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Survey: State of art on UAV trajectory planning with communication constraints

Sommaire

Abstract

UAVs and more particularly UAVs fleets are increasingly used in our society. Technological and legal progress allows, not yet fully, to use its special vehicles to improve our daily lives. In this paper, we make a state of the art on trajectory planning and communication for a fleet of UAVs. With the help of some 60 scientific journals studied, we have been able to write this document which gathers the methods used until now (algorithms, technologies, flight training, training control) which allow the good progress of the missions attributed to the UAVs.

1/ Introduction

In recent years, there has been a growing interest for the research on wireless communication for UAV (Unmanned Aerial Vehicle) network. One of the fundamental operation of UAV fleets is trajectory planning. The problem consists in finding a trajectory that allows a UAV or a group of UAVs to go from a starting point S to an objective point G, while avoiding collision with obstacles or among UAVs and optimizing the UAVs-UAVs and UAVs-GCS (ground control station) communications. As a result, the topics that we will discuss are not necessarily valid with other types of vehicles because the environment in which UAVs operates and the technology that embeds it, are elements that radically alter trajectory planning. A deployment of a functional multiple UAVs network would offer a lot of possibilities and applications. This could improve and facilitate daily life and other specific tasks, with one purpose: improve human’s comfort. For example, road traffic is more and more overloaded, transportation is slower and slower, and this ends up having an impact on many services like logistics. Scientists are trying to use aerial traffic and improve trajectory planning for better efficiency. Many aerial vehicles have been studied and manufactured for this purpose. In this survey, all aspects that we will discuss will be specific to multiple UAVs with propellers flying together, and not with fixed wing UAV, which generally fly alone and offer a different set of possibilities, which is out of the scope for this work. The various applications where UAVs are used present complex scenarios with very dynamic functionalities. Thus, in this survey, we will try to establish a state of the art of the trajectory planning for a UAVs fleet and of the networking of such a system.

In the road traffic context, mentioned above, these aerials vehicle could help avoiding traffic jams and many other obstacles. As a result, travel times would be reduced, and this mode of travel would become much more efficient than a terrestrial movement.
A good point for UAVs is that their aerial position and their small size, allow them to move everywhere and to have angles to take photos or videos that a terrestrial robot could not have. One of the possible usage of this image capture is fire detection. UAVs quickly detect the extent of fire and images are sent to firefighters who can do their job with exceptional field knowledge. In civilian protection, UAVs can move around a city and monitor suspects

attitude. The UAVs can capture pictures of a crime or an offense and then these pictures can be used as evidences in court. These robots are also able to move by using maps and find a fugitive through facial recognition, and thus to transmit his position to the police. Another use in logistics is to deliver packages. A single UAV can carry few kilos for the most powerful models. But a UAVs fleet would be able to carry bigger packages. The challenge lies here in coordinating robots to achieve this goal. To achieve this goal, communications technologies and robotic are the key.

In a lot of subjects, many problems have been solved because scientists have taken inspiration from nature, especially from social animals, such as ants. These insects can join forces to accomplish awesome things, yet only one ant is quickly limited. We will see in detail several examples of these algorithms, called "bio-inspired algorithm" that will lead to an optimal trajectory planning for our case. Scientists have also turned their attention to physics in order to solve this problem of trajectory planning, notably with electrons movements in the presence of electromagnetism. There is a method called potential method, which generates attraction or repulsion signals. This allows a perfect knowledge of the environment. There are some problems with the use of these algorithms applied in the research of a trajectory planning, we will develop them in this work. Genetic algorithms are part of the category of so-called evolutionary algorithms that are being developed more and more at the research level for their link to AI. They give an approximated solution for a problem that does not have an exact solution method in a reasonable time. They use the notion of natural selection to improve the solution. The disadvantage of this method is its inaccuracy which is sometimes vital for UAVs navigation. Its main advantage is the speed at which it gives an approximate result. The Voronoi diagram can give good results to our problem, it consists in drawing lines around obstacles, but these lines must respect the following constraint, they must be at the shortest distance from each obstacle. So, we obtain a balance and this diagram could approach us to the best possible trajectory to pass among obstacles and brush them as little as possible. But the disposition of each vehicle in a fleet of UAVs can prevent an algorithm from working well, because to move a fleet is not as simple as move a single UAV. That's why fleet formation and it’s control are also two important things

The formation of a UAV fleet can be decisive for the mission they have to accomplish. It is therefore necessary, depending on the purpose to be able to modify the formation of flight. There is not predefined formation that must be followed, but we often find certain types of patterns such as column formation used for sweeping an area, line formation for narrow space, formation on V for a more peripheral vision and diamond formation that is a derivative of the previous one. Many formations are inspired by the group movement of animals such as birds or fish that tend to move strategically depending on the situation (if there is danger, if they have to go fast, etc).

Then there are different types of formation that characterize the layout of a UAV fleet, depending on the environment and the mission, the type of formation may have to change. Pretty famous formation control like Virtual Structure, leader/follower, behavior-based formation and hybrid model will be presented later. To achieve such formations, very effective communications and information exchange at any time are required. So this implies choices that will be explored later in this document, such as the communication technologies, but also other choices, such as the transmission hardware (antenna type, etc.), which will not be detailed in this work.

To move a fleet of drones, so that they can avoid obstacles and maintain established formation, communication is essential. Indeed, if information is erroneous or lost, the consequences can be dramatic financially (UAV destroyed) or if a UAV falls on a risk area (highway, pedestrians,etc.). There are several communications strategies for UAV to UAV communications and UAV to GCS communications, each strategy has advantages and disadvantages. UAVs can communicate directly with the ground control station and use it as a relay to communicate with another UAV, but this is limited in terms of data transfer, latency and range. Indeed, the signal must go from the transmitter to the station, and the station must transmit the message to the receiver. This latency can give rise to obstacles avoided too late and lead to a destruction of the vehicle. Another problem, typical of urban environments, are the presence of buildings that could hinder the transmission of the message. A second strategy is based on satellite communication that provides better ground coverage and requires less infrastructure, but it does not work inside buildings, and in urban areas where physical barriers and electromagnetic interference, can interfere with communication. Data transfer is also too low if a critical exchange is necessary. A third mode of communication would be cellular communication based on telephone antennas. It provides a better range by using 4G for live video for example. But 4G is mostly used for ground communications, for a higher altitude it would not work (< 60 meters) and it is not present in rural areas. Finally, the problem of using the 4G for communication is the high download rate and the low upload rate, whereas for a UAV that plays a live video, it needs a high upload rate, which may be will be provided by 5G.
UAVs also can communicate with each other, either with the IEEE 802.11 standard or for other usages, in infrared. The first advantage is that the communications do not depend on a station and therefore the communication is more reliable. Then, the distances that the signal must travel are shorter, so he is faster and there are less losses.

There are also problems or rather choices to make on robotics concerning the functioning of the mobility or the optimization of the energy to move the UAVs. However, these issues will not be presented in this survey, even if they should not be neglected for the achievement of the final goal.

The problem here is that setting up a UAVs fleet is not so simple. As the optimal trajectory planning requires a good trajectory algorithm on the one hand and good communication between UAVs on the other hand, in order to adapt with their environments, these different solutions presented above will need a correct analysis to see which ones guarantee the feasibility and the least vulnerability for the proper functioning of the UAV.

So we decide to organize a survey like this, in section 1 we will, at first, lay some essential basics, including introducing the concept of trajectory planning but also the difference between path planning and trajectory planning which are two notions very often confused. We will also present in this section the different algorithms that exist for obstacle avoidance and therefore a perfect trajectory planning as well as their current evaluations and applications (optimal for the UAV).
In Section 2 we will discuss communication within UAV fleets and between a UAV and a ground base station and more specifically the technologies in the different network layers of wireless communication protocols. We will analyze in a first part the data link layer and in a second part the network layer. We will detail network technologies, topology and training in

each case. Finally, the last section of our review is the concluding part that will summarize our work and present future research and potential future problems.

We examine the results of some fifty references on this subject published in international research journals.

2/ 2D/3D Trajectory Planning

In this part, we begin at first, by some indispensable definitions and key concepts like the concept of trajectory planning, as well as the notion of path planning which are two very different notions and often confused. These definitions are necessary to understand because they will then be used consistently throughout this article. Some terms are defined again here, but most correspond to the terminology used in the literature. We will also see in a second time, the current algorithms of trajectory planning and more particularly their principles, their characteristics, their evaluations, and their possible applications.

1) Définitions

A. Trajectory planning

In many areas, including robotics, we have to calculate, plan trajectory so that the vehicle can move from one place to another in the best conditions taking into account the surrounding environment. But before going further, some definitions of key concepts are needed. A vehicle, for example here a UAV, is an object capable of moving. Most vehicles can be considered as rigid bodies in a three-dimensional space. The trajectory planning of UAV is a special case of the general motion planning problem, which is usually very difficult to solve. A path is a curve traced by the vehicle in the configuration space, and a trajectory is a path that includes the time along the path.

Trajectory planning is therefore about finding segments of smooth and continuous pathways to move along the trajectory of a path, which is a path along the trajectory.

Simply put, it is about successfully planning an optimal path from one place to another and achieving your goal by avoiding obstacles as described in the following illustration.

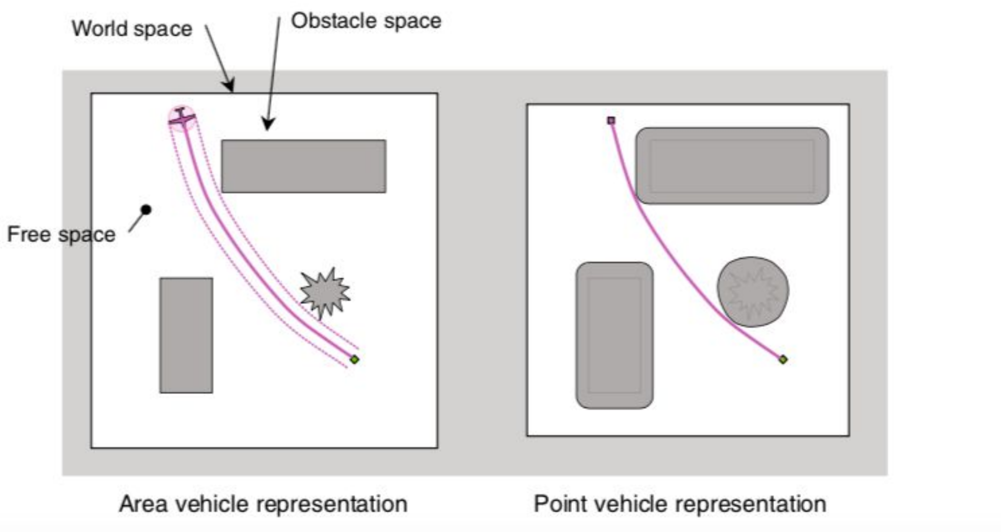

Figure 1. Area and point vehicle representation

In our case, a fleet of UAV with multiple objectives. From parcel delivery to military use, to network extension, our drone fleet must be able to move in its environment and any movement must be calculated to avoid collisions. In a typical UAV application, the vehicle thus operates in a three-dimensional space, and in addition to facing obstacles of different nature the UAV is subjected to differential constraints, including limited speed and maximum acceleration. In the literature, a problem is either considered static, if the knowledge of the environment is perfect. Typically, a UAV encounters in this case, fixed obstacles such as: buildings, trees, ground, ceiling,etc. Or on the contrary, the problem is considered dynamic if the knowledge of the environment is imperfect or may be varied during the course of the task. In this case the UAV encounters dynamic obstacles like; cars, humans, animals, other UAVs, etc. When obstacles are fixed in space, so in the case of static problems, the problem is called invariant in time and, when they are allowed to move in the case of dynamic problems, the problem is called variant in time.

Of course, the category with dynamic problems is the most difficult to predict and put in place because the fleet needs to constantly analyze its environment to detect likely collisions. Another difficulty that we will have to face is that as we mentioned before the UAV fleet evolves in a 3D environment, so the obstacles are also in 3 dimensions and can be located in a 360 degree zone around of the UAV. Moreover, the obstacles are of different natures, some reflect the light, others absorb it, all these behaviors induce different reactions to the sensor data. The UAV must therefore have a variety of sensors to overcome the problems of each type of obstacle. Therefore, we will solve these problems related to difficulties add with the three-dimensional dimension in the following. We can thus consider a trajectory planning algorithm as complete if, and only if, it finds a collision-free path, if there is one, and returns a variable indicating that there is no path when it does not exist. there are none and that with any type of problem. It is considered optimal when it returns the optimal path with respect to a criterion. Robustness may be the most crucial property for trajectory planning algorithms, because the results of a collision are catastrophic. These algorithms, which are essential for the proper functioning and behavior of the fleet, are not always sufficient. Indeed, imagine a fleet that must pass through a window large enough to let one UAV at a time. Each UAV in the fleet will calculate the trajectory to adopt to pass the window and there is a risk of a collision among UAVs. To solve this problem and many other dynamics or static, it is necessary that in addition to these algorithms of trajectory planning, that the UAV can communicate with each other and to agree to know the order of passage by the window. With communication, a UAV can warn others of a hazard or obstacle and they can set a new trajectory to avoid collisions at best.

B. Differences between Path Planning et Trajectory Planning

Trajectory planning and path planning are two distinct problems in robotics, but they are extremely linked. There are several works that explicitly differentiate these two notions but many scientists do not differentiate them in the literature. By grouping together all the corresponding knowledge, this part wants to present these two very different notions.

