UAV Flocks Forming for Crowded Flight Environments

Rina Azoulay[1] and Shulamit Reches[2]
[1]*Department of Computer Science, Jerusalem College of Technology, Havaad Haleumi Street, Jerusalem, Israel*
[2]*Department of Mathematics, Jerusalem College of Technology, Havaad Haleumi Street, Jerusalem, Israel*

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Abstract: In this study, we consider a situation where several privately owned unmanned aerial vehicles (UAVs) are supposed to travel on several routes. We develop a model for grouping them into UAV flocks that are supposed to travel on similar routes within the same time window. Our proposed flocking protocol enables each UAV to optimize its own preferences concerning its flights. Using this protocol enables all UAVs to enjoy freer routes and fewer encounters with other UAVs, thus saving time and energy during their flights. The protocol allows each UAV to create a flock or to join an existing flock to save its resources. Joining flocks in a crowded environment can reduce the overhead caused by encountering additional UAVs in the environment. We developed a flocking protocol that allows each UAV to design its optimal route. The protocol is based on a public on-line communication blackboard, which enables each UAV to receive information about existing flocks, join an existing flock or build a new flock and publish it on the blackboard. In addition, we defined a strategy for each UAV to assist in deciding which flock to join or whether to create a new flock to optimize its expected utility. Finally, the effectiveness of the proposed algorithm is verified by means of simulations.

1 INTRODUCTION

Recently, the field of unmanned aerial vehicles (UAVs) has gained momentum. UAVs are used today for diverse tasks, and their usage has vastly grown over the years in various fields (Valavanis and (editors), 2015) such as photography, surveillance, agriculture, communication, testing, and military. Future commercial usage may also include delivery of products, documents and food. The decline in the price of UAVs, among other things, has contributed to their popularity, and it seems that their usage in the near future will become increasingly common, resulting in a situation of overload along their various paths.

The most significant challenge in the near future will be to build communication protocols to enable individual heterogeneous UAVs, developed by different companies based on various technologies, to communicate with each other. Currently, there is no such protocol. This communication would enable the UAVs to coordinate their routes and share common routes to avoid collisions with obstacles or other UAVs in crowded environments and thus decrease their flight times. This communication is essential in light of the expected crowded and overloaded environments. The flight of each UAV in its own direction can cause a significant slowdown in UAVs' progress and may even lead to deadlocks if none of the UAVs in the crowded environment can progress.

In this study we consider the problem of multiple UAVs, each with its own goal of moving from source location s to target location t. In crowded environments, where multiple UAVs exist, loads may occur and thus UAVs may disturb each other. We developed a protocol that will enable UAVs to be clustered as flocks according to their appropriate goals and needs such as source and destination points. The protocol defines how flocks will be created, how different and heterogeneous flying objects (UAVs and flocks) will communicate with each other, and how the priority of flocks and UAVs will be defined in cases of collisions. In addition, we have defined stable strategies for each UAV that operates in the above environment. In particular, the UAV will use these strategies to decide whether to join an existing flock and which to join, or create a new flock.

We contract a model in which individual UAVs from different manufacturers and with different interests and different sources and targets communicate, in order to form flocks that serve the interests of the individual UAVs in the flocks and maximize their gains. We propose a model where flocks of self-interested UAVs are created. The information about current and future flocks is saved in a shared cloud

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and can be viewed by all the UAVs in the given area. Each UAV can decide whether to create a new flock, or join an existing flock in order to maximize its own benefits.

The algorithm we present assists the UAVs decision making processes while using the shared information about the existing UAVs, and prior information about the distribution of the loads in the given environment throughout the day. The model allows the individual UAV to decide whether to join an existing flock and thereby benefit from higher priority of the large united flock or create a new flock and benefit from the flexibility and shorter track length, determined exactly according to the needs that suit it. To summarize, an individual UAV should examine the advantages and disadvantages of using flocks in some or in all of its journeys, and it should make its decision while considering the current situation (current load and distribution of additional load) of the dynamic environment. Unlike other studies in this field, that deal with finding an efficient path for a given flock of UAVs (see (Mohammadreza Radmanesh, 2018) for an overview), or creating an efficient flying structure in order to avoid collisions, our unique model deals with the problem of how to form UAV flocks given different individual UAVs, from different manufacturers and with different interests and targets. It also addresses how UAVs can communicate with each other in order to form flocks that serve the interests of each of the individual UAVs while maximizing their individual gains.

In order to verify the effectiveness of our model, we present our simulation results. The simulation results prove that our model significantly improves the flight time, especially in crowded environments.

