Mobility Models for UAV Group Reconnaissance Applications

Erik Kuiper
Saab Aerosystems
Linköping, Sweden
g-eriku@ida.liu.se

Simin Nadjm-Tehrani
Dept. of Computer and Information Science,
Linköping University, Sweden
simin@ida.liu.se

Abstract

In MANET research the mobility of the nodes is often described using standard synthetic models. Given a particular application, e.g. networks of unmanned aerial vehicles (UAVs) performing a cooperative task, the use of a standard synthetic mobility model can result in incorrect conclusions, as the movement pattern can impact the networking performance of the system. In this paper we present the criteria that characterize desirable mobility properties for the movement of UAVs in a reconnaissance scenario, and provide two mobility models for the scenario. In the first mobility model the UAVs move independently and randomly, and in the second model pheromones guide their movement. The random model is very simple but it achieves mediocre results. The pheromone model has very good scanning properties, but it has problems with respect to network connectivity. The study shows that there in an inherent conflict between the two goals of maximum coverage by frequent rescanning and adequate communication connectivity.

1   Introduction

Future applications of mobile ad hoc networks (MANET) are envisioned to cover a variety of scenarios in which networks of mobile entities cooperate in collecting, processing, and transmitting data in large geographical areas. Examples of such novel constellations are studied with a focus on mobile sensor networks [4], vehicular ad hoc networks (VANETS) [9], swarms of unmanned vehicles [10], and instances of human-centered mobile networks [5]. While the ultimate goal of MANET research is to develop networking functionality that can support novel applications, to test and evaluate this functionality one requires several supporting models, including the model for mobility of the nodes.

Since applications are emerging as the networking technology is being developed, most research proposals employ simulations as a validation tool, and concentrate on design of algorithms and protocols.

Mobility models are often considered to be dependent on specific application domains; hence, simplified universal mobility models are generally used.

To model the movement of the nodes a standard synthetic model is often chosen [1]. The use of a standard mobility model is good since it enables comparison of results. The problem with a standard model is that if the model heavily impacts on the networking performance then it is important that the mobility is representative with respect to the intended real application. This has already been demonstrated by comparative studies on some mobility models [3][11]. In this paper we address the specific requirements of ad hoc networks of unmanned aerial vehicles (UAVs) cooperating to achieve a common mission. Our long term goal is to study MANET algorithms and protocols that provide optimised performance with respect to utilization of resources, and exhibit robust behavior in presence of adversary attacks. To begin with, however, we focus on mobility models. The aim is to propose models that are an abstraction of realistic future mission traces.

The paper defines and evaluates two different mobility models describing the movement of fixed wing UAVs that shall perform reconnaissance over a rural area to detect hostile ground units. The first model uses no coordination between the UAVs and a UAV has no memory of where it has previously been. In the second model the UAVs coordinate using a distributed pheromone repel model. As the UAVs are cooperating to achieve a common goal the mobility models are not limited to only describe the mobility, they may also prescribe the mobility.

The contribution of the paper is the characterization of suitable criteria for appropriate models in the UAV domain, implementation of the two models and a comparative analysis of the models based on simulations. The study shows that coverage of the area and continuous communication are goals that work in opposite directions and the models should be optimized to choose one of these two as primary criterion.

Relation to other works on mobility modeling can be found under section 5. Here we briefly introduce the use of the pheromone model in the application in question. The concept of using pheromones to control movement is inspired by observation of behavior in animals like ants [7]. In the paper by Parunak it is stated that agents in naturally adaptive systems are small in mass, time and space. To be small in mass means that each agent is almost a negligible part of the system, and the loss or incorrect function of an agent is not important. To be small in time means that the knowledge dissipates relatively quickly if it not reinforced, which means that incorrect data is soon forgotten. To be small in space means that each agent is only aware of its immediate vicinity, a good property for distributed systems. To be small in time and space is relatively simple to implement in a system of UAVs. The ability to be small in mass might be more difficult to achieve. The size and cost of UAVs depend on the technology development and the required capability of each UAV. In this paper it is assumed that the number of available UAVs will be relatively limited, and for the simulations we have used ten UAVs.

2 The Scenario

In this section we provide a sketch of the application domain, including the salient aspects of the application that affect the mobility models. In section 3 we present our implementation details.