Initially, a path planning problem can be reduced to a problem of finding the best path between a point A and a separate point B. The trajectory planning as presented previously generally corresponds to the problem of extracting the solution from a path planning algorithm of a vehicle and determining how to move on that path. Trajectory planning is therefore about finding smooth and continuous trajectory segments to move along a path. The trajectory then corresponds to a curve. The trajectory planning will therefore depend on the result of the path planning, this is not reciprocal. In the case of our subject, we are specifically interested in trajectory planning which is still a field in full exploration concerning the development of UAVs in a three-dimensional universe. Unlike path planning which is a resolved domain for such a scenario. Indeed, simple 2D trajectory planning algorithms are not able to deal with complex 3D environments, where there are many constraints and uncertainties on structures. Thus, it is urgent to have 3D trajectory planning algorithms for UAV navigation, especially in complex environments such as forests or urban areas, as shown in Fig.1.

(a) urban area (b) Forest

Figure 2. Examples of 3D environments

Trajectory planning in 3D environments has great potential, but unlike 2D trajectory planning, the difficulties increase exponentially with dynamic constraints and cinematic constraints becoming much more complex. Thus, we will present the algorithms that solve trajectory planning in a 3D environment.

2) Existing Algorithms

Men has often been inspired by nature to imagine new inventions. For example, the observation of the behavior of the dolphin has allowed humans to realize that this mammal uses ultrasound to analyze its environment. By copying this behavior, men created the sonar. This tool quickly became indispensable in underwater navigation and for the military field. Scientists have tried to apply this method to solve the problems of trajectory planning and have succeed to find algorithms called "bio inspired" for these problems. In this family of algorithms, we find potential method algorithms that are inspired by the movements of bacteria with attractive fields and repulsive fields. In the category of "bio inspired" algorithms, there are algorithms inspired by the functioning of the brain and that touch on the field of artificial intelligence, especially with the use of neural networks. These algorithms can learn situations, maneuvers and make the best choices depending on the environment. We will see a last category of algorithm, swarm algorithm inspired by ant colony. Finally we will describe another no-bio-inspired algorithm.

A. Potential Field Methods

The Artificial Potential Field (APF) algorithm works by associating artificial potential fields with different elements of the environment to allow robots to be attracted to a target and repelled by an obstacle. This method uses two types of potentials: the attractive potentials to represent the goal that the UAVs have to reach, and the repulsive potentials to represent the obstacles of the environment. In [41], the attractive potential field U_{att} :

$$U_{att}(\vec{p},\vec{v}) = \alpha_p \|\vec{p}_{target} - \vec{p}\| + \alpha_v \|\vec{v}_{target} - \vec{v}\|$$

is calculated as a function of the position $\overline{p}$ and the speed $\overline{v}$ of the UAV in relation to the target position $\overline{p}_{target}$ and the target speed $\overline{v}_{target}$. α_p and α_v are balancing coefficients. The field of repulsive potential:

$$\begin{aligned}
U_{n_{rep}}(r) &= G_{rep}\frac{r^{n_{rep}-2} - r_{max}^{n_{rep}-2}}{r_{min}^{n_{rep}-2} - r_{max}^{n_{rep}-2}} && si \quad n_{rep} \in [0,2[\cup]2,+\infty[&& et \quad r \in [r_{min}, r_{max}] \\
U_2(r) &= \frac{\ln(r_{max}) - \ln(r)}{\ln(r_{max}) - \ln(r_{min})} && si \quad n_{rep} = 2 && et \quad r \in [r_{min}, r_{max}] \\
U_{n_{rep}}(r) &= 0 && && si \quad r \notin [r_{min}, r_{max}]
\end{aligned}$$

depends on the radius of the obstacle r_{min} and r_{max} the radius of the obstacle plus the limit radius from which it is considered that the obstacle has no more importance and n_{rep} the order of the obstacle determining a potential shape. The order of the obstacle n_{rep} means that we try to classify the obstacles that the UAVs meet according to a parameter like size or volume for example. The repulsive force emitted by the obstacle increases as the UAV approaches the obstacle. The order is a value between 0.1 and 3. If we decide to order the

$$n_{rep_k} = f(Vuln_k, \Delta v_k, v_k)$$

obstacles according to their dangerousness, the order n_{repk} of an obstacle k will depend on three parameters:

The function f will increase according to the dangerousness of the situation. The dangerousness of a situation depends on the vulnerability $Vuln_k$, the speed shift potential Δv_k and the current speed of the obstacle vk. The vulnerability $Vuln_k$ is a value between 0 and 5 and may be defined by:

$$Vuln_k = Vuln_k^{ego} + Vuln_k^{alter}$$

$Vuln_k^{ego}$ represents the vulnerability of the UAV compared to the obstacle and $Vuln_k^{alter}$ corresponds to the vulnerability of the obstacle compared to the UAV. It has been decided that the UAV and the obstacle have the same importance and therefore their vulnerability is considered equal. So $Vuln_k^{ego}$ and $Vuln_k^{alter}$ are values between 0 and 2.5. The speed variation potential deltavk is defined by:

$$\Delta v_k = \max(|v_k - v_{min}|, |v_k - v_{max}|)$$

This potential depends on the current speed of the obstacle vk, the minimum speed v_{min} and maximum v_{max} that can reach the obstacle. UAVs have a table that lists the type of obstacle, its minimum and maximum speed, and the $Vuln_k$ vulnerability calculation. Here is an example of tables:

Kind of obstacles	$[vk_{min}\ ;\ vk_{max}]\ (km/h)$	$Vuln_k$
Motorized vehicle	[0 ; limited speed]	4 = 2 + 2
Pedestrian	[0 ; 10]	2.5 = 0 + 2.5
Street furniture	[0 ; 0]	2 = 2 + 0
Building	[0 ; 0]	3.5 = 2.5 + 1
Other UAV	[0 ; 70]	5 = 2.5 + 2.5

The function f is defined such that:

$$f(Vuln_k, \Delta v_k, v_k) = Vuln_k \left(\frac{2}{5v_{lim}}(v_k + \Delta v_k) + 0.2 \right)$$

and can order any obstacle that is listed in the table according to the speed of the UAV vk and the maximum speed of the obstacle v_{lim} . Here is a possible implementation of the APF algorithm on [8].

Algorithm 3. APF (fitness function)

```
1: procedure APF(q_0, q_f, k_a, k_rN, O_N, η, ε, M)
2:    m ← 0        ▹Iteration counter
3:    d_a ← sqrt(q_f^2 − (q(0) ← q_0)^2)      ▹d_a is the distance from
   the desired to the start position of the MR
4:    while (d_a > ε and m < M) do
5:       U_total(q(m)) ← U_att(q(m)) + Σ_{i=1}^{N} (U_rep(q(m)))
6:       F(q(m)) ← −∇U_total(q(m))
7:       q(m + 1) ← q(m) + η * F(q(m))/‖F(q(m))‖      ▹MR
   configuration position
8:       d_a ← sqrt(q_f^2 − q(m)^2)
9:       m ← m + 1
10:   end while
11:   if d_a ⩽ ε then
12:            ▹The algorithm returns the path planned (MR
   configuration position array, q)
13:      return [q, d_a, m, goal ← 1]      ▹Target position
   achieved (goal = 1)
14:   else
15:      return [q, d_a, m, goal ← 0]      ▹Target position not
   achieved (goal = 0)
16:   end if
17: end procedure
```

Figure 3. APF implementation

“APF requires the next set of values: a starting position $(q(0) \leftarrow q0)$, a goal position (qf), the proportional gains (k_a and k_{rN}) which are the gains of attractive and repulsive potential respectively, where N represents the number of obstacles. The step size (η) used in the iterative calculation of the next position q (step 7), the convergence radius (ε) that can be also be given by the user as an input to the algorithm, and the number of maximum number of iterations (M) which represents the target. The parameters and M are the algorithm stop conditions, as it is shown in step 4. Note, that depending on the number of obstacles $O_N = [O_1; \ldots; O_N]$ several $[k_{r1}; \ldots; k_{rN}]$ repulsive proportional gains may exist. In the APF, the k_a and k_r is gains are provided heuristically, therefore, for being compatible and achieving fair comparisons against the APF, only one k_r is used for all the obstacles. The algorithm starts calculating the Euclidean distance (d_a) to determinate de distance between the mobile robot position and the goal position. Next, it enters into a loop to move the robot step by step. Inside the loop, the $U_{total}(q)$ (APF) is calculated using equation of step 5, where N is the number of obstacles. Step 6 consists in calculating the negative gradient of $U_{total}(q)$ to obtain the generalized force $F(q)$, which is used in step 7 to iteratively calculate the new position of the robot, in step 8 it is calculated the new existing distance d_a between the actual robot position and the goal position. The loop iterates until the stop conditions are presented. From steps 11–17, the Algorithm 3 verifies whether the robot reached the target or not and returns the path planned." They are a lot of advantages for this algorithm, it gives a feasible path and the robot reaches the goal autonomously. In addition, this technique does not require knowing the movement of obstacles, it is very responsive and can handle an unexpected event as an obstacle that cuts the trajectory to the UAV. Unfortunately, in large spaces, the APF algorithm is very slow and reduces the speed of movement of the robot, so it is not enough to handle the problem of path planning. And, APF is sensitive to local minima, so our UAV may be stuck. For example, in the article [num], "A route planning method based on improved artificial potential field algorithm" has already shown the limits of APF in some situations. To overcome these weaknesses, we use for example, the algorithm Bacterial Potential Field (BPF) which finds very quickly the optimal parameters and is insensitive to local minima. BPF is inspired by the movements of bacteria, the major advantage of this algorithm is that it can find the values of the attractive forces $k_a(opt)$ and repulsive $k_r(opt)$ with a very reduced computation time. N_p is the number of processors to use. APF is used as the $FitFunc$ fitness evaluation function of the BPF algorithm. This function measures the quality of the individual expressed as a number or a vector. It is said that an individual x is better than the individual y when the result of the fitness function of x is closer to the solution than the result of the fitness function y.

Algorithm 1. BPF path planner

procedure BPF($q_0, q_f, O_N, \eta, \epsilon, M, N_p$)
  FitFunc = @ APF ($q_0, q_f, k_a, k_{rN}, O_N, \eta, \epsilon, M$) ▹Assign a function handler to the APF fitness function
  $[k_a, k_{rN}, \eta, d_a, m, goal] \leftarrow$ BEA ($[k_a, k_{rN}, \eta], BEA_{param}$, FitFunc, N_p)
  if $goal == 1$ **then** ▹Target achieved
    $k_{a(opt)} \leftarrow k_a$
    $[k_{r1(opt)}, \ldots, k_{rN(opt)}] \leftarrow [k_{r1}, \ldots, k_{rN}]$
    $\eta_{(opt)} \leftarrow \eta$
    $M \leftarrow m + 1$
    APF ($q_0, q_f, k_{a(opt)}, k_{rN(opt)}, O_N, \eta_{(opt)}, \epsilon, M$) ▹Performs optimal path planning
  else
    Target not achieved, a reachable path does not exist
  end if
end procedure

Figure 4. BPF implementation

B. Genetic Algorithms

Genetic algorithms are stochastic research techniques. They are directly inspired by nature. We can make the analogy with a pack of wolf, the alpha male is the dominant group, it is the strongest, the bravest and the best hunter and it is the only wolf that can have descendants, if another male mates, the newborn will be killed by the pack. This ensures a strong lineage within the pack with members ever more adapted to the environment. This principle is called natural selection and scientists have succeeded to create algorithms that copy this concept. To overcome the problems of the APF algorithm, we must change the shape of the potential. The trick is to place a dynamic virtual target that generates an attractive field so that the UAV is always attracted to the best direction to avoid blockages. The goal of the genetic algorithm is to optimize the trajectory of the target. It represents a trajectory by a set of points and calculates the cost of the trajectory several times according to different points and chooses the best trajectory. This algorithm does not replace the method of artificial potential fields but comes in addition to the latter to fill these disadvantages as local minima. In our case, the initial population corresponds to a set of trajectories. First, a reproduction phase is applied to this initial population. This involves applying genetic operators to them to generate new individuals. The two main genetic operators are cross-over and mutation. The cross-over cuts two chromosomes at a randomly chosen point and gives two new chromosomes after exchanging the cut parts.

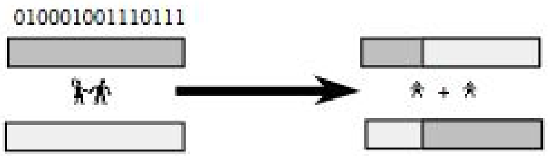

Figure 5. Cross-over representation in article [5]

The mutation randomly changes one or more elements of the chromosome.

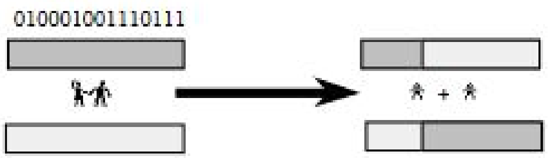

Figure 6. Mutation representation in article [5]

As the analogy with the behavior of wolves, the basic principle of the algorithm is "better is an individual, the greater the probability of selection is great". In a second step, the algorithm performs a replacement phase. The worst individuals are removed and replaced by the best individuals produced. This phase puts all the individuals in competition, and it is carried out in loop to improve the individuals until a certain criterion of stopping. The third phase is the selection phase, followed by the reproduction phase of the individuals.