It has already been proven (Jenhui Canny, 1987) that computing the shortest obstacle-avoiding paths among obstacles in three dimensions is NP-complete. However, because the surface and the technology constraints allow the UAVs to fly in a very limited range of heights, we have built our simulation in a two-dimensional environment.

The paper is organized as follows: In Section 2 we present some of the previous works in this field. We provide our basic model in Section 3 and we introduce the flocking protocol in Section 4. The UAVs preferences and decision-making process are detailed in Sections 5 and 6, respectively. Our experimental results are provided and discussed in Section 7. Finally, in Section 8 we conclude with directions for future work.

2 RELATED WORK

Many studies present methods to allow a group of UAVs (or robots) to move in a harmonious manner (Panov and Yakovlev, 2017). These methods aim to enable a group of autonomous vehicles (robots, UAVs, or autonomous cars) to move in a stable manner without collisions with the other agents in the group. In particular, the problem of coordinating the motion of multiple autonomous agents has been discussed in (Herbert G. Tanner and Pappas, 2003a) and (Herbert G. Tanner and Pappas, 2003b). These studies generate a stable flocking motion for a group of multiple vehicles while trying to imitate a group of autonomous moving creatures such as flocks of birds or schools of fish.

The method of building a simulated flock has been discussed in detail by Reynolds (Reynolds, 1987). His approach relies on several components: (1) collision avoidance: avoiding collisions with nearby flockmates, (2) velocity matching: attempting to match velocities of nearby flockmates, and (3) flock centering: attempting to stay close to nearby flockmates.

Our study does not deal with the technical aspects that enable a flock of UAVs to fly in a stable manner without collisions between the flock members, and instead builds a second stage of coordination between UAVs by constructing a communication protocol that enables them to create flocks, in a way that serves the interests of each UAV.

The problem of assigning multiple UAVs to perform tasks cooperatively is a challenge that requires the development of specialized algorithms. Many studies deal with multiple robots that cooperate with each other in order to achieve a specific mission or to maximize their effectiveness.

In (Jenhui Chen, 2005), a communication protocol for a sensor multi-robot system is presented in which the energy consumption, as well as the duration of reaching the goal, is reduced. Yang et al. (Yanli Yang and Minai, 2007) describe a cooperative search problem where a team of UAVs seeks to find targets of interest in an uncertain environment. Passino et al. (Kevin Passino, 2002) instigated the performance of strategies for cooperative control of autonomous aerial vehicles that seek to gather information about a dynamic target environment, evade threats, and coordinate strikes against targets.

Ben-Asher et al. (Yosi Ben-Asher, 2010) developed a distributed algorithm for task assignment, coordination, and communication of multiple UAVs engaging multiple targets in an arbitrary theater. They aimed to maximize the ratio between the number of intercepted targets and the number of launched munitions given a fixed number of flock payloads. Coordination of UAV motion is achieved by implementing a simple behavioral flocking algorithm utilizing a tree topology for target list routing. In (Gurfil and Kivelevitch, 2007), a hierarchical algorithm was developed for autonomous formation flying, communication, and task assignment for cooperating UAVs. This research showed, inter alia, that using communication improves the cooperation among the flock members.

Recently, many researches have investigated the multi-UAV path planning (Liang Yang and Xia, 2016), which is a process whereby the UAVs find their own paths from their starting points to their destinations cooperatively. Recent studies (Li and Duan, 2012; YongBo Chen and Luo, 2015; Joongbo Seo and Tsourdos, 2017) have considered the multi-UAV formation path planning in which each UAV finds its own collision free path and simultaneously tries to keep the formation structure of the flock to which it belongs. Recent studies (Selim Temizer and Kuchar, 2010; Ragi and Chong, 2013; Dabbiru and Siddhabathula, 2016) consider the issue of path planning and collision avoidance using the Markov Decision Process. The difference between our study and previous work on UAVs' path planning and collision avoidance lies in the fact that we concentrate on the issue of flocking autonomous UAVs in order to avoid potential collisions.

Swarm robotics (Bayndr, 2016; Arne Brutschy, 2014; Christopher M. Cianci, 2007; Winfield, 2008) is an approach inspired by social insects that coordinates large numbers of relatively simple robots. This study considers groups of robots that operate without relying on any external infrastructure or on any form of centralized control. An important component of this study is the communication between the members of the group that build a system of constant feedback. The swarm behavior involves constant change of individuals in cooperation with others, as well as the behavior of the whole group.

There are many applications for swarm robotics. One is in disaster rescue missions. Swarms of robots of different sizes can be sent to places that rescue workers cannot reach safely, to detect the presence of life via infrared sensors. Furthermore, swarm robotics can be used for tasks that demand cheap designs such as mining or agricultural foraging tasks.

