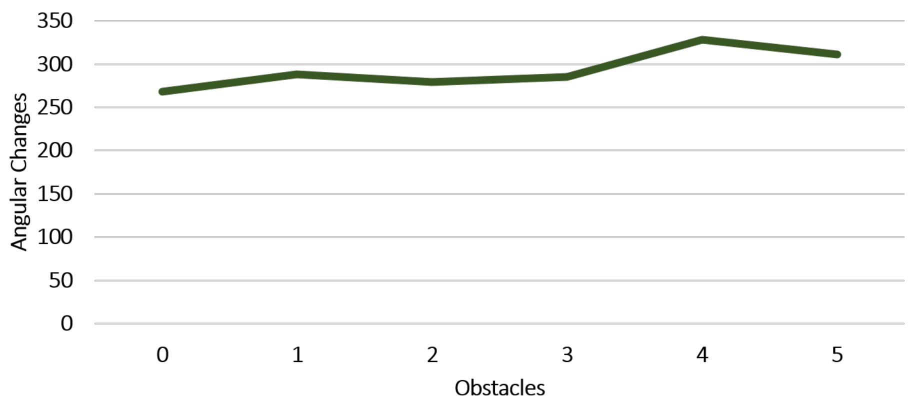


Figure 4.9: Total angular changes

Total Trip Time:

Table 4.5 and figure 4.10 show the results of this scenario.

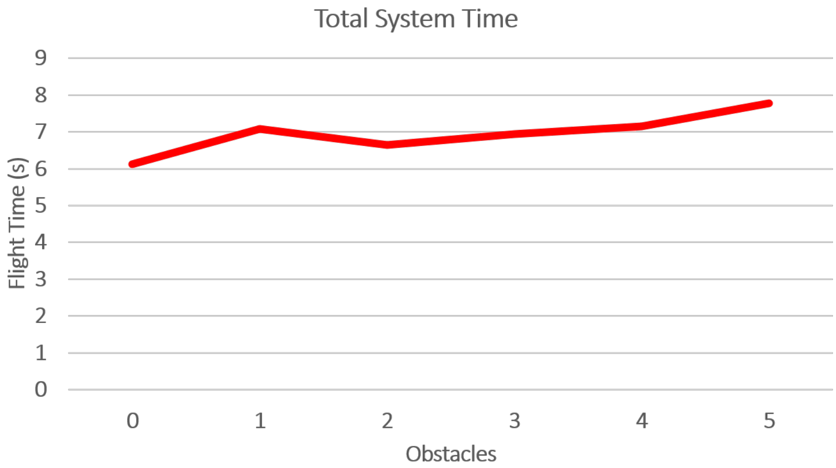


Figure 4.10: Total trip time

Time/Obstacle	0	1	2	3	4	5
Total Trip Time	6.13	7.08	6.65	6.95	7.15	7.77

Table 4.5: Total trip time

Success Rate:

The figure 4.11 illustrates the performance measuring the avoidance success rate in a variety of obstacles.

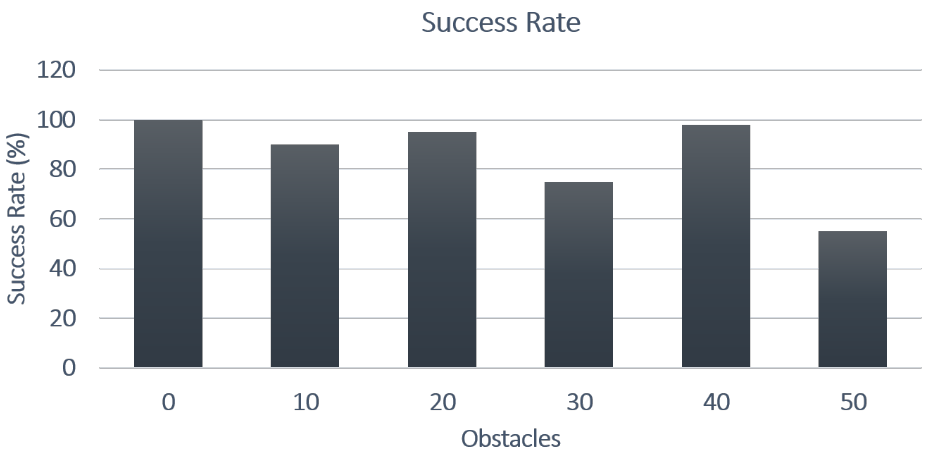


Figure 4.11: Success rate graph

From figure 4.8 to 4.11 we notice the the distance and time added by avoidance maneuvers are very small which prove that costs added by the protocol are not very important. Moreover, the success rate is very high even for a large number of obstacles in a small area.