Algorithm 2. BEA

```
procedure BEA([var_1, ..., var_n], BEA_param, FitFunc, N_p)
    t ← 0    ▷Iteration counter
    Create an initial population P(t) of N_B bacteria
    Evaluate each bacterium in P(t)
    while not termination do
        Perform bacterial mutation P'(t)
        Perform genetic transfer P'(t)
        Divide the workload by N_P processors to obtain P_i(t) subpopulations
        for each processor do in parallel
            Evaluate each chromosome of subpopulation P_i(t) with APF
        P'(t) ← ⋃_∀i P_i(t)
        P(t+1) ← P'(t)
        t ← t+1
    end while
    return [var_1, ..., var_n, fitValue]_opt
end procedure
```

Figure 7. BEA implementation

The BEA algorithm (Bacterial Evolutionary Algorithm) is a genetic algorithm, it introduces two operations inspired by the phenomenon of microbial evolution. The bacterial mutation operation which consists of optimizing the chromosome of a single bacterium, and the gene transfer operation to ensure the transfer of information among bacteria in the population. The BEA algorithm uses the differential equation : $P(t+1) = s(v(P(t)))$, t represents time, $P(t+1)$ is the new population, $P(t)$ is the initial population, v is a random function and s is a selection function. To obtain the new population, we apply to the initial population a random variation and a selection. He uses the principle of divide and rule especially with the slave master approach. $BEAparam$ contains the parameters on the rate of mutations, the number of infections and the stopping condition. BEA returns optimized values as a table.
This algorithm may become more powerful if other criteria to classify different levels interactions, as gene neighborhood is added for evaluation. Genetic algorithms have several advantages. First, apart from the evaluation function, they are simple and quick to program. This is a big advantage for application development costs. Second, they are generic algorithms. In most cases, it is enough to modify the evaluation function to adapt these algorithms to new problems. Thirdly, this type of algorithm is easily parallelizable, in contrast to simulated annealing type algorithms which are extremely complex to parallelize and generally give a bad solution, too slow or not adapted.

C. Swarm algorithms

In robotics, swarm behavior is inspired by social insects such as ants, termites and bees. The principle, each individual has a basic behavior, almost trivial which brings little interest. But when these individuals regroup and form a swarm, they are capable of very complex actions. This principle is called aggregation, it is the ability to communicate between individuals, to observe the behavior of these neighbors to avoid collisions and to work in groups to reach a goal. The advantages of the principle of swarm formation are a low cost for a large coverage of the environment and a capacity for redundancy, if an individual is out of service, the system will not be disturbed because another individual can replace it. Social insects such as ants have inspired these algorithms. The main activity of ants is the foraging, without food the colony will not survive long, yet this activity is not so simple to set up. Ants must find food, bring it back to the nest and warn its partners. In 1983, to understand the collective functioning of the ants, Deneubourg offers his experience of the bridge and in [11] the experience is explained. The nest is the source of food are separated by a multi-lane bridge. Deneubourg analyzes the behavior of ants to reach food and finds that the majority of ants take the shortest route.

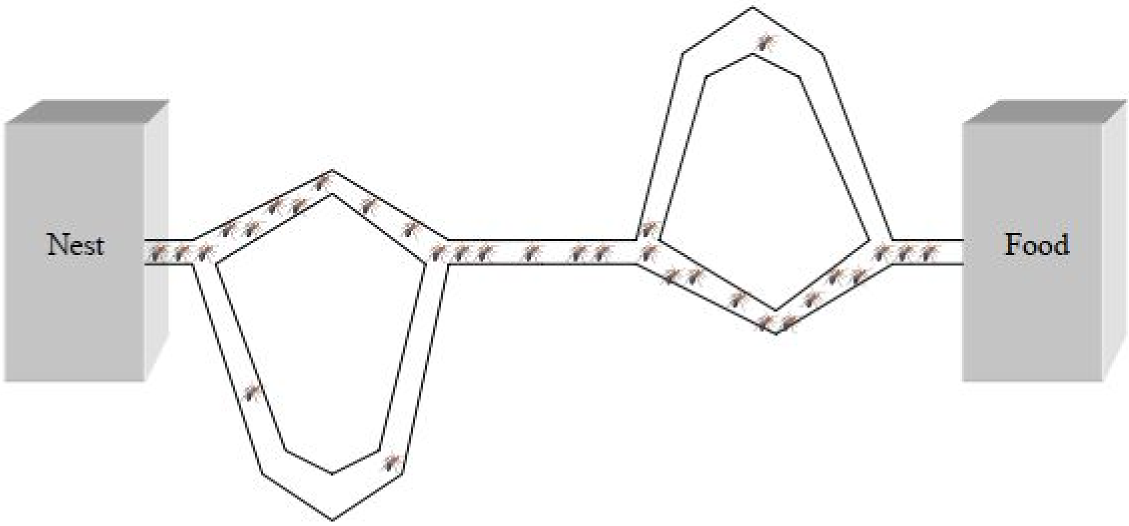

Figure 8. Deneubourg's Bridge experience

Biologists give an explanation for this observation. At first, ants have the same probability to choose between the path on the left and the path on the right. If an ant finds food, she returns to the nest, leaving pheromones in her path. Pheromones attract other ants that pass nearby. The latter will then follow the track and return to the nest, leaving also pheromones and thus strengthen this track. Biologists explain that ants often find the shortest way to food, because the shorter the path between the nest and the food, the more ants will go back on this path and thus increase the rate of pheromones per day. report to a longer path. This phenomenon is reinforced by the property of the pheromones that evaporate over time slowly removing the longest path.

Now apply this principle to UAV behaviors. To apply the foraging, the environment must be mapped. Each point placed contains a value. This value which we will call int corresponds to the pheromones deposited by the ants, they will allow to inform the fleet of drones of the level of interest of this geographical area. If int is less than 0, the area must be absolutely avoided, this may be an obstacle. If int is greater than 0, the zone must be visited, it contains interesting things. If int is 0, the area is uninteresting, it can still be explored if the UAVs have not yet found areas of interest and are in an exploration of the environment. When a UAV finds an area of interest, such as food, it will increase the value of int for that area. If he encounters an obstacle and avoids it with his proximity sensors, he will reduce the value of interest. Now we will see at a tracker robot. His goal is to look for attracting pheromones, so he looks at the mapped map and moves around looking for points where the int value is maximum. If the robot does not find pheromones, it will seek to move to a partner. If no partner is found, he randomly explores the environment to find an area of interest, as the ants do. If all the food has been collected, the area is no longer interesting, in the ant system, the tracks that led in the past to interesting areas were removed because the pheromones evaporate over time. So we reproduce this phenomenon with the UAVs, the value int decreases slowly over time. To maintain an area as an area of interest, UAVs must deposit their pheromones regularly due to their round trips. We theses differents interactions between each ant and the others and each ant with the environnement, a simple bug can have a complex behavior and make impressive things.

D. Others algorithms

The majority of efficient algorithms are bio-inspired, but somes algorithms can give good results to planify a reliable trajectory. In [6] the author speak about the breadcrumb algorithm. It is made of two very distinct parts. Each part is provided by a sub-algorithm. The first is called Explore, it collects information about the reachable space from the starting position and places tags in the search space and memorizes the path between these tags and the starting position. To improve the quality of the information collected, Explore tries to place its tags to cover the maximum of the search area.

The second sub-algorithm Search has for role to find a way between each tag and the target to reach. To understand how the algorithm works, we need to define the role of the preimage. The pre-image is an area of space from which we can reach the target. If Search reaches this area, then a path is found. If Explore places a tag in the vicinity of the pre-image, Search will find a path from that tag to the target, so we will get a path from the robot to the target. So, the breadcrumb algorithm always finds a solution if it exists. The larger the pre-image, the more efficient the algorithm will be, because the greater the probability of placing a beacon in this zone and thus finding a path is great. First, Search was used for trajectory planning but when trying to find the best trajectory planning, two problems occurred. The first concerns local minima. Indeed, the environment, the position of the robot, the position of the obstacles can form situations conducive to local minima.

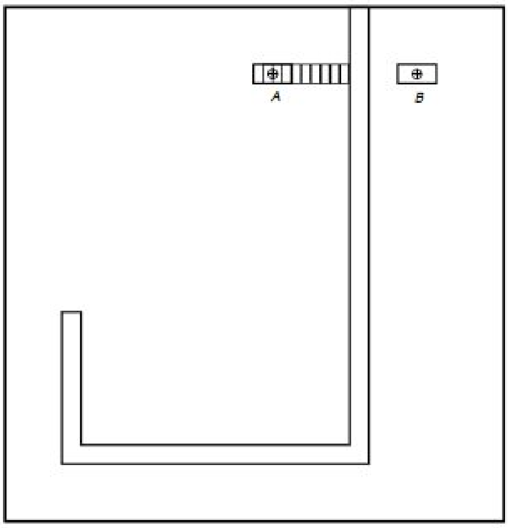

Figure 9. Local minima representation in article [6]

In this configuration, because of the algorithm, the robot A is certain to be closer to the target to reach B. Or the wall prevents to achieve this goal and the algorithm will never find a solution is the robot will remain blocked. The second problem is that with this algorithm, the zone or robot can search is limited by a fixed value. Here is an example on the image below with a search box around the robot in the form of a circle with a radius of 4 steps.

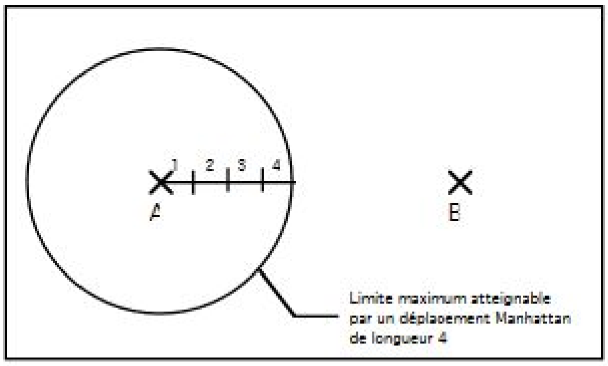

Figure 10. Search area representation in article [6]

The robot A is limited in displacement by the accessibility zone authorized by the algorithm. The target to be reached can therefore be outside this zone. This configuration is a global minimum problem. It is the algorithm Explore which is used to overcome these two problems. One of the difficulties for the Explore algorithm is the trade-off between exploring free space or finding the target to reach. But the algorithm favors the least explored regions. It starts by searching in large areas and as time is reduced this area to explore further. We can see on the example below that in a first step (fig11, fig12, fig13), the beacons are placed as far as possible from each other to be able to extend the search zone to the maximum, then in a second time, when the whole environment is squared, the algorithm now explores in depth, the tags are closer to each other (fig14)

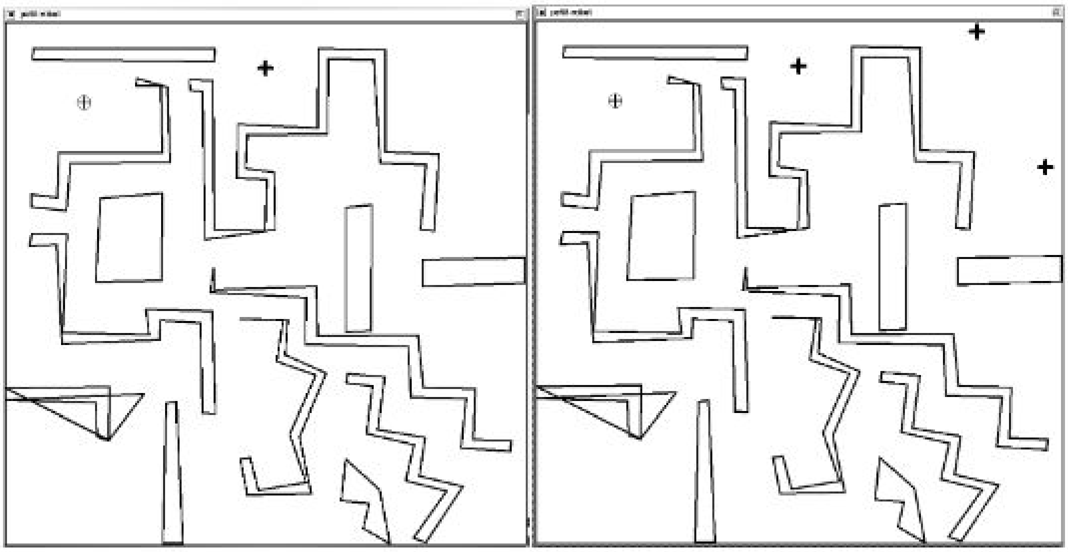

Figure 11 & 12. Exploration and first tags drop *in article [6]*

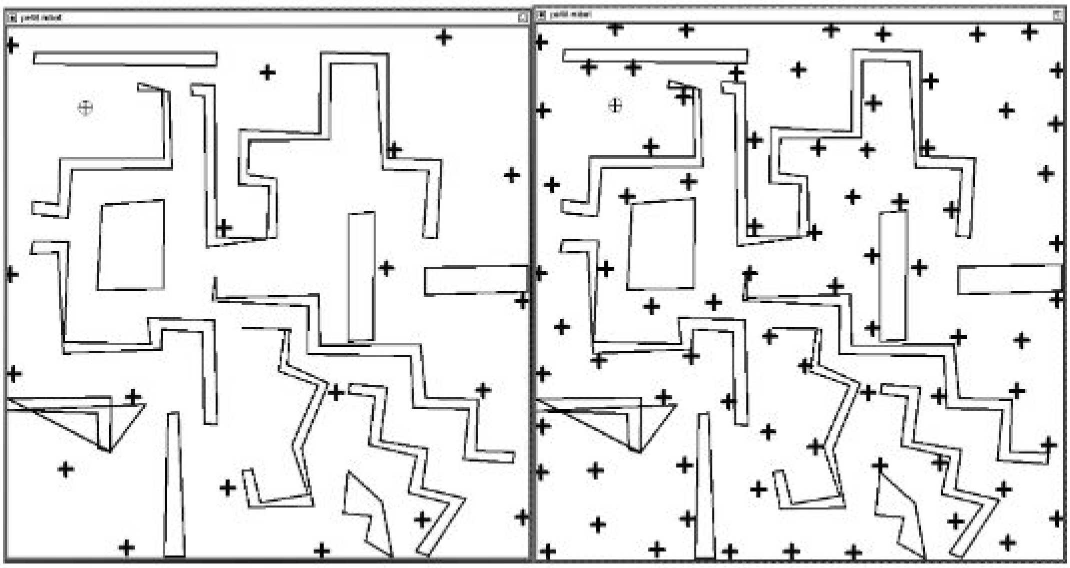

Figure 13 & 14. Behavior between explore space and precision search in article [6]

The breadcrumb algorithm is interesting because it adapts its research according to the complexity of the problem, it always finds a solution if it exists and it does not require the calculation of the configuration space. It comes down to using the tags produced by Explore as input parameter for the Search algorithm. To find the path between the starting position and the target to reach, just go back the tags created by Explore.