In contrast to these studies in which the collaboration among players in the flock aims to achieve a common goal, or make it more efficient, our model deals with the use of flocks to maximize the utility of the **individual** UAVs. Furthermore, the protocol we developed assists them in cooperation in a way that is beneficial to each UAV, although each has its own goals and targets.

3 PROBLEM DESCRIPTION

In the environment considered in this research, dynamic set of UAVs exists, of a size less than or equal to N. Each UAV u_i must travel from a source point S_i to a destination point T_i. In addition, each UAV u_i has its time constraints, where it cannot leave S_i before time $Start_i$ and it must reach point T_i no later than time $Finish_i$.

Each UAV has the option to decide whether to travel directly from S_i to T_i independently, without joining other UAVs or join a flock to avoid delays caused by other UAVs or UAV flocks that will cross its route. Thus, it may be beneficial for a UAV to join a flock of UAVs that have a route heading toward its destination. In the following sections, we propose a protocol for creating flocks and stable strategies for UAVs to decide which flock to join or attempt to create a new flock. We call the creator of a flock the manager. The manager of a flock is committed to its flock and determines the source point and the destination point of the flock's flight. It is also authorized to accept another UAV to its flock or reject it. The flock manager can restrict its flock to certain manufacturers, models, to travel at certain heights, etc. It can also limit the size of its flock to a maximum size, and so forth.

The goal of each UAV is to meet its constraints, i.e., to leave starting point S_i at time $Start_i$ or later, and to reach point T_i at time $Finish_i$ or earlier, while saving resources of power and flight time (including the required travel time and waiting time in cases of collisions with other flocks until other UAVs finish crossing its route) and reaching the destination as early as possible.

Also note that in cases of a possible collision of flocks, the protocol we define provides a higher priority to the larger flock to proceed before the other flock/s, and this could motivate UAVs to join flocks in crowded environments, even if it might increase the length of their total route.

In contrast to other studies in the field of UAV flocks where the motivation of forming a flock is to fulfill a specific task that a single UAV finds difficult or cannot do alone, our research deals with the use of flocks in order to achieve and optimize the goal of every UAV.

The environment studied includes the following parameters:

- G: the identity of a group/flock of UAVs.
- L_G: current size of flock G. There is an advantage for a large flock in cases of intersections of a number of flocks. In such cases, the smaller flock will change its direction, or wait in its place until the larger flock passes. In other words, the larger group has a higher priority at an intersection. Thus, the flock's route time decreases as the flock size increases.
- $I(size_{G_i})$: the expected delay due to the intersection of flock G with a particular flock G_i with a size $size_{G_i}$. It depends on the current values of L_{G_i} and on the expected value of the number of UAVs that will join the flocks until the departure time. Note that if the size of flock G is greater than the size of flock G_i, no delay is expected because flock G will be given priority to proceed.
- T_G: the expected time required for the travel of flock G, given the route s_G to d_G (if no intersection exists). T_G depends on the distance between s_G and d_G, the expected speed of the flock, the expected wind direction, and the expected wind speed.
- DT_G: the flock's required arrival time, which is defined by the flock manager.
- s_u and d_u: the source and destination of the required route of UAV u.
- s_G and d_G: the source and destination of the expected route of flock G.
- $D_{u,G}$: the time that will be spent due to the deviation of UAV u from the original UAV shortest path to the route of the flock. When a UAV joins a flock, it might lengthen its path if the flock's route is not identical to its shortest path, and this might increase the required time. Note, however, that if $s_u = s_G$ and $d_u = d_G$, or if both s_u and d_u are points inside the route of flock G, then $D_{u,G} = 0$, because no deviation is required to adapt the UAV route to the flock route.
- T_u: the expected time required for the travel given the direct route from s_u to d_u (if no intersection exists).
- $[T_a, T_b]$: time window range for the departure time of a flock .

Figure 1:Up and Figure 1:Down demonstrate the advantage of flocking in situations where multiple UAVs act in the same loaded environment. In both figures, three UAVs, named A, B, and C, exist, which have similar routes within the same time window.