Second Scenario:

To show the effectiveness of our approach, we compare it with VO and Potential Field methods

Comparing OVO to VO: We compare the success rate of OVO and VO by changing the number of obstacles. Figure 4.12 shows that our approach provides a better response in avoiding than VO developed in [26]. It illustrates that the success rate in OVO reach in the best case 78% while VO success rate [26] do not succeed 47%.

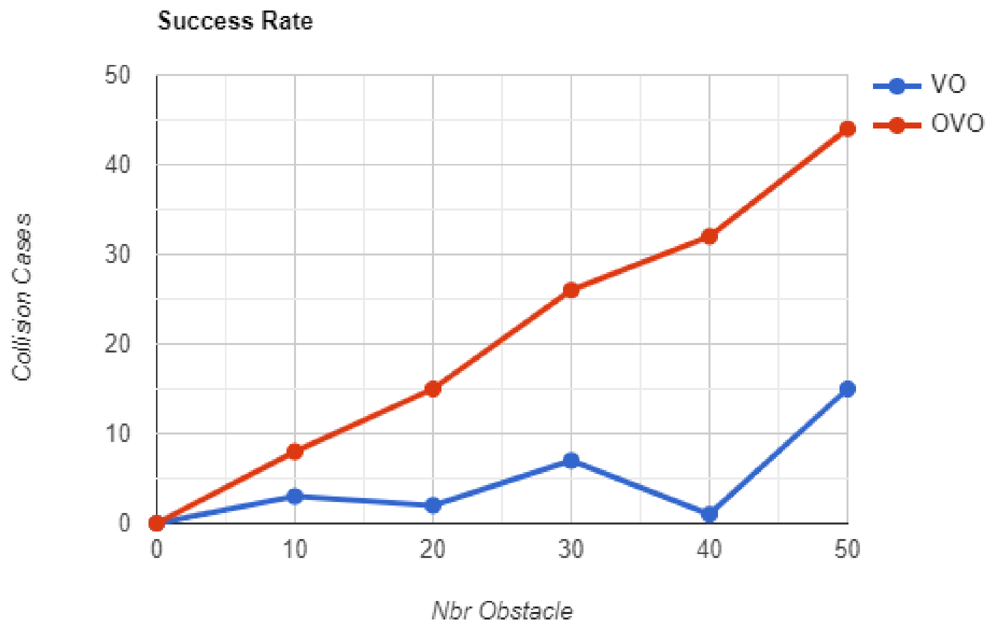


Figure 4.12: Success rate comparison

Comparing OVO to Potential Field meethods (PF): By comparing OVO with PF [28, 29], we notice that the total angular changes for UAVs is optimized using PF approach while it increases using our approach.

The difference here is that the PF approach focuses only on static obstacles while OVO focuses on both static and dynamic obstacles which is an advantage compared to PF approach. The figure 4.13 shows a comparison in angular changes between OVO and PF in presence of a variety number of obstacles.

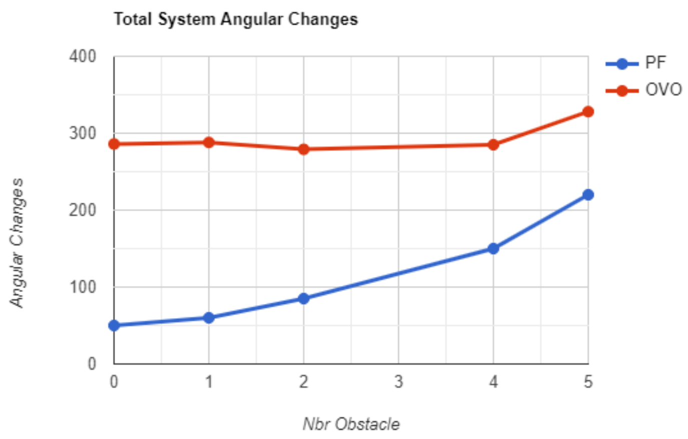


Figure 4.13: Total angular changes comparison

4.5 Conclusion

In the first part of this chapter, we presented our approach, the simulation environment and how we built the OVO from scratch. In the second part, we evaluate our protocol and discussed the limits of optimized velocity obstacle and compared it to other existing methods.