E. Algorithms with communication constraints

Until now we have seen algorithms whose main objective is to optimize a path to go from a starting point to a point of arrival while avoiding obstacles. Now we are going to talk about algorithms whose main purpose is to fulfill the communication constraints among UAVs and between UAV-GCS. There are two types of algorithms, those that multiple drones from one point to another and those that post UAVs that will be static or they will have small movements not moving away from the point of origin.

To begin we will talk about the first type of algorithm. In [52], an algorithm that takes as parameter the communication between a UAV and GCS is used. The problem is to find an optimal path, in distance and therefore in time, to rally two points while maintaining during the mission a communication between UAV and GCS. To do so, on the trajectory, there is the presence of a multitude of GCS that one after the other establish the connection with the UAV to have a constant communication throughout the mission. UAVs and GCSs are represented in a Cartesian space like fig. 15 where Uo is the starting point, Uf is the end point, UAV has a position x and y at a time t and a constant height H. The list of GCS and their locations is known before the missions start.

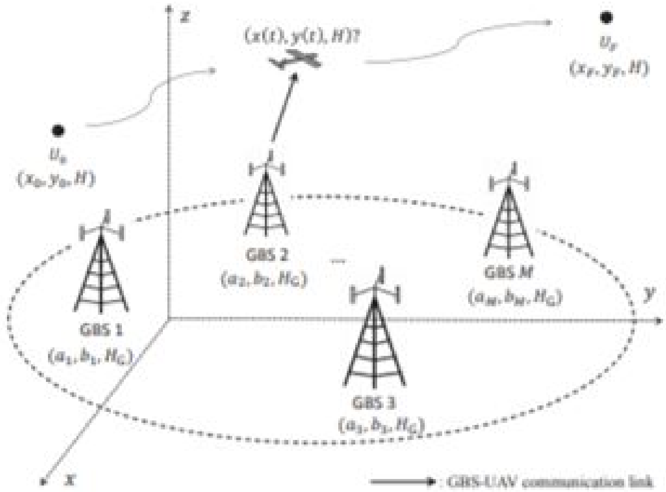

Figure 15.

The last important parameter for this algorithm is a distance d, which corresponds to a radius around a GCS that must always be respected during the mission in order to keep communication between UAV and GCS. This distance is chosen according to a minimum value for the signal-to-noise ratio (SNR). This algorithm gives a solution if there is a list of GBS that can respect this distance from them from the starting point to the point of arrival, otherwise it is not feasible.

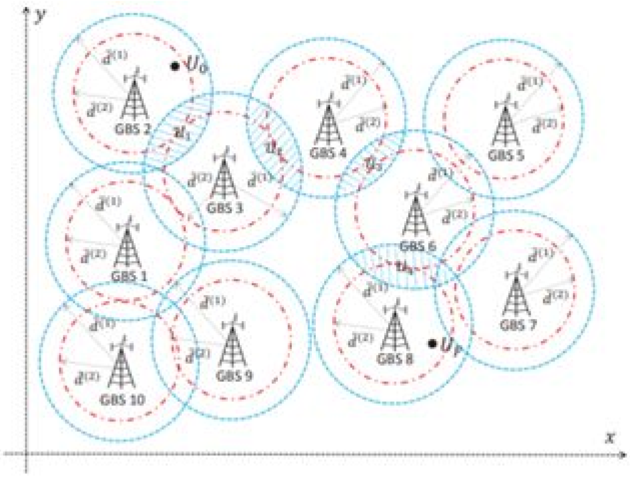

Figure 16.

This image represents several GBS, a starting point Uo and an ending point Uf. Around a GBS, the blue circle represents an area with a radius d1 and the red circle represents an area with another radius d2. With the algorithm, to solve this problem is the same thing as to draw a graph where the GBS are represented by nodes and a direct line is present between two nodes if their zones are connected.
In fig. 17, there is an example of a graph obtained if we take the blue zones. We see that a path exists between Uo and Uf. But in fig. 18, we have the graph obtained with the radius d2 of the red zones. In this case there is no possible solution.

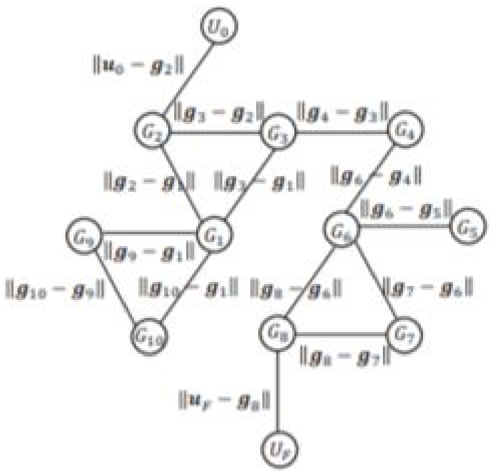

Figure 17. Fig. 16. Blue solution

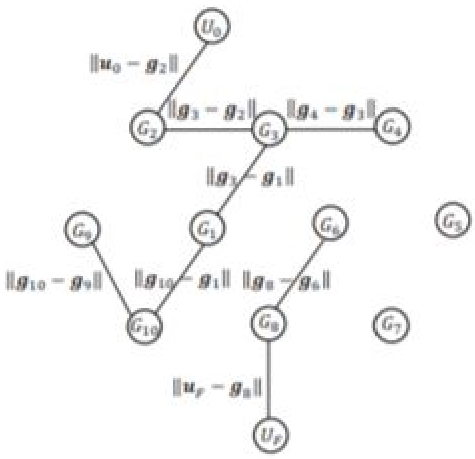

Figure 18. Fig.16 Red solution

So with this algorithm, any trajectory can be used if there is enough GCS to ensure the signal throughout the mission.
If there is not enough, In [53], there is a variation of this algorithm, which takes the same bases except that in this one, the communication between UAV-GBS can be disconnected but only during a time interval chosen beforehand. This offers more possibilities of paths as on the situation of fig. 18 which now becomes achievable. It also allows to find, potentially, better path as in fig. 17, where without disconnection the path is Uo-G2-G3-G4-G6-G8-Uf, but with the second algorithm the path Uo-G3-G6-G8-Uf is better if the time interval of disconnection is respected .

In [50], there is another approach to optimize the trajectory that minimizes a certain cost depending on the amount of served traffic. The approach is based on the Lagrangian mechanics framework.

In [48], [49], [51] and [54], there are other algorithms involved in an already established network of UAVs that exchange with each other and provide a service to ground users. In [48], the goal is to keep a fluid network without saturation due to too much data traffic. UAVs make circular motions, or are static, over an area where they provide their services. The position of the drones is obtained thanks to the algorithm which calculates where they must be according to several criteria, such as the distance between two UAVs which influences the communication among them. This distance makes possible to maintain a stable connection because if it is too small then the capacities of the UAVs to communicate are underutilized, and if the distance is too high then the quality of the communication is degraded very quickly while the delay grew. The effectiveness of the algorithm is based on simulations performed by a computer on the ground thanks to the data sent by UAVs such as GPS coordinates, flight speed, accelerometer, battery remaining. In return the ground station, with all its data, can predict a flight plan.
So, if, as in fig. 19, the communication of the UAV 5 and the UAV 4 is overused, the algorithm will bring one of the two UAVs closer to pass more quickly all the data that transit, and it will restore the formation once the network back to normal.

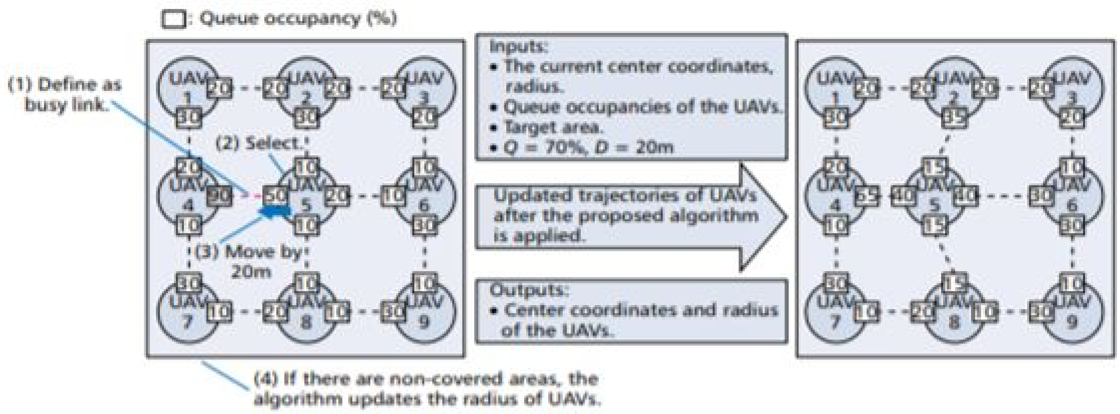

Fig. 19. An example of how the algorithm works.

This kind of algorithm avoids the congestion of a network provided by UAVs by adjusting the distance between two UAVs or otherwise by planning a trajectory to a new UAV that joins the fleet, which allows to regulate data rate transfer.

Algorithm Type	Advantages	Disadvantages	Inspiration
Potential Field	-Give a feasible path autonomously -Not require knowing the movement of obstacles -Very responsive	- Ineffective in large space -APF is sensitive to local minima	Electron moves
Genetic	-Goods performance with low costs -Able to explore a lot of solutions quickly	-Need to find good selection criteria to be efficient -Sometimes, any solutions in a finish time	Bacteria
Swarm	-Fiability (a individual can be down without disturb the system) -Each individual is low cost -Collective performance	-Need much individuals to work (conflict risk) - Sometimes, blocking behavior	Ants, Bees
Breadcrumb	-Adapt to the problem difficulty -Easy to implement (even for parallelization)	-Use many mathematical concept	---

3/ Network

The growing evolution of wireless networks has generated a lot of interest in recent years. Cellular telephony, which has reached a very high level of use, with a need for mobility, has encouraged the development and research of wireless technology. This technology has been divided into two categories: cellular networks with communication infrastructure and ad hoc networks that are wireless, mobile and without fixed communication infrastructure. It is this last category which interests us in this survey. Indeed, the ad hoc network called in our case AANET is the network that intervenes in the UAV scenario because of its permanent mobility. Air vehicle networks are ad hoc multi-hop networks in which the nodes are UAVs. To designate these networks, the term AANET is normally used. The term FANET (Flying Ad hoc NETwork) is also used in the literature. In the absence of a fixed communication infrastructure, the nodes are no longer linked to any access point as in a so-called infrastructure network. The communication among the nodes can be done only through other nodes. Each node has several functions, they play the role of host but also that of router. In an ad hoc network, a node can either communicate directly (point-to-point mode) with any node if that destination node is located in its transmission zone or through several intermediate nodes if the destination node is located in outside his zone of
transmission.

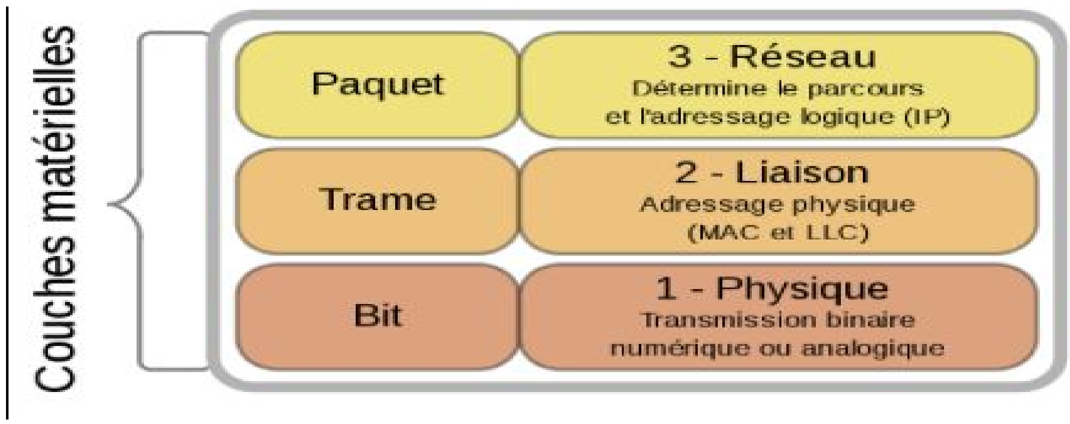

Figure 20. First 3 layers of the OSI model

In the OSI Reference Model, which defines the layered architecture of a network, the main purpose of the data link layer is to transmit data to the physical layer by performing error checking and flow control before providing data. reliable data at the network layer. This last layer builds an end-to-end communication path from communication paths with its direct neighbors. Its main functional contributions are therefore: routing and routing. The network layer is therefore directly concerned by the topology of the network. It is also the last layer supported by all network objects for transporting user data.
This is why in this part we will be interested in these 3 layers mentioned above. We will therefore firstly focus on the data-link layer, and more precisely on the technologies that are used, then we will see in more detail the topology and training in an AANET network. Finally,

in a final part, we will discuss routing in a communication involving several UAVs or between a UAV and a ground base station. We will unveil the main routing protocols used in UAV scenarios.