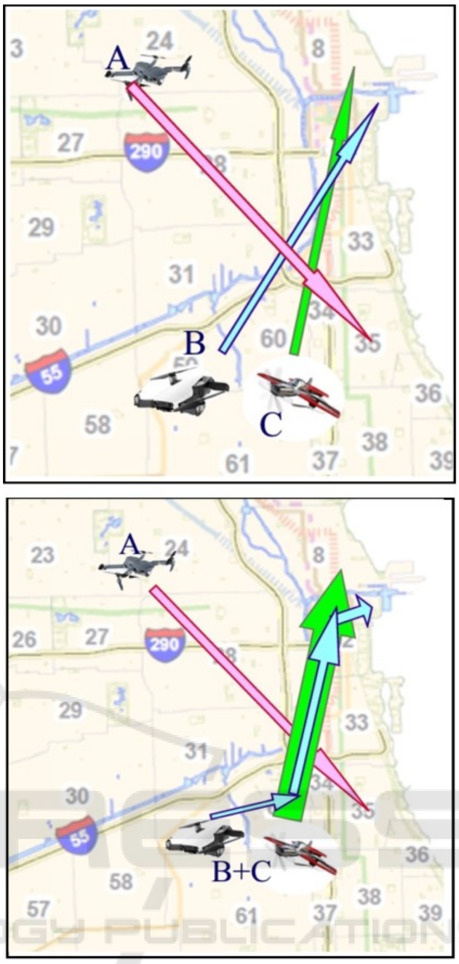

Figure 1: Up: demonstration of intersections between unflocked UAVs. Down: advantage of a flocking protocol for the same scenario depicted in the figure above.

In Figure 1:Up, each UAV proceeds with its own route and interacts with the two others. Then, Figure 1:Down shows a situation where a flocking protocol exists: UAVs B and C find it beneficial to form a flock, and in this case, only one interaction occurs, which is between A and the BC flock. UAV B has to lengthen its route, but does not have to wait for any other UAV or flock (because the B,C flock is larger than A, A will have to wait for B,C at their crossroad).

4 PROPOSED PROTOCOL

In this section, we will describe a communication protocol that enables the individual UAVs to estimate the expected flight space and to plan the formation of UAV flocks. The basic protocol is as follows: An online blackboard exists for all UAV flocks that are supposed to be organized in a predefined radius. Each flock contains the following information:

- flock manager (flock creator)
- flock starting point Si and flock destination point Ti.
- estimated departure time and estimated arrival time.
- size of flock.

Note that the blackboard contains shared knowledge about several departure and arrival nodes in its geographical area. In addition, the blackboard can also share relevant information from other blackboards about flocks that are supposed to reach its geographical area. Each UAV that wants to take a route will first search the blackboard in order to find an appropriate flock that matches its requirement. If such a flock is found, the UAV sends the flock manager a request to join it.

In addition, in case of a collision between flying objects (flocks or UAVs), the larger flying object with more members is given priority to proceed.

The UAV message includes:

- its contact details,
- point where it would like to join the flock,
- point where it would like to leave the flock,
- and its time constraints.

The flock manager, upon receiving the UAV message, will decide whether to accept the UAV to the flock or not and it will send an appropriate message to the UAV.

If the UAV is accepted to the flock, the managers message to it will include the time and place where and when the UAV is supposed to join the flock (the starting point of the flock, or a point along the flock's route).[1] The flock route details, i.e., the exact route and the exact departure and arrival times, may be partially defined during the flock organizing process, and they may dynamically change with time when the journey begins and even during the flight, if necessary. Thus, the manager can continue to send updates to the flock participants concerning the route details until the journey is completed.

If a UAVs request to join a flock is accepted, it is committed to the flock, and it should reach the meeting point by the time that was sent to it. The UAV may reach the flock at a different meeting point and leave it at a different splitting point. However, during the time that it is a member of the flock, it must keep the flock's direction and speed, and it must keep the required distance from the other flock members.

If a UAV cannot find any appropriate flock, it may create a new flock and publish it on the common blackboard[2]. When creating a new flock, the UAV should decide which requirements to publish such as the starting point, the ending point, and the time window. This UAV will be the flock manager: it will be committed to this flock and it will be responsible for accepting additional UAVs to the flock and for keeping the flock details (route and expected time window) up to date. The manager is authorized to accept only UAVs of models and manufacturers that meet the basic requirements of the flock (speed, distance, etc.). There is a possibility to join a flock during the flight. In this case, the flock's details are already determined, and a UAV can join it by receiving the manager's agreement and receiving the exact joining time and place.

To summarize, the flock blackboard contains the following details:

- For each organizing flock: (flocks that are now being organized and not yet flying)
  - flock manager's contact details,
  - expected departure time
  - current flock size.
  - current information about the flock's route.
- For each airborne flock: (flocks that already began their route)
  - flock manager's contact details,
  - flock's current point
  - flock's remaining route and estimated times.

A new UAV can do one of the following:

- view the current flocks on the blackboard.
- ask to join an existing flock (organizing or airborne flock).
- create a new flock.

Note that a UAV that is already a member of a flock should be committed to it, but it can agree or disagree to a new member joining or to merging with another flock if this will change the flock's route or time.