CHAPTER 5

CONCLUSION AND FUTURE PERSPECTIVES

5.1 Summary of our work

UAV technology has known a revolutionary upgrades in the last decade which resulted in some sort of mutation in their aspects, functions, application and most importantly in their hardware. UAVs are generally deployed as a set of swarms that aim to accomplish a mission rapidly and more effectively which attracted industrial and academic communities due to their great potential.

In this work, we presented the UAVs and all its different aspects. Then, we studied and presented the collision avoidance systems and we extracted the limits of the presented methods. To overcome these limits, we propose a new avoidance technique based UAVs communications. Finally we analyzed the simulation results and compared them with those obtained by other approaches.

5.2 Future Perspectives

As a future works, we would like to further improve and decrease total system distance travelled, add the aspect of energy as a cost function to find a maneuver, try to increase the success rate and add a new z-plane to our solution since it works on 2D environments only.

BIBLIOGRAPHY

[1] P. Raj, "active and passive sensors," 2010. Online; accessed 06-june-2022.

[2] V. S. o. Engineering, "Presentation of drones components syst 460," Online; accessed 06-june-2022.

[3] B. Zhang, Z. Song, F. Zhao, and C. Liu, "Overview of propulsion systems for unmanned aerial vehicles," *Energies*, vol. 15, p. 455, Jan 2022.

[4] A. Sharma, P. Vanjani, N. Paliwal, C. M. Basnayaka, D. N. K. Jayakody, H.-C. Wang, and P. Muthuchidambaranathan, "Communication and networking technologies for uavs: A survey," *Journal of Network and Computer Applications*, vol. 168, p. 102739, Oct 2020.

[5] D. Chaoyou, "Communication among uavs," Jun 2010.

[6] J. N. Yasin, S. A. S. Mohamed, M.-H. Haghbayan, J. Heikkonen, H. Tenhunen, and J. Plosila, "Unmanned aerial vehicles (uavs): Collision avoidance systems and approaches," *IEEE Access*, vol. 8, p. 105139–105155, 2020.

[7] G. Singhal, B. Bansod, and L. Mathew, "Unmanned aerial vehicle classification, applications and challenges: A review," 2018.

[8] M. Arjomandi, "Classification of unmanned aerial vehicles," *The University of Adelaide, ...*, Jan 2007.

[9] H. Nawaz, H. M. Ali, and A. A. Laghari, "Uav communication networks issues: A review," *Archives of Computational Methods in Engineering*, vol. 28, p. 1349–1369, Mar 2020.

[10] A. M. Vegni, V. Loscri, C. T. Calafate, and P. Manzoni, "Communication technologies enabling effective uav networks: A standards perspective," *IEEE Communications Standards Magazine*, vol. 5, p. 33–40, Dec 2021.

[11] M. Khelifi and I. Butun, "Swarm unmanned aerial vehicles (suavs): A comprehensive analysis of localization, recent aspects, and future trends," *Journal of Sensors*, vol. 2022, Feb 2022.

[12] E. Yanmaz, S. Yahyanejad, B. Rinner, H. Hellwagner, and C. Bettstetter, "Drone networks: Communications, coordination, and sensing," *Ad Hoc Networks*, vol. 68, p. 1–15, Jan 2018.

[13] S. Huang, R. S. H. Teo, and K. K. Tan, "Collision avoidance of multi unmanned aerial vehicles: A review," *Annual Reviews in Control*, vol. 48, p. 147–164, 2019.

[14] A. Mcfadyen and L. Mejias, "A survey of autonomous vision-based see and avoid for unmanned aircraft systems," *Progress in Aerospace Sciences*, vol. 80, p. 1–17, Jan 2016.