1) Data link (layer 1 et 2)

A. Network technologies

Defined by the Institute of Electrical and Electronic Engineering (IEEE), the IEEE 802.11 standard is a family of standard protocols [37]. IEEE 802.11 standards, commonly known as Wi-Fi, define the specifications for creating wireless local area networks (WLANs). This standard covers the physical layer and the MAC sublayer of these networks.
The 802.11 standard has two modes of operation similar to network categories: a mode with infrastructure (static scenarios) and a mode without infrastructure (dynamic scenarios). In our case, it is this second mode that will interest us.

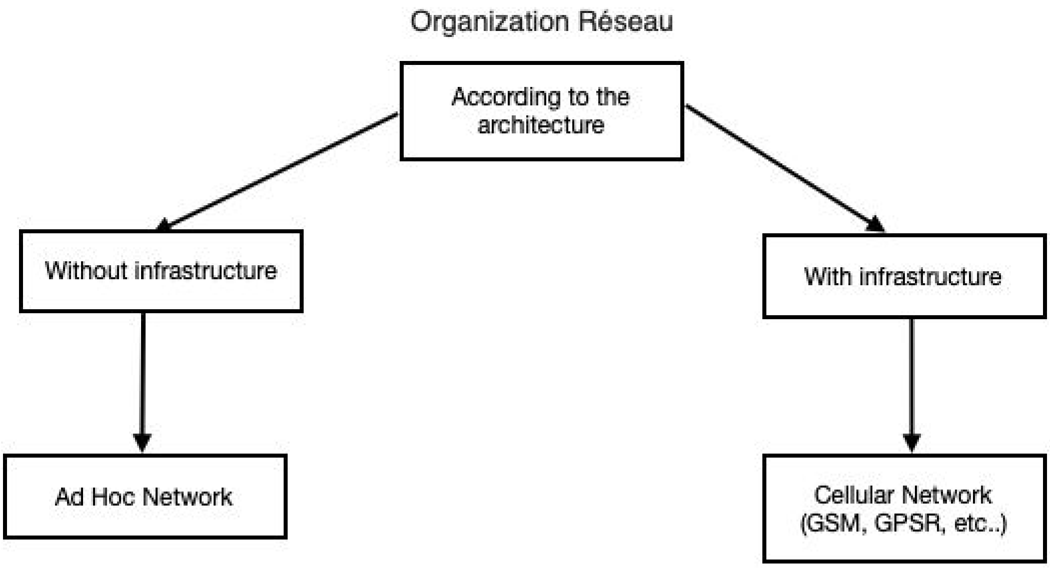

Figure 21. Network Organization

This standard family therefore includes several versions, some of which have been widely used for AANETs. The first versions of the IEEE 802.11 standards, such as IEEE 802.11b, mainly target static scenarios, that is to say when the nodes of the network have a very weak or nonexistent mobility. An example of this situation is a desktop computer connecting to a fixed Wi-Fi access point.

Through development and research, new versions of the IEEE 802.11 family have emerged over the past two decades. Thus we saw the light of day; IEEE 802.11a, IEEE 802.11g, IEEE 802.11n and IEEE 802.11ac. With the increase in the number of IEEE 802.11-compliant portable devices, such as smartphones, scientists have had to start taking into account high-mobility nodes in many of these versions. For example, we can mention IEEE 802.11a and IEEE 802.11p which are standard versions compatible with mobility. This situation has logically favored the use of IEEE 802.11 technologies in AANETs.

But the IEEE 802.11 standard is not the only wireless technology used for UAV-UAV communication links in particular. Thus, we also find the use of 802.115.4 technologies and infrared technologies in the literature. We will see in the first place, the specific technologies of the 802.11 standard used in the AANET networks then the 802.115.4 technology and finally the infrared technology.

In the case of performance studies, we will mainly look at the bit rate and transmission range of each technology when it is in our possession.
To get a first idea, we can see that in [28], the standards used are IEEE 802.11ac and IEEE 802.11n. In this review, these technologies allow communication among several UAVs but also between a UAV and a base station on the ground. IEEE 802.11n is also studied in the works [17].

IEEE 802.11ac is an IEEE standard wireless Wi-Fi family wireless standard that allows high-speed wireless connection to a local area network and uses only a 5 to 6 GHz frequency band. Thanks to the development of the 802.11ac standard, new technologies have been introduced:
A channel width of 80 MHz, up to 160 MHz. In 802.11n, the maximum was 40 MHz.
Use of different spatial flows in MIMO
Support of up to 8 spatial streams, compared to 4 in 802.11n
256-state QAM modulation versus 64 states in 802.11n
Some non-standard implementations provide 1024-state QAM modulation, which is 25% higher.
Standardized beamforming. In comparison, 802.11n beamforming did not allow compatibility among different vendors equipment.
The IEEE 802.11n experiments are performed under different scenarios: direct communication between a UAV and the earth station, between an UAV serving as an access point and another UAV and the base station on the ground but also between two UAVs and a station ground being all three nodes of a mesh network.

IEEE 802.11n is an amendment to the IEEE 802.11 standards group (Wi-Fi) for wireless data transmission. The IEEE 802.11n standard achieves a theoretical rate of up to 450 Mbit / s (in MIMO 3x3: 3 antennas) on each of the usable frequency bands (2.4 GHz and 5 GHz). It improves the previous standards: IEEE 802.11a for the 5 GHz frequency band, IEEE 802.11b and IEEE 802.11g for the 2.4 GHz frequency band. The standard provides improvements over IEEE 802.11a / b / g through the following technologies:
MIMO (Multiple Input Multiple Output), which allows multiple antennas and several space transmissions to be used simultaneously for receivers and transmitters.

Grouping 2 radio channels doubles the peak bandwidth.

For the IEEE 802.11n mesh configuration, the standard implementation of the IEEE 802.11s mesh is used. IEEE 802.11s is a standard amendment that extends the lower layers of other IEEE 802.11 versions to support mesh topology configurations.

In [28], in the case of an indoor scenario, it appears that IEEE 802.11ac has higher data rates and better throughput compared to IEEE 802.11n.
While in external scenarios, including higher mobility characteristics, IEEE 802.11ac displays a significant decrease in throughput in the event that the UAVs move away from the base station. Thus, we can see in this review that for the use of IEEE 802.11 ac in AANET networks, research must necessarily be pursued.

Another standard appears in [64] for AANET networks, this is the IEEE 802.11b standard. In this document, two scenarios are mainly tested with the IEEE 802.11b standard.

IEEE 802.11b is an amendment to the IEEE 802.11 (Wi-Fi) group of standards for wireless local area network (WLAN) networks that allow data transmission at speeds up to 11 Mbps on the band frequencies of 2.4 GHz.
IEEE 802.11b allows point-to-multipoint line-of-sight transmission over distances up to 300 meters with signal quality-dependent rates of 1, 2, 5.5 or 11 Mbit / s. This standard uses the CSMA / CA media access method specified in the IEEE 802.11 basic standard and the MAC sublayer of the data link layer of the OSI model. At the PHY layer, it uses Direct Sequence Spread Spectrum (DSSS) technique, BPSK and DQPSK modulations for 1 and 2 Mbit / s rates, CCK (Complementary Code Keying) modulation and optionally by switching the Packet Binary Convolutional Code (PBCC) coding scheme for the 5.5 and 11 Mbit / s rates. This makes this standard incompatible with the IEEE 802.11a standard which uses the OFDM technique and the 5 GHz frequency band.
The operational frequency range is 2.4 to 2.4835 GHz and corresponds to the ISM free band (Industrial, Scientific and Medical). The authorized 83.5 MHz frequency band in Europe is divided into 13 separate 5 MHz channels. Each occupies a frequency range of +/- 11 MHz around its center frequency, a range of 22 MHz, so the channels overlap widely.

The first scenario in [64] uses UAVs to connect two disconnected halves of a terrestrial network.
The second scenario uses UAVs to provide communications from a terrestrial base station to remote locations. This presents us with the creation, through relay operations, of an ad hoc multi-hop network. The performances of the IEEE 802.11b standard are thus presented according to the bit rate and the quality of transmission. But other performance criteria are considered in this review, such as network congestion, connectivity, and node failure. The simulations of the two scenarios in this document show us that the performance of the network depends essentially on the location of the UAVs compared to the others and the terrestrial node.

In order to provide connectivity to remote end-to-end systems, an AANET network is used in [23]. In this review, UAVs establish a wireless mesh network acting as a terrestrial node relay. UAVs have two wireless interfaces here.

IEEE 802.11s is used for the first interface. Each node then serves as an access point. This interface is used to connect UAVs to each other.

IEEE 802.11g is used for the second interface. In this case, this interface allows the ground nodes to connect to the UAVs.

IEEE 802.11g that has not yet been presented is an amendment making modifications and additions to the IEEE 802.11 standard. The IEEE 802.11g standard specifies a wireless data transmission mode at rates up to 54 Mbit / s in the 2.4 GHz frequency band.
The IEEE 802.11g standard includes, at the PHY level, the OFDM digital modulation method recommended by the IEEE 802.11a standard so as to reach a theoretical peak rate of 54 Mbit / s. It also incorporates the CCK technique (Complementary code keying) and the Packet Binary Convolutional Code (PBCC) coding scheme specified by the IEEE 802.11b standard. By this combination of methods, IEEE 802.11g is backward compatible with IEEE 802.11b but not with IEEE 802.11a which defines a wireless network in the 5 to 6 GHz frequency band.

The methods of spread spectrum, modulation and coding of digital signals used by the standard allow a range of bit rates from 1 to 54 Mbit / s in the 2.4 GHz frequency band, depending on the propagation conditions radio. These methods can be broken down as follows. Those enabled by the new OFDM modulation using multiple subcarriers (48 useful) and on each subcarrier QAM modulations:
BPSK, QPSK, 16QAM or 64QAM: combined with the OFDM multiplexing method to have the sequence of rates 6, 9, 12, 18, 24, 36, 48 and 54 Mbit / s.
Those supported for backward compatibility with 801.11b (spread spectrum technique DSSS):
CCK: coding modulation method allowing 4 bits to obtain a rate of 5.5 Mbit / s and 8 bits a rate of 11 Mbit / s.
QPSK: Modulation method that allows to obtain a bit rate of 2 Mbit / s.
BPSK: modulation technique allowing to have a flow of 1 Mbit / s.

In this same journal, the researchers present the results of two scenarios.
The first is an airborne relay scenario with a single UAV. While the second is an airborne relay scenario with several UAVs. UAVs also have the ability to find ground nodes to establish a communications link.

The IEEE 802.11a standard has not yet been presented. The use of it appears in [62] to perform a performance analysis operation in terms of speed and quality of transmissions. IEEE 802.11a is an amendment to the IEEE 802.11 standard group (Wi-Fi) for wireless data transmission at speeds up to 54 Mbit / s over the 5 GHz frequency band.

IEEE 802.11a is part of the Wireless Local Area Network (WLAN) family of standards. This defines the PHY and MAC layers corresponding respectively to the physical layer and link of the ISO OSI model.

The OFDM multiplexing system uses here a division of the digital signal, to transmit and receive, in 52 sub-carriers occupying a band of frequency of 20 MHz of width (one channel), has a theoretical maximum flow of 54 Mbit / s, in reality about 30 Mbit / s because the channel "half-duplex" can be shared by several transmitters which requires an arbitration protocol (allocation of the frequency band to a single transmitter at a given time). This rate can be reduced to 48, 36, 24, 18, 12, 9 or 6 Mbit / s depending on the quality of the radio signal (interference, distance attenuation). The subcarriers are modulated either by phase change (BPSK or QPSK) or quadrature amplitude modulation (16-QAM or 64-QAM).
This technique recommended by the IEEE 802.11a standard makes it possible to achieve a reliable and safe connection over a low frequency band. However, this makes the standard incompatible with the IEEE 802.11b and IEEE 802.11g standards that use the 2.4 GHz band. This 802.11a standard is gradually being replaced in the 5 GHz band by 802.11n and 802.11ac (2014) Wi-Fi standards, which offer higher bit rates.
The IEEE 802.11a family operates in the 5.2 GHz band and aims to achieve higher data rates and reduced interference compared to IEEE 802.11b / g.

In [23] several scenarios are tested. The first is a scenario where a UAV serves as an access point between another UAV and the ground station. the second is a scenario where two UAVs and the ground station are mesh nodes. These two scenarios are obviously located in the external environment.