During flight, if two or more flocks are involved in a possible collision (intersection), the largest flock

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[1] Another possibility may be a union of two flocks waiting on the blackboard, which may decide to move together on a particular route.

In this case, the estimated departure time, estimated arrival time, and common route will be decided together by the flock managers and agreed upon by all participating flocks.

[2] According to the protocol, it may also build a rival flock with similar route and departure time as an existing flock, but in this case, the precedence of the rival flock will be lower than that of the existing flock

will be given permission to proceed first. This will motivate UAVs to join flocks and thus reduce the traffic load. If both flocks are of the same size, then a lottery will be performed to decide which flock will be given the right of way.

We proceed by defining the UAV preferences and expected flying time given the current knowledge about organizing flocks and flying in flocks.

5 UAV PREFERENCES AND EXPECTATIONS

Given the flight protocol we defined above, we proceed by describing the preferences and expected utility of a UAV that operates in an environment that uses this protocol. In order to decide which flock to join or whether to open a new flock, the UAV is motivated to minimize its expected total flight time[3].

We first assume that the UAV knows the current information about the flocks that currently fly or the flocks that are currently organized, using the knowledge in the relevant area blackboards. However, it does not have complete information about the actual time that each flight will require, due to unknown parameters (wind, etc.). In addition, it does not know the exact time and place of the intersections with other flocks, and how long it will take each of them to reach such intersections. This is due to two reasons: (1) unknown parameters on the actual route, which can influence the meeting location and the length of delay that will be caused as a result; (2) the final size of each group is dynamic and therefore not known in advance. Thus, the UAV should evaluate the **expected time** of the flight whether it will fly alone or join any given flock. Given the list $\{G_1,..G_n\}$ of flocks with departure time within the range $[T_a,T_b]$, and given the source, s_G, destination, d_G, the estimate time required for the travel of flock G, T_G, and current size L_{G_i} of each flock, attribute 5.1 defines the expected time for flock G to complete its route.

Attribute 5.1. *The expected route time of flock G is defined as follows:*

$$expected\_Route\_Time(G) = T_G + \Sigma_{i=1}^{n} expected\_delay\_time(G,G_i)$$

where $expected\_delay\_time(G,G_i)$ is the expected time that flock G will need to wait until flock G_i has passed, in a case of an intersection between the two flocks. Note that if the size of G_i is lower than the size of G, or if there will be no expected crossroad between them, then $expected\_delay\_time(G,G_i) = 0$

We will now proceed by calculating $expected\_delay\_time(G,G_i)$, the expected delay time of flock G due to an intersection with flock G_i. We use FL_{G_i} to denote the future size of a flock in the departure time. The future size FL_{G_i} of each flock G_i depends on its current size L_{G_i} and on the distribution of UAVs that will join it. Attribute 5.2 defines the distribution of UAVs that are expected to join flock G_i during time window $t = [a_t, b_t]$.

Attribute 5.2. *Let $JF_{G_i,t}$ be defined as a Poisson random variable that represents the rate of UAV's that will join flock G_i within a given time $t = [a_t, b_t]$, ($JF_{G_i,t} \sim Poisson(\lambda_{G_i,t})$).*

The expected rate $\lambda_{G_i,t}$ can be estimated as the expected number of UAVs in the area aimed in the direction of flock G_i in time range $t = [a_t, b_t]$, which can be deduced from an analysis of the loads in the area as a function of the hour. The expected rate λ_{t,G_i} of joining a flock G depends on both the path of G_i and the hour of the journey. There are busy hours and load locations in which $\lambda_{G_i,t}$ is very high due to the traffic load and hours and locations in which λ_{t,G_i} is lower. Given the expected arrival rate of new UAVs and their joining the different flocks, we will find the expected route time of a flock.

Attribute 5.3 describes the distribution of the future size FL_{G_i} of flock G_i at time b_t, given its current size L_{G_i} at time a_t and the expectation of the random variable $JF_{G_i,t}$.

Attribute 5.3. *Given a time window $[a_t,b_t]$, the expected size of flock G_i at a departure time b_t is as follows: $FL_{G_i} = L_{G_i} + JF_{G_i,t}$ where $JF_{G_i,t} \sim Poisson(\lambda_{G_i,t}), t = [a_t, b_t]$ and L_{G_i} is the size of flock G_i at time a_t.*

Given two flocks G_1 and G_2 with intersecting routes, $JF_{G_1,t}$ and $JF_{G_2,t}$ are random variables that represent the rate of UAVs joining flocks G_1 and G_2, respectively. Because flocks G_1 and G_2 have an intersection, we can infer that they have different directions and that the arrival rates of new UAVs to both of them are independent. In other words, joining one flock does not reduce the size of the other flock. As a result, the random variables $JF_{G_1,t}$ and $JF_{G_2,t}$ can be considered as independent random variables.