[15] A. H. Sawalmeh and N. Shamsiah Othman, "An overview of collision avoidance approaches and network architecture of unmanned aerial vehicles (uavs)," *International Journal of Engineering and Technology*, vol. 7, p. 924, Nov 2018.

[16] M. Orefice, V. Di Vito, and G. Torrano, *Sense and Avoid: Systems and Methods*, p. 1–9. John Wiley ; Sons, Ltd, Dec 2015.

[17] Nichols, Ryan, Carter, Mumm, and Lonstein, *Chapter 7: UAS SAA Methodologies, Conflict Detection, Resolution Principles*. 2018.

[18] A. Israr, Z. A. Ali, E. H. Alkhammash, and J. J. Jussila, "Optimization methods applied to motion planning of unmanned aerial vehicles: A review," *Drones*, vol. 6, p. 126, May 2022.

[19] B. M. Albaker and N. A. Rahim, "A survey of collision avoidance approaches for unmanned aerial vehicles," in *2009 International Conference for Technical Postgraduates (TECHPOS)*, IEEE, Dec 2009.

[20] P. Lauren, "Cooperative collision avoidance strategies for unmanned aerial vehicles," *unknown*, Dec 2021.

[21] E. Ferrera, A. Alcántara, J. Capitán, A. Castaño, P. Marrón, and A. Ollero, "Decentralized 3d collision avoidance for multiple uavs in outdoor environments," *Sensors*, vol. 18, p. 4101, Nov 2018.

[22] A. Patel, *UAV Collision Avoidance: A Specific Acceleration Matching Approach.* 2011.

[23] J.-W. Park, H.-D. Oh, and M.-J. Tahk, "Uav collision avoidance based on geometric approach," in *2008 SICE Annual Conference*, pp. 2122–2126, 2008.

[24] Y. I. Jenie, E.-J. van Kampen, and B. Remes, *Cooperative Autonomous Collision Avoidance System for Unmanned Aerial Vehicle*, p. 387–405. Springer Berlin Heidelberg, 2013.

[25] P. Machado and K. Bousson, "Automatic collision avoidance system based on geometric approach applied to multiple aircraft," Jun 2014.

[26] J. A. Douthwaite, S. Zhao, and L. S. Mihaylova, "Velocity obstacle approaches for multi-agent collision avoidance," *Unmanned Systems*, vol. 07, p. 55–64, Jan 2019.

[27] A. Desilles, H. Zidani, and E. Crück, "Collision analysis for an uav," in *AIAA Guidance, Navigation, and Control Conference*, American Institute of Aeronautics and Astronautics, Aug 2012.

[28] H. V. Abeywickrama, B. A. Jayawickrama, Y. He, and E. Dutkiewicz, "Algorithm for energy efficient inter-uav collision avoidance," in *2017 17th International Symposium on Communications and Information Technologies (ISCIT)*, IEEE, Sep 2017.

[29] H. V. Abeywickrama, B. A. Jayawickrama, Y. He, and E. Dutkiewicz, "Potential field based inter-uav collision avoidance using virtual target relocation," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, IEEE, Jun 2018.

[30] J.-K. Park, "Boundary-rrt* algorithm for drone collision avoidance and interleaved path re-planning -journal of information processing systems," *Journal of Information Processing Systems*, vol. 16, p. 1324–1342, Jan 2020.

[31] M. Radmanesh, M. Kumar, P. H. Guentert, and M. Sarim, "Overview of path-planning and obstacle avoidance algorithms for uavs: A comparative study," *Unmanned Systems*, vol. 06, p. 95–118, Apr 2018.

[32] K. Dushime, L. Nkenyereye, S. K. Yoo, and J. Song, "A review on collision avoidance systems for unmanned aerial vehicles," in *2021 International Conference on Information and Communication Technology Convergence (ICTC)*, IEEE, Oct 2021.

[33] L. Tingsheng, “Uav collision avoidance using a* algorithm,” Apr 2012.

[34] J. Jiang and K. Wu, “Cooperative pathfinding based on memory-efficient multi-agent rrt ieee,” vol. 8, p. 168743–168750, 2020.

[35] E. Mai, “Obstacle detection and avoidance techniques for unmanned aerial vehicles design and simulation of a reactive collision avoidance system,” 2019. Online; accessed 06-june-2022.