When comparing these two scenarios, the results show that the mesh configuration uses the direct link between the UAVs and the ground station, to the extent of its availability. This means that when a UAV is separated from the ground station and the direct link is still available, but intermittently, the mesh configuration will favor the direct link on the two-hop path, which will result in lower throughput . This is because the mesh configuration, implemented using the IEEE 802.11 standard, prefers available paths with fewer jumps, regardless of bit rate or link quality. In this situation, the configuration of the two-hop infrastructure works better in terms of throughput.

IEEE Standard	Year adopted	Frequency	Max. Data rate	Max. Range
802.11a	1999	5 GHz	54 Mbps	400 ft.
802.11b	1999	2,4 GHZ	11 Mbps	450 ft.
802.11g	2003	2,4 GHZ	54 Mbps	450 ft.
802.11n	2009	2,4 / 2,5 GHZ	600 Mbps	825 ft.
802.11ac	2014	5 GHz	1 Gbps	1,000 ft.

Figure 22. Table of the various technologies of the 802.11 standard

Now that we have seen the IEEE 802.11 technologies that can be used in AANETs, we will see the IEEE 802.15.4 technology and infrared technology for communication in an AANET network.

802.15.4 is a communication protocol defined by the IEEE. It is intended for wireless LAN networks of the LR WPAN (Low Rate Wireless Personal Area Network) family due to their low power consumption, their short range and the low speed of devices using this protocol.
We can quote as one of these technologies: ZigBee. This standard is used to create WSN applications.
We also have XBee as the 802.15.4 technology. XBee is a commercial implementation similar to ZigBee.

In [65], an antenna array uses the IEEE 802.15.4 standard. The scenario presents five UAVs that are used as sensing devices, which allows the network to be considered as an aerial WSN. The UAVs are equipped with 2.4 GHz class XBee Pro ZigBee radios. Thus we can see through the reviewed journals and their results that the main problem related to the use of the IEEE 802.15.4 standard in an AANET network is its low data rate. This communication technology appears more for virtual storage networks; These networks are actually focused on saving energy consumption. In addition, another disadvantage of this technology is that the transmission range is of the order of a few tens of meters to 100 m. While this may seem important to some, we need to realize that this can become a major drag on some applications. Take an example where UAVs execute missions separated by distances greater than one hundred meters. In this context, the IEEE 802.15.4 technology can not be used.

Infrared wireless communications [are for their part studied in [24]. Infrared communication was one of the first widely used optical communications. Indeed, this communication has a number of advantages. The first is that they are inexpensive communication systems. The second is that the link bit rate and aggregated system capacity can be maximized in comparison with radio frequency technologies. However, they present today a lot of inconveniences like the inability to cross opaque objects like walls if we take back our scenario of UAV in a city. There are also many sources of thermal noise. The most concrete example is sunlight during the day.

In [25] a communication based on a navigation algorithm for a land robotics swarm is presented. An infrared range communication system (IrRB) is implemented for robot-to-robot communication links. In the case of aerial robots, infrared communications are generally used for positioning in an indoor environment.

In addition, the researchers present a scenario consisting of a group of 2 to 5 UAVs performing assembly and construction tasks in an indoor environment in [64]. « Each drone has several passive infrared markers stuck at different points in its frame. A system of 20 VICON infrared cameras is used to detect the position and heading of each UAV. This information is then transmitted to a central controller that calculates and controls the trajectories of each UAV. »

Although UAVs are passive in this communication system, infrared technology makes possible the inland navigation of UAVs.
Infrared communications are commonly used as sensing devices rather than as communication technology for multi-robot systems. However, we can see through the reviewed journals that indoor scenarios are ideal spaces for using infrared communication technologies.

GPS-based systems are not suitable for indoor scenarios. For this reason, the use of infrared communication technologies for domestic drone networks should not be neglected and should be further investigated.

Network	Technology	Communication device	Computing platform	Usage
AANET	IEEE 802.11s	OM1P from Open-Mesh[a](universal 802.11b/g interface)	PC Engines Alix boards[b]	- Connect separated ground nodes multi-hop relaying mesh network
	IEEE 802.11b	- 2.4 GHz 802.11b card Fidelity-Comtech bidirectional amplifier	Soekris single board computer	- UAVs and ground nodes in several configurations ○connecting ground nodes multi-hop mesh network
	IEEE 802.11n	Compex WLE300NX 802.11abgn mini-PCIe	Intel Atom 1.6 GHz CPU with 1 GB RAM	- AANET single-hop and two hop performance analysis with the ground station ○Infrastructure Mesh
	IEEE 802.11ac	Compex WLE900N5-18 miniPCIe Doodle Labs ACM–5500–1 802.11ac 5 GHz miniPCIe		
	IEEE 802.11a	Compex WLE300NX 802.11abgn mini-PCIe modules	Intel Atom 1.6 GHz CPU with 1 GB RAM	- Two hop analysis - Infrastructure and mesh configurations Connections with the ground station
	IEEE 802.15.4	XBee Pro Zigbee class 2.4 GHz radios (Maxstream)	CUPIC avionics board (Microchip PIC18F8722 8-bit)	- Generic monitoring tasks: ○Temperature ○Gases Other
	Infrared	VICON system[c]	Intel Atom Processor Z530	Collaborative assembly and construction tasks

Figure 23. Summary table of the different technologies involved in AANET networks and their characteristics

B. Formation control

The formation and its control are just as important as the technologies used because if each UAV acts alone, it will quickly become chaos.
First of all, there are many formations possible for a fleet of UAVs. There are basic formations, and formations, as said in the introduction, inspired by the movement of animals such as birds or fish. Each has its advantages and disadvantages depending on the terrain where the mission of the group takes place. Even if the formations are very numerous, there are some which are very used as line shape for the raking, column shape for the narrow places, V shape which offers a more peripheral vision and the formation in diamond which is a variant from that in V.

Formation control must follow several rules:
• **Inter-vehicle collision avoidance**: Vehicles in the formation need to consider each other as additional moving obstacles and take appropriate evasive actions.
• **Coordinating of multiple vehicles**: The designed controller should avoid the situation that waiting or coming to full stop occurs due to one or more vehicles in the formation lagging behind.
• **Avoiding deadlock situation**: the movement of the vehicles should be controlled in such a manner that the scenario where one or more vehicles block the paths of others does not occur.

There are three widely used formations controls: leader / follower, virtual structure training control (VS), behavior-based formation control.

<u>Leader/follower:</u>
This control is based on the principle that a UAV is selected to be the leader and all others must follow it. This method makes it possible to have a minimum of information exchanged since each UAV will have a link only with the leader and not with the others. It is easier and faster to set up, it just need to select a UAV on which all others will copy it which leads to good communication efficiency since the UAVs communicate with the leader. But on the other hand, it creates a strong dependence on the performance of the leader and it must be able to communicate perfectly otherwise the follower will not know what to do. If ever the UAV leader has a technical problem or if it crashes it must be another UAV that can quickly take its place. There is also a disadvantage in the feedback of the followers, a faulty vehicle will not be detected by the other vehicles.

<u>Virtual Structure formation control (VS):</u>
UAVs have a rigid geometrical formation, this minimizes positional errors among them. The formation is made according to the mission, the terrain, the vehicles. The displacement is done by calculation, according to the formation and the vehicles. First the virtual structure is moved and calculated, then the vehicles move to reach the point assigned to them.

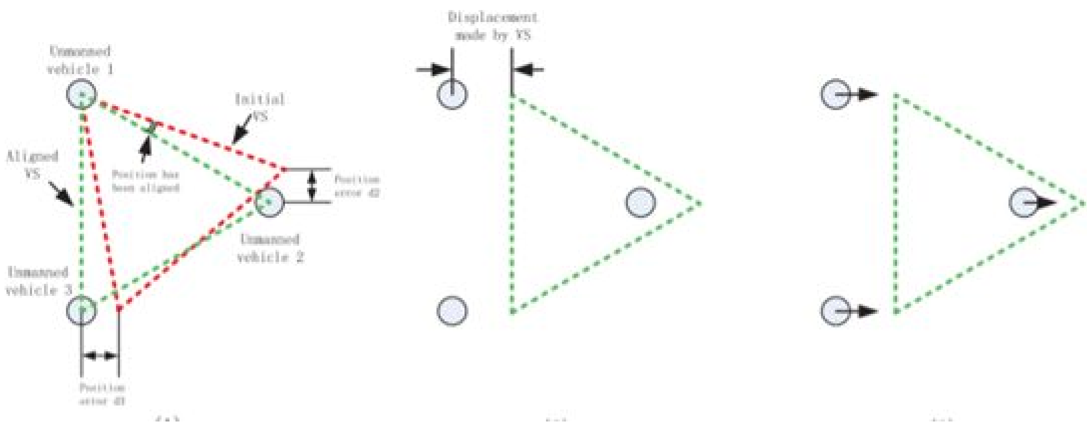

Figure 24. Example of VS movement

This control allows better communications compared to the leader-follower. It minimizes the risk of breaking the formation or if a vehicle has a problem since unlike the leader / follower a faulty vehicle will be more easily detectable. But this control is more rigid to avoid obstacles because of the rigid disposition of the UAVs. It has the same disadvantage as leader-follower on the communication, it must be irreproachable otherwise it causes problems for example if information does not arrive in time, it can lead to a shift in training resulting in a collision.

<u>Behaviour-based formation control:</u>

The last type of formation control is behavior-based using a vector-weighted hybrid control function that typically takes four parameters into account: move-to-goal (uMG), avoid-static-obstacle (uAO), avoid-robot (uAR) and maintain-formation (uMF).

u = a1 · uMG + a2 · uAO + a3 · uAR + a4 · uMF

where a1, a2, a3, a4 are the weighting gains for controllers with high gain value representing high importance for the corresponding behaviour. The results show that this type of control is better than the previous ones to maintain training and avoid obstacles. it can accomplish a number of different requirements through one control command. But the lack of system stability makes it easier to use.

So a hybrid approach is getting more and more uses where the formation is maintained by the leader / follower while the behavior-based scheme focuses specifically on the motion planning of individual vehicles.

Table I. Comparison of formation control strategies.

Methods	Advantages	Disadvantages	Formation maintenance types	Platforms
Leader–follower[45,47,48]	1. Easy to be designed and implemented 2. Efficient communication within the system	1. Highly dependent on the leader vehicle 2. Lack of the feedback from the follower to the leader	Type 1, Type 2 and Type 3	Widely adopted across various platforms
Virtual structure[54–56]	1. Good performance in shape keeping 2. Good representation of the relationship and the coordination between each vehicle in the formation	1. Not flexible for shape deformation 2. Not easy for collision avoidance	Type 1 and Type 2	Most applications seen on mobile robots. Less application on unmanned vehicles
Behaviour-based[57,59,61]	1. Capable of dealing with multi-task mission	1. Not easy to mathematically express the system behaviour 2. Difficult to prove and guarantee the system stability.	Type 1, Type 2 and Type 3	Mobile robots and UGVs are two popular platforms

Figure 25. Comparison of formation control strategies.

2) Routing (layer 3)

In this part, we will focus on the layer 3 corresponding to the network layer and more particularly to the protocols used for the scenario application comprising UAVs. First, we will present the routing protocols involved in communications among several UAVs, so we will detail their principles, the technologies needed for their use, the results of their simulations but also their possible applications. We will also see, in a second time, the protocols of the network layer intervening in a network between a UAV and a base station on the ground. In the same idea as the previous part we will support the principle, characteristics, evaluation, and possible applications of each routing protocol involved in this type of network. To begin, we must categorize, sort the different routing protocols before presenting which will be specific to the typical networks among several UAVs. A routing protocol allows UAVs on the same network to communicate information about the topology and the state of the links with each other. This communication keeps the routing tables up-to-date and determines the best routes based on network congestion. The list of the best paths for each destination is called the Routing Table. The dynamic routing that is the routing that interests us here, allows an automatic maintenance of the routing of a network, without human intervention, even in case of failures of some routers. It helps to increase productivity and responsiveness to changes. Unfortunately, this routing is complex to implement because of the initial configuration tasks of the protocol used. As a result, routing protocols can be organized according to different aspects. Thus in the literature, two classes of routing protocols appear to us.

The first category can be defined as the broadcast protocols, ie those in which each node of the network must receive a given packet. This packet is sent by a source node. The most common classification defines two main categories. This classification is related to the guarantee provided by routing protocols on the arrival of packets sent by a source node to a destination node. These two main categories are, on the one hand, the category of proactive protocols and, on the other hand, that of reactive protocols.

Reactive protocols must systematically request their routes by flooding the network with their request and receiving the associated response. The use of a protocol of this category within an AANET implies the construction of a topology in the area concerned only when the need arises.

Proactive protocols ensure that each node has the necessary topology information at all times to build a route to any other point on the network. This is made possible through regular updates on the topology.

Nevertheless, a third category could be added to this classification. This category would correspond to that of the geographical protocols [14]. These protocols route the packets to the geographic information of neighboring nodes. In addition, a fourth category would appear taking into account the protocols combining the advantages of reactive and pro-active protocols, they are hybrid protocols, such as Zone Routing Protocol (ZRP) and TORA that will not be detailed here. In order to compare the performance of routing protocols designed for typical UAV networks, some work on this topic includes static protocols (from fixed infrastructure networks) as a reference. The latter category would constitute the second category of routing protocols.

Routing algorithms used in UAAV networks.