In Lemma 5.1, we describe the expected delay of flock G_1 due to an intersection with another flock G_2 during its flight.

Lemma 5.1. *Given two flocks G_1 and G_2 with prior sizes L_{G_1} and L_{G_2}, respectively, the expected delay of*

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[3] Other criteria which take into account other parameters, such as route length or expected arrival time, can also be considered.

flock G_1 *due to an intersection with flock* G_2 *is*

$expected\_delay\_time(G_1,G_2) =$
$\Sigma_{k_2=0}^{\infty} P(JF_{G_2,t}=k_2)\cdot($
$[\Sigma_{k_1=0}^{L_{G_2}-L_{G_1}+k_2-1} P(JF_{G_1,t}=k_1)]+$
$0.5\cdot P(JF_{G_1,t}=L_{G_2}-L_{G_1}+k_2))\cdot$
$P(G_2\_intersects\_with\_G_1|JF_{G_1}=k_1, JF_{G_2}=k_2)\cdot$
$I(L_{G_2}+k_2)$

where $I(s)$ *is the expected delay time for a flock of size* s*, and* $FL_{G_i} = L_{G_i} + JF_{G_i,t}$ *for* $JF_{G_i,t} \sim Poisson(\lambda_{G_i,t})$.[4]

Proof. Given two flocks G_1 and G_2 with prior sizes L_{G_1} and L_{G_2}, respectively, the expected delay of flock G_1 due to an intersection with flock G_2 is $expected\_delay\_time(G_1,G_2) = P(FL_{G_1} < FL_{G_2}) \cdot P(G_2\_intersects\_with\_G_1|FL_{G_1} < FL_{G_2}) \cdot I(FL_{G_2})$. Now, $P(FL_{G_1} < FL_{G_2}) = P(L_{G_1} + JF_{G_1,t} < L_{G_2} + JF_{G_2,t}) = P(JF_{G_1,t} < L_{G_2} - L_{G_1} + JF_{G_2,t})$. Because $JF_{G_1,t}$ and $JF_{G_2,t}$ are independent Poisson random variables:

$$P(JF_{G_1,t} < L_{G_2} - L_{G_1} + JF_{G_2,t}) = \Sigma_{k_2=0}^{\infty} P(JF_{G_2,t}=k_2) \cdot\Sigma_{k_1=0}^{L_{G_2}-L_{G_1}+k_2-1} P(JF_{G_1,t}=k_1)$$

In addition, if both G_1 and G_2 are of the same size, then a lottery is performed, and the probability of flock G_1 to be the one that must wait till flock G_2 passes is 0.5. Thus, given the size of G_2 as $L_{G_2} + k_2$, the probability of flock G_1 to be of the same size as flock G_2 and to be the one that will wait is $0.5 \cdot P(JF_{G_1,t} + L_{G_1} = L_{G_2} + k_2)$ and this probability is $0.5 \cdot P(JF_{G_1,t} = L_{G_2} - L_{G_1} + k_2)$. Thus, the expected delay time of G_1 can be formulated as

$\Sigma_{k_2=0}^{\infty} P(JF_{G_2,t}=k_2)\cdot$
$([\Sigma_{k_1=0}^{L_{G_2}-L_{G_1}+k_2-1} P(JF_{G_1,t}=k_1)]+$
$0.5\cdot P(JF_{G_1,t}=L_{G_2}-L_{G_1}+k_2))\cdot$
$P(G_2\_intersects\_with\_G_1|JF_{G_1}=k_1, JF_{G_2}=k_2)\cdot$
$I(L_{G_2}+k_2)$

$\square$

As a result of the above lemma, the expected delay of a single UAV due to an intersection with flock G_i is defined as follows:

$expected\_delay\_time(u,G_i) =$
$\Sigma_{k=0}^{\infty} P(JF_{G_i,t}=k)\cdot$
$P(u\_intersects\_with\_G_i|JF_{G_1}=k)\cdot I(L_{G_i}+k)$.

Given the above expectations, we proceed by describing the decision-making process of the UAVs.

6 UAV DECISION-MAKING PROCESS

In this section, we will describe the decision-making process of the UAV, given its knowledge about the environment. Let $\{G_1,...,G_n\}$ be flocks such that $DT_{G_i} \in [T_a,T_b]$, $|d_{G_i} - d_u| < k_1$ and $|s_{G_i} - s_u| < k_2$ for each $i \in 1,2,...n$. Denote u to be the UAV that is supposed to travel from s_u to d_u.