Network	Type	Routing protocol		Technology
Aerial	Broadcasting	Flooding		IEEE 802.15.4
	Proactive	OLSR	Pure OLSR	IEEE 802.11n
			P-OLSR	IEEE 802.11n
		BATMAN		IEEE 802.11n
		GPSR	Pure GPSR	IEEE 802.11a
			MPGR	
	Reactive	AODV	HWMP	IEEE 802.11s
			Pure AODV	IEEE 802.11n
			RGR	IEEE 802.11
		GGF		IEEE 802.11
		DSR		IEEE 802.11b
	Geographic	Greedy Geographical Routing		IEEE 802.11n
		A-GR		IEEE 802.11
	Not specified	Not specified		IEEE 802.11g

Figure 26. Table table showing the different routing protocols for AANET

We must emphasize that these conventional routing protocols are generally very poorly suited to UAV-type networks, as they are unstructured, experience spontaneous extensions / reductions and are by nature unreliable.

To measure the performance of a routing protocol, we need to define what is a "good" routing protocol. It must have several characteristics. First, it must be able to adapt to the evolution of the network. Scalability defines the maximum size of a network based on the routing protocol that is deployed. The larger the network, the more scalable the routing protocol must be. It must have a simple configuration. It is also noted on its speed of convergence. Convergence speed is the speed at which routers in the network topology manage to share routing information and have a consistent knowledge base. The faster the convergence, the more the protocol is recommended. Routing loops can occur when inconsistent routing tables are not updated due to slow convergence in a changing network.
The objectives of a router are also multiple:

-Optimization: selection of the best roads

-Eliminate routing loops (circular routes)

-Efficiency: low bandwidth and CPU consumption

-Stability: convergence and reconfiguration after

-Simplicity: simple configuration

A. Network between UAVs

As we have seen through our studies, every search work on UAV networks uses a different routing protocol in most journals. The applied protocol is selected in relation to its chances of functioning correctly in the designed scenario application. Normally, the most commonly cited and experienced routing protocols for ad hoc networks are those that appear most often in the literature as presented in journals [16].
However, it should be noted that several efforts are underway to develop new routing protocols specifically adapted to UAV networks [28].

We will present the different routing protocols according to our classification, we will firstly study the reactive protocols and then the pro-active protocols.

1/ Reactives Protocols

For routing in the AANETs in [28], a mesh network is built among the UAVs and a base station on the ground. The IEEE 802.11s implementation is used for building the mesh network. For routing purposes, the IEEE 802.11 standard uses the Hybrid Wireless Mesh Protocol (HWMP). HWMP is a variant of the well-known Ad Remote Demand Vector Routing Protocol (AODV) [34].

We will explain the HWMP protocol in the next section for networks between a UAV and a ground base station. Nevertheless, we must introduce the general principle of the AODV protocol. AODV is a routing protocol for mobile networks (ad hoc network). It is able to communicate according to modes: unicast communication and multicast communication. This protocol is loop-free, self-starting and accommodates a large number of mobile (or intermittent) nodes. When a source node requests a route, it creates the routes on the fly and holds them as long as the source needs them. AODV builds a tree for multicast groups. The advantages of this routing protocol are multiple. It is primarily energy efficient and secondly it does not require a lot of computing power. It is also easy to install on small mobile devices. The AODV protocol is based on the DSDV and DSR algorithms that we will see later. The cost of maintaining the routing tables is important. It takes an advantage over AODV in small and medium sized networks.

AODV defines five distinct types of messages, referenced to the Internet Assigned Numbers Authority (IANA), transmitted via the UDP port 654. Among these messages are the requests RREQ (route request) and the responses RREP (route reply) which allow to build its routes used to relay information on the network. When a source node wants to establish a route to a destination source for which it does not yet know a path, it broadcasts a packet RREQ. If an RREP response is received then the route discovery operation is complete. Otherwise, after a NET_TRANVERSAL_TIME timeout, it rebroadcasts the RREQ message and waits for a period longer than the first one. If there is no RREP response, this process can be repeated until RREQ_RETRIES times (by default RREQ_RETRIES = 210). If there is still no response after the three (or RREQ_RETRIES + 1) attempts, the route search process is aborted. A new route request will be initiated after 10 seconds. A node receiving a packet RREQ will then issue a packet RREP (route reply) if it is the destination or if it has a route to the destination with a sequence number greater than or equal to that of the packet RREQ otherwise it rebroadcast the packet RREQ . The nodes each keep a record of the source IPs and broadcast identifiers of the RREQ packets. In the event that they receive a RREQ packet that they have already processed, they delete it. Once the source has received the RREP packets, it can begin sending data packets to the destination. If, later, the source receives a RREP containing a sequence number greater than or equal to, but with a smaller number of hops, it will update its routing information to that destination and start using the best route. A route is maintained as long as it continues to be active, that is, as long as data flows between source and destination. The link expires when there is no more data in transit on the link and after a delay called ACTIVE_ROUTE_TIMEOUT. In the event of a link break, the end node sends a Route Error (RERR) packet to the source node to warn that the destination is now unreachable. If the source node still wants to get a route to that destination, it must restart the route discovery process. The AODV routing protocol is used in [27] with IEEE 802.11n technology for these previous layers.

In the journal [18], the AODV routing protocols are improved. Indeed, in the improvement of this protocol, geographic information on the request packets during the formation of the route are included. The goal of the Reactive-Greedy-Reactive (RGR) algorithm is to speed up the recovery process after a predetermined route is broken between two UAVs.

The AODV-RGR protocol is a UAANET routing protocol that combines the reactive and geographical modes. AODV is used as a reactive part and GGF (Greedy Geographic Forwarding) for geographical concerns.

RGR is based on the following assumptions: Each UAV can receive its position, its neighboring position and the destination position without implementing a position-sharing mechanism. The position sharing process is performed by incorporating position information into the request packet upon discovery of the neighbor. Indeed, reactive routing is mainly used and greedy transfer is enabled only in cases where the source of the UAV can not find a path to the destination. During the discovery phase of the route, the source node sends a request packet RREQ in which the node adds its position information, so that the neighbor and the destination are informed of its location. This is also the case with an RREP response packet. In addition, during a data transmission phase, AODV transmission techniques are used. If there are link breaks, the routing protocol uses the greedy transmission algorithm in which the packet is sent to the neighbor closest to the destination. In the meantime, a route request is made to find a new route.

A notable advantage of this routing protocol lies in its property of being executed without position sharing technique. Another advantage is that RGR handles frequent changes in the UAANET topology because it can switch to another mode that takes into account link failures.

However, the disadvantage is that network congestion can be created due to the size of the overhead and the increased number of control packets. The idea is to have a table of neighboring nodes, including their coordinates. When a route is detected as unavailable, the source node selects a node near the destination position to restore the interrupted route as soon as possible. This technique is derived from the Greedy Geographical Forwarding algorithm.

The Geographic greedy forwarding as a simple, efficient and scalable strategy is the most promising routing scheme for wireless ad-hoc sensor networks (WASN). In such a scheme, the routing path from the source to the destination is determined by selecting the transfer node at each intermediate node in a fully distributed manner. The packet is transmitted hop by hop along such a path.

The authors still compare in this same review, the proposed RGR algorithm with the AODV and GGF approaches, showing better results in terms of delay in communications.

Another reactive routing protocol is used in [44]. This is Dynamic Source Routing (DSR) among all network nodes, whether they are antenna or ground nodes.
Dynamic Source Routing (DSR) is a routing protocol for wireless mesh networks. It is similar to AODV in that it forms a demand-driven route when an element of the network solicits it. However, it uses source routing instead of relying on the routing table of each intermediate router. Determining source routes requires accumulating the addresses of each router between source and destination during route discovery. Path information is cached during the discovery of the route. Learned paths are used to route packets. For this, routed packets contain the addresses of each router that the packet traverses.AODV has potentially lower cost routing than DSR. Dynamic Source Routing (DSR) is similar to AODV in that it forms an on-demand route when a computer wants to transmit. The DSR protocol is not very efficient in large networks as each source must have the vision of the network. The DSR routing protocol is used with the IEEE 802.11b standard.

In [23], the authors do not use any specific routing protocol in their searches. Instead, this work is intended to become a platform for testing different routing protocols in UAV networks. This work nevertheless uses the IEEE 802.11s standard.

2/ Pro-actives Protocols

In the journal [36], two different routing protocols are tested and compared: Optimized Link State Routing (OLSR) and OLSR Predictive Routing (P-OLSR). We are going to watch the OLSR protocol first. OLSR (Optimized Link State Routing Protocol) is a routing protocol for mesh, wireless or mobile networks. The protocol is an optimization of the pure link state algorithm. The key concept used in the protocol is the use of multipoint relays (MPRs). The MPR set is chosen so that it covers all the nodes that are two jumps away. It works as a proactive protocol, topology information with other nodes in the network is exchanged regularly. In OLSR two types of messages are introduced: "Hello" and "TC" (topology control). Each node broadcasts a Hello message containing information about its neighborhood and the state of the links. The exchange of these messages makes you aware of your neighborhood. To build the tables necessary for routing packets, each node periodically sends a packet TC containing the list of its neighbors having chosen it as MPR. The TC message is broadcast throughout the network. Only MPR neighbors rebroadcast a TC packet to avoid flooding.

The OLSR protocol is a variation of the LSR (in English "Link State Routing") specially designed for MANETs originally. Unlike LSR where all nodes are undifferentiated, OLSR optimization is to use multipoint relays (MPRs). MPRs are selected nodes that send broadcast messages during the flood process. They are the only ones to declare their links and are selected by the other nodes so that they can reach anyone in two jumps. This technique substantially reduces message overhead compared to a typical flood mechanism, where each node retransmits each message when it receives the first copy of the message. In OLSR, link state information is produced only by nodes elected as MPR, so a second optimization is achieved by minimizing the number of flooded control messages in the network. As a third optimization, an MPR node must report only links between itself and its selectors.
The two main features of OLSR are:

-the discovery of the neighbors
-the diffusion of the topology

OLSR is an optimization of a link state protocol for ad hoc mobile networks.
First, it reduces the size of the control packet: instead of all links, it states that part of the links with its neighbors, which are its multipoint relay selectors. Secondly, it minimizes traffic floods by this control by using only the selected nodes, called multipoint relays, to broadcast its message in the network. Only the multipoint relays of a node can retransmit its broadcast messages. This technique dramatically reduces the number of retransmissions in a flood or broadcast procedure. The protocol is designed to operate in a fully distributed manner and therefore does not have to rely on any central entity. The protocol does not require reliable transmission for its control messages: each node sends its control messages periodically, messages that may suffer loss of some of the packets, which happens very often in radio networks due to collisions or other transmission problems.

P-OLSR uses UAV position information to estimate changes in the quality of links. In addition, P-OLSR is presented as a routing protocol exclusively designed for AANETs.

Indeed, the first question arises as to how position, speed and steering ratio can be known in ad hoc wireless networks.

The position of the nodes can be deduced from positioning techniques such as the Global Positioning System (GPS). Similarly, the speed (speedi) and the steering ratio (dx, dy, dz) can be deduced from either the GPS or the instruments and sensors specific to the nodes, e.g. campus, odometer, speed sensors, etc. Instead, P-OLSR also uses the radio range of the node in its algorithmic approach. This radio range can be determined from the

transmission power and radio propagation properties. The neighborhood prediction scheme described in the journal [33] assumes that nodes move at the same speed and in the same direction for a very small interval. For P-OLSR, this interval is considered a HELLO interval. Moreover, if a knot moves with a variable speed, direction, and surface, it is very likely that for a very small interval it will move at the same speed and in the same direction, that is, say with the same speed. P-OLSR assumes that the speed obtained from the HELLO packet remains the same until it receives the next HELLO packet. This may not be true for all cases. Cases where the node changes speed and / or direction during the HELLO interval do not match this assumption. However, a significant difference in the results of P-OLSR and OLSR proves that this hypothesis fits well into the scenario of mobile ad hoc networks.
In comparison with OLSR, P-OLSR provides more bytes of data with less delay and less standard routing time. Routing overhead is higher, but normalized routing overhead is still higher than OLSR.

In the journal [65], scientists simulate an antenna array comprising 5 UAVs and use the IEEE 802.15.4 standard as a technology. The default routing protocol in this scenario for ZigBee is disabled on drones, equipped with XBee Pro ZigBee class 2.4GHz radios. Nevertheless, a flood-like protocol is used instead to perform several experiments on wireless links.

Several routing protocols are tested in a simulation with two UAVs and a ground base station in the journal [27]. The routing protocols studied are AODV, OLSR that we have already seen before, and BATMAN (Better Approach To Mobile Networking) in [43].

OLSR, which until now was the most promising solution, clearly had to change its original design before it could move towards the challenge of city-wide mesh networks. Some of its basic building blocks have proved unsuitable in practice (such as hysteresis or MPR (MultiPoint distribution Relays)), or limit the mesh network to a maximum size, for example via sending too much data, and the continuing need to calculate the complete topology of the network. Despite readjustments the limits of OLSR are rapidly manifesting, particularly through the growth of networks. BATMAN developers decided to learn OLSR protocol experiments and other existing ideas to build their own protocol.

The central idea of BATMAN lies in sharing information about the best connections among all BATMAN nodes in the entire network. Thanks to this, the need to inform all BATMAN nodes with each modification of the mesh network disappears. Each of the nodes looks only, where the data received by their communication partner comes from, and sends back the corresponding data via the same path. On the way to the destination, the data will be transmitted in this way step by step. Scientifically speaking, this approach is similar to the orientation of ants by pheromones. As a result, a network of collective intelligence results.