Let G_u be a new flock that is organized by UAV u. Its initial size is 1, but note that its size when starting the flight can grow over time due to the arrival of new UAVs that might join it once the flight is in progress.

When a UAV plans its route, it will look for a flock that will require the shortest expected time to complete its route. In order to make the process of flock selection more efficient, the UAV can filter the relevant flocks and consider only flocks with relevant attributes with respect to their paths and their departure times.

To perform this filtering, we will define the following constants: T_a and T_b denote the required time interval in which the UAV will depart, and $k1$ and $k2$ are the maximum radius of departure and arrival locations, respectively, in which the UAV will search for a relevant flock. If the UAV will take into account also flocks with departure or arrival locations that are not in its area, then it can set $k1$ and $k2$ as ∞.

Given flock G_i and UAV u, denote $s_{u,i}$ to be the best location where UAV u can join flock G_i, and denote $d_{u,i}$ to be the best location where UAV u can leave flock G_i, if it decides to join this flock for part of its journey.

In addition, use $Expected\_Route\_Time(F,x,y)$ to denote the expected route time of flock F, during part of its route, from source location x to destination location y. Finally, recall from Attribute 5.1 that $Expected\_Route\_Time(G_i)$ is defined as the expected route time of a new flock, which is managed by UAV i. Attribute 6.1 defines the flock with the minimal expected root time from UAV u's point of view.

Attribute 6.1. *Denote* min_G *to be defined as follows:* $min_G = min_{G_i \in \{G_1..G_n\}}\{ExpectedRouteTime_u(G_i) + D_{u,G_i}\}$

where

$ExpectedRouteTime_u(G_i)$ *denotes the expected time of the partial route of flock* G_i*, during which UAV* u *joins it, and it is evaluated as follows:*

$ExpectedRouteTime_u(G_i) = Expected\_Route\_Time(F, s_{u,i}, d_{u,i})$

---

[4] When $L_{G_2} + k_2 - L_{G_1} - 1 < 0$, the obtained value is 0.

Attribute 6.2 describes the expected total time of UAV u if it joins flock G_i.

Attribute 6.2. *Denote* $Expected\_Total\_Time(u, G_i)$ *to be:*

$$
\begin{aligned}
&Expected\_Total\_Time(u, G_i) = \\
&Expected\_Route\_Time(\{u\}, s_i, s_{u,i}) \\
&+ Expected\_Route\_Time(G_i \cup \{u\}, s_{u,i}, d_{u,i}) \\
&+ Expected\_Route\_Time(\{u\}, d_{u,i}, d_i).
\end{aligned}
$$

Using Attribute 6.2, Attribute 6.3 describes the UAV's decision of whether to join an existing flock G_i or create a new flock and manage it.

Attribute 6.3. *UAV* u *will decide to initiate a new flock* G_u *if*

$$
\begin{aligned}
&Expected\_Route\_Time(G_u) < min_{i=1..n} \\
&\{Expected\_Total\_Time(u, i)\}.
\end{aligned}
$$

Otherwise, UAV u *will join flock* G_{min_G} *that minimizes the value of* $Expected\_Total\_Time(u, min_G)$.

The explanation for the above attributes is as follows. UAV u is interested in finding a route that will minimize the total expected time. If it creates a new flock, the expected required time for the total route will be $Expected_{R}oute_{T}ime(G_u)$, and if it joins an existing flock, the most beneficial flock for it is min_G, which is the flock that minimizes the time it will need to complete the entire journey, including the part it joins the flock and the resulting deviation. Thus, the UAV will choose the alternative that will minimize the expected time required for its total journey.

7 SIMULATION RESULTS

In order to check the influence of flocking on the UAV's performance, we implemented a simulation system that demonstrates the UAV's arrival process and the flocking organization protocol via a blackboard and we examined the efficiency of the proposed protocol. In the following section, we present the simulation results that compare the performance of a flight space with flocking and without flocking. We ran our simulation on data of taxi travels in Chicago based on the Chicago smart city database[5]. The source and destination locations, and the community area of each location were taken from that dataset. In addition, the mean number of trips per hour for each source community area to each destination community area was calculated given the Chicago smart city database. The motivation for using this database stemmed from the assumption that the distribution of the transfer of people and journeys by means of riders in the not too distant future can be similar to the distribution of people and journeys through current taxis. Given that information, we ran our simulation in the following way: For each run, the mean total number of UAV trips per day was determined, and the mean number of trips for each source area to each destination area was calculated. Then, for each run, the actual number of travels per day, for each source area to each destination area, was derived from the Poisson distribution of the number of trips for each source, destination, and hour. Table 1 presents our results, where the simulation was run 50 times by assuming a Poisson distribution of required flights with mean number of 240 UAVs per hour.

Table 1: Simulation results for the mean number of 240 UAVs per hour.

	without flocking	with flocking
Average UAV route time	2.08818	1.10685 saving ratio: 47%
Average ratio of UAVs that join flocks	0	31.32% of the UAV
Average size of flock	1	1.249

As can be observed, using flocks reduces the traveling time of the UAVs by 47%. Note, however, that the level of reduction depends on the traffic level, and the efficiency of joining flocks increases as the mean UAV number increases. This can be viewed in Figure 2, which shows the saving ratio due to flocking for a mean number of 10 UAV per hour to 240 UAVs per hour. Note that each point in the curve is based on the average result of 50 runs of the simulation.

In order to better understand the results shown in Figure 2, Figure 3 illustrates the average route time required for a UAV to fly independently and the average route time required for a UAV that has the ability to join a flock. Note that as the number of UAV per hour increases, the environment becomes more crowded, and the effect of the load becomes greater when the UAVs cannot form flocks.

As depicted in the figure, the mean saving ratio increases as the number of UAVs per hour increases. This can be easily explained by the fact that the flocking technique is developed for crowded environments, and its importance increases as the environment becomes more crowded.

To summarize, the simulation results show that flocking into groups can save the flight time of individual UAVs, and the saving ratio increases as the environments become more crowded. Thus, the flocking protocol can be implemented by UAV designers in

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[5] https://data.cityofchicago.org

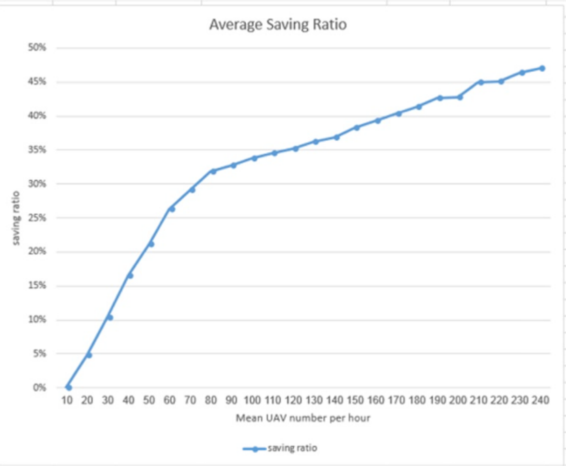

Figure 2: Average saving ratio for different numbers of UAVs per hour.

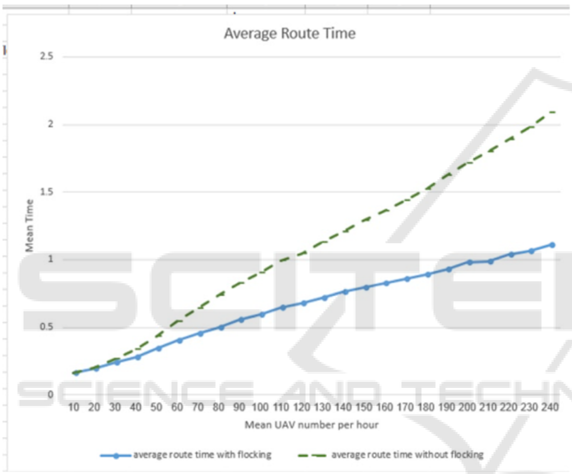

Figure 3: Average journey time with and without flocking.

order to increase flight efficiency and decrease UAV flight time, especially in crowded flight spaces and during busy times.

8 CONCLUSIONS

In this research, we propose a detailed protocol that enables heterogeneous UAVs to join flocks of UAVs that are supposed to travel on similar routes within the same time window. The protocol is based on a common blackboard in which organizing flocks publish their details and interested UAVs can join a flock that matches their requirements Our model allows the individual UAV to determine the optimal route from its point of view.

We checked our protocol by means of simulations and found that it significantly reduces the overhead caused by collisions of UAVs by dozens of percent in the average flight time of UAVs in the airspace.

For future work, we intend to consider situations where the size of the flock is limited and develop strategies that are appropriate for such situations. We will also take into account the possibility of uniting or splitting flocks as needed. In addition, we intend to build a three dimensional simulation of our model. We plan to consider the details of the path planning process and the effect of this process on the profitability of UAV flocking in crowded environments. Finally, in the future we would like to conduct experiments with actual UAVs (instead of working with simulations), in order to examine the effectiveness of our model in real world domains including faulty sensors and actuators and environmental uncertainties such as wind speed.

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