The main task of BATMAN is the same as for traditional routing protocols: it is to discover the other BATMAN nodes and calculate the best route to these nodes. On top of that, he informs his neighbors about new nodes and routes to them. In static networks, network administrators or technicians decide by what cable or what means (eg waves) a computer is reachable. In wireless networks this is defined by the power of the signals, but these can

undergo strong variations, which is a first obstacle to reach the most important prerequisites for the UAV networks. These tasks must therefore be largely automated:
-Each node regularly informs its neighbors through a broadcast message of its existence.
-Each neighbor responds with their existence message, which allows neighbors to also learn about this node. This is how the information on each of the nodes is distributed in the complete network.

To find the best path to all neighbors, BATMAN counts the messages received from the same origin, and memorizes which neighbor has transmitted to him. In contrast to existing solutions, the protocol does not attempt to define the full path to another node, but uses the origins of the collected messages to evaluate the first jump in the right direction. This data will then be transmitted only to the best neighbor for this direction, which will apply the same principle. This process repeats until the data reaches the recipient.
The BATMAN protocol outperforms AODV and OLSR in terms of throughput. However, OLSR is very close to the rate reached by BATMAN. It is important to note that BATMAN generates much more routing time than others. BATMAN is also compared to an implementation of the greedy geographic routing scheme. The results showed that the geo-routing solution implemented in [27] was better than BATMAN most of the time.

On the other hand, the authors proposed a geographical routing based on the mobility forecast (MPGR) in [19]. It is a routing algorithm for UAV to UAV communications based on the traditional GPSR (Greedy Perimeter Stateless Routing) routing protocol for multi-hop networks [39]. We will therefore explain the GPSR protocol before going into more detail in the operation of the MGPR protocol.

In wireless networks composed of many mobile stations, the routing problem of finding paths between a traffic source and a traffic destination via a series of intermediate transmission nodes is particularly difficult. When the nodes move, the network topology can change quickly. Such networks require a responsive routing algorithm that quickly finds valid routes as the topology changes and old routes break. However, the limited capacity of the network channel requires efficient routing algorithms and protocols, which do not lead the network to a congested state as they learn new routes. The tension between these two goals, responsiveness and bandwidth efficiency, is the essence of the mobile routing problem.

Greedy Perimeter Stateless Routing, GPSR, is a responsive and efficient routing protocol for mobile wireless networks. Unlike established routing algorithms, which use the concepts of short path graph theory and transitive accessibility to find routes, GPSR exploits the correspondence between geographic position and connectivity in a wireless network, using Node positions for making packet transfer decisions. The GPSR uses a greedy transfer to transfer packets to nodes ever closer to the destination. In regions of the network where such a greedy path does not exist (that is, the only path requires a temporary movement away from the destination), the GPSR recovers by transmitting in perimeter mode, in which a packet successively traverses faces closer to a plane, sub-graph of the connectivity graph of the complete radio network, until reaching a node closer to the destination, where greedy transmission resumes.

Once the GPSR protocol is introduced, we can delve deeper into the GPSR-based MGPR protocol. The basic idea of MPGR is to predict the next UAV movements in order to transmit the incoming data packets to the predicted positions. MPGR (Mobility Prediction Geographic Routing) is a geographic mobility prediction routing used for a battlefield application based on the GPSR algorithm [66]. The choice of the prediction algorithm is justified by the need to correctly choose the next hop and thus to select a stable route within the UAANETs. The particularity of this routing protocol lies in its position-sharing mechanism. Indeed, an on-demand position acquisition technique is used. This means that if the UAV does not send a message, it will navigate in silent mode without activating the routing protocol daemon. If a UAV has to send a message, it starts by broadcasting the Neighbor Discovery (ND) packet. It contains the destination position, the delivery mode parameter (greedy or perimeter) and the distance from the destination. Each neighbor then responds by forwarding their neighbor list information to the sender. This will eventually allow the sender to build his own neighborhood table.

In addition, during the packet transmission phase, a prediction method is integrated into the geographical algorithm. If a routing gap occurs, MPGR switches to the two-hop perimeter transfer algorithm. Its principle is to calculate the Euclidean distance among the node and its two neighbors of jumps and to select the one that offers a better feedback in terms of the result of the prediction function. It should be noted that a Gaussian mobility model is used in prediction computing. A simulation study on the Gauss mobility model was performed to compare the MPGR with GPSR and AODV. The results show that MPGR outperforms GPSR and AODV in terms of PDR, end-to-end delay and overhead.
Even if a promising result has been achieved, it is important to note that this depends strongly on the GAUSS mobility model implemented. As a result, results should be verified and validated with other mobility models in the same test case. Another significant disadvantage is that the load balancing of heavy traffic (eg, video traffic) is not considered in this study.

It is therefore a routing protocol based on the location of the nodes (coordinates) and, therefore, the UAVs should be equipped with a GPS system. Scientists compare the proposed MPGR algorithm with GPSR and AODV routing protocols. Thus they demonstrate better results than the two traditional multi-hop routing protocols.

3/ Geographic Protocol

Geographic Random Greedy Protocol is a geographic protocol that uses random walks on the local spherical structure to escape voids when a packet is blocked at local minima. The solution used to exit local minima through random walks is non-deterministic and generally leads to long and high delays. air. It uses a spherical double-graph structure to extract the packet from the local minimum. This protocol is also modeled in a grid structure using Unit Ball Graphs (UBG). However, UBGs are based on the assumption that the transmission radius is always a sphere, which is not the case in practical sensor nodes. Random Walk is a greedy routing scheme that uses constant storage and storage complexity. However, the

GRG protocol is of a theoretical nature. Thus, it can not be used in a convenient wireless sensor application.

A geographic routing protocol for AANETs is another possible routing protocol for UAVs. This routing protocol is based on a new broadcast approach, ADS-B, which includes local topology information to build neighborhood tables. Scientists compare this protocol to the GPSR routing protocol, showing better results in terms of packet delivery and end-to-end delay metrics.

To another extent, in reviews [28, 62], the authors highlight the need to develop new routing protocols for UAV networks that take into account throughput, link quality and other metrics for the selection of the routing path. The reason is that the implementation of IEEE 802.11 mesh favors less jumping paths without taking into account the quality of the link.

In addition, the performance of a routing protocol depends on the specific metrics measured and those that the UAV network must guarantee. For example, some proactive protocols such as BATMAN outperformed the reactive protocols in terms of throughput, as demonstrated in [27]. However, BATMAN generates much more routing time than other proactive and responsive protocols. Thus, if a UAV network in a specific application has to offer a high throughput and is able to cope with a routing overload, the BATMAN protocol would be a good routing solution. On the contrary, if the conditions of the application scenario change over time, other routing approaches would be better than BATMAN. It is important to note that geo-based routing protocols have outperformed protocols such as BATMAN [27]. However, this type of routing has not yet been widely explored in these networks.

B. Network between UAV and base station

The researchers used different technologies for communications between UAV networks and control centers or base stations. We would like to point out that when we refer to a control or command base station, the types of commands that may appear in these applications are high-level, as we focus on networks of unmanned vehicles. The control base stations are also used to monitor the remote network.

This is the case when a system is unavailable due to failures. Then, it is always possible to use an alternative for the connection with the UAV network. There are implementations using cellular communications, satellite, WiMAX (IEEE 802.16) and even proprietary wireless technologies (Ubiquity Airmax). However, IEEE 802.11 is clearly the first choice when designing this type of network because of its massive use in commercial wireless devices. Indeed, we can see in the review [35] that the DSR routing protocol is also used with the IEEE 802.11b standard. This is the same routing protocol used previously as part of a network between multiple UAVs.

The IEEE 802.11 standard has a high bandwidth of the order of Mbps and a range of tens of meters to 1 km in some of its versions (for example, IEEE 802.11ah). However, this technology only supports star or multiple star topologies. Other technologies would be needed to implement the ideal case of hierarchical or flat mesh networks [14]. Another disadvantage of the IEEE 802.11 standard is the power consumption because it was not designed to be used in energy constraint scenarios, as is the case with UAV networks. An alternative to this is the IEEE 802.15.4 standard. Although its bandwidth is less than 10 Kbit / s, it has been developed for use in energy constrained mesh networks, such as WSN networks.

We have previously seen that the key concept used in the OLSR protocol is the use of multipoint relays (MPRs). This protocol design is used in a network between a UAV and a ground base station. However as in the case of a network among several UAVs, OLSR is not the most optimal protocol, the disadvantages are similar in these two types of networks.

Like the DSR protocol, the BATMAN protocol is associated with the use of 802.11 technologies in the journal [27]. However, BATMAN generates much more routing time than other proactive and reactive protocols such as networks among several UAVs. Take the example of a UAV network in a specific application that should offer high throughput and should be able to cope with a routing overload, the BATMAN protocol would be a good routing solution. If not, for example, if the application scenario conditions change over time, other routing protocols would be better than BATMAN.

Nevertheless, a new routing protocol that we have seen in the scenario of networks among several UAVs, is studied in the scenario of a network between a UAV and a ground base station. This protocol is the HWMP protocol also known as the AODV-HWMP protocol. The Hybrid Wireless Mesh Protocol (HWMP) is a hybrid routing protocol for wireless mesh networking. It is based on the AODV protocol and uses the peer-link management protocol to discover neighboring nodes. The protocol operates on the same lines as the AODV to determine the optimal path among the sending nodes via the PREQ (path request) messages. This protocol has been tested with the NS3 simulator and it has been determined that it is perfectly suited to UAV communication because it determines the best optimal path using the Air Time Link (ALM) metric. This protocol is associated in this same journal with the use of IEEE 802.11s technology.

Dynamic routing protocols allow you to automatically adapt to changes that may occur in network life:

-addition or removal of new networks,
-panels of links,
-addition of backup links.

The table below summarizes the routing protocols most commonly used in UAV networks.

Protocol	Specificites	Advantages	Disadvantage
OLSR	improvement of LSR via introduction of MPR	decrease in the number of messages exchanged and their size	problem if very important mobility
BATMAN	choosing the route via the neighbors who have sent the most messages	choice of the most reliable routes	memory needed to store the history of received messages
GPSR	constant maintenance of a routing table	very fast packet propagation, suitable for mobility	slow reaction to changes in topology, massive exchange of messages
AODV	next-hop choice located on the minimum cost route	roads always up to date, no excessive mailings of control messages	time needed to find a route, not optimized for high mobility
GGF	routes obtained on demand	roads always up to date, no excessive mailings of control messages	time needed to find a route, not optimized for high mobility
DSR	complete route stored in each node, route inserted into the packet to be sent	choice of the road independent of the other nodes, total knowledge by a node of the borrowed road	overhead on the package, memory to store the routes
GGR	knows its geographical location, that of its neighbors and that of the destination	scalable, no loops, no state and no memory	absence of neighbors closer to the destination than the current node

Figure 27. Table showing the characteristics of the protocols presented

4/ Conclusion

Trajectory planning is a complex task. It depends a lot on the environment in which UAVs operate. The 2D or 3D dimension, indoors or outdoors, in a terrestrial, underwater or aerial environment, all these factors change the trajectory planning strategy. Obstacles can also radically change this strategy. Some obstacles are static, others are dynamic, in some cases big obstacles as buildings can have an influence on UAV-UAV and UAV-base station communication, which can lead to planning errors, or worse, a drone crash. We have studied the different categories of algorithms that provide viable solutions to trajectory planning, despite the fact that each category has its advantages and disadvantages. Potential methods are very efficient for their reactivity to an obstacle but can be blocked in a local minimum. Genetic algorithms are very powerful and offer great potential to solve complex cases at low cost, unfortunately these algorithms do not necessarily give an optimal solution. Swarm algorithms provide an efficient solution to complex problems at lower costs and have robustness and foolproof redundancy. However, there are cases where the solution is blocked in a local optimum. All these algorithms have one thing in common, they were invented through the observation of nature such as the behavior of ants, the organization of a pack of wolves, or the principle of natural selection. Finally, algorithms with communication constraints are more and more studied since communication between UAVs or UAVs-GCS plays a major role. Trajectory planning also depends on the technologies that man has. Some technologies are the best over very short distances, in situations requiring a high reactivity, others are more useful for the quality of the communication, or for the communication rate. Technologies evolve rapidly and sometimes require radical changes in strategy. Still with an aim of improvement, we studied the formations and their control that best correspond to the situation. We still find bio-inspired systems including moving groups of birds. Each formation has its advantages in some environments, depending on the type of mission, depending on the type of drone. The control of formation has a major impact on the smooth running of a mission, it must be able to ensure that a drone fleet is organized and that it can avoid obstacles. The leader / follower is the fastest and easiest to set up while Virtual Structure offers better support as well as a better idea of where each drone is but it is less adept to avoid obstacles. Behavior-based formation control offers better results than the other two but is more unstable on a large scale, so a solution that is spreading more and more is a hybrid model that uses several types of control and depending on the situation, the one that is fit to better manage it is used. The network part also plays an important role, indeed for an optimal trajectory and a good formation maintenance, the UAV must be able to communicate its trajectory to the neighboring UAVs which are located close to it. Thus, if two UAVs have identical coordinates at a future time t, they must be able to communicate so that one of the two UAVs change their trajectory in order to avoid a disaster. Therefore, the network part plays an important role. The technologies used for the first 3 layers must guarantee optimal communication. Thus we presented technologies such as the IEEE 802.11 standard but also 802.15.4 technology or infrared communications. For the routing protocol part, a lot of research is still conducted on reactive, pro-active or hybrid protocols. We find that many solutions have been found by copying animal behavior, their interactions with each other and with their environment. In future research on trajectory planning, it may be interesting to continue to observe and try to mimic nature, it surely still reserves some beautiful discoveries.

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