2.1 Application characteristics

The reconnaissance area in the scenario is a square with a side length of 30 kilometers and all UAVs start at the middle of the south edge heading north. The main objective is to scan the entire area regularly, but at least once every hour. Since the units on ground do not want to be detected the reconnaissance pattern should contain a random element so the units cannot predict when the area they are in will be scanned. The same type of requirements can be found on the searching behavior in the FOPEN (Foliage Penetration) scenario reported in the work by Parunak et al. [8].

For the reconnaissance data to be of any use it needs to be transmitted to the users that need it. In this scenario the user is a command and control center (C&C) located at the UAVs' starting point. This means that all UAVs need a communication path to C&C. As nodes move the direct communication link between a node and C&C will break. To maintain contact with C&C routing via peer UAVs is required. In the scenario it is assumed that the UAVs can only rely on themselves and their peers for the communication. In

Figure 1 a trace of the first 15 minutes of a simulation for one mobility model is illustrated.
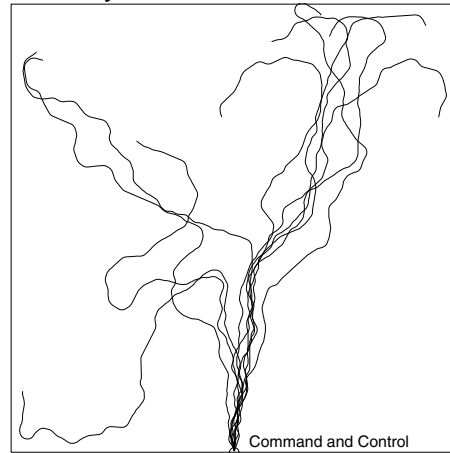

Figure 1. Example movement trace 15 minutes after the start of a simulation.

2.2 Requirements

In this section we cast the above application characteristics into requirements on the mobility models we devise and evaluate. There are 6 main requirements that guide our choice of mobility models. (1) The UAVs are autonomous, meaning no ground-based navigation is allowed. (2) The data provided by UAVs may not be older than prescribed, which requires regular (repetitive) scans of the area to be covered. (3) The application dictates unpredictable movement patterns for UAVs, which should be reflected in some randomness element in mobility models. (4) The mission is successful only if the collected data can be returned to C&C, meaning that maintaining connectivity to C&C is important. (5) The scenario may involve lost or unavailable UAVs, meaning that mobility models and the resulting coverage property should be robust (should not abruptly degrade) as a result of lost UAVs. (6) Communication bandwidth is a limited resource, meaning that there should be no excessive use of bandwidth for routing or mobility-related information exchange.

3 Proposed Mobility Models

For the reconnaissance scenario two mobility models have been developed. The first model is a simple random model with no coordination between the UAVs, an "entity model" according to the taxonomy of Camp et al. [1]. The second model is a distributed pheromone repel model, where the mobility of one UAV can depend on the mobility of the other UAVs.

3.1 UAV Movement

A fixed wing aircraft is limited in its movement in that it has a minimum and maximum air speed and that an instant change of direction is not possible. As we are mainly interested in the behavior of the system of UAVs a coarse description of the movements of the individual UAVs (as opposed to a detailed kinematic model) has been used. The UAVs' movements are described using a 2D model with fixed speed, constant radius turns, and no collisions. The reason to use a 2D model is that all UAVs are flying at about the same altitude and there is no need to model start and landing. A fixed speed is relatively realistic in a reconnaissance scenario. There should be a speed drop during turns, but the benefit of modeling that is expected to be minor. The reason to use constant radius turns is that it is much easier to model, and a more realistic progressive turn model is not expected to add any major value to the simulation. The reason that collisions do not have to be modeled is that it is assumed that the UAVs can make altitude adjustments to avoid collisions.

The following parameters are used:
Flight altitude: 3500 meters (11 000 feet)
Flight speed: 150 km/h (41.7 m/s, 81.0 knots)
Turn radius: 500 meters

3.2 Communication

The pheromone repel mobility models use one hop neighbor communication. For this reason there has to be a communication model detailing the use of common resources (e.g. bandwidth). In this paper a very simple model has been chosen: UAVs within 8000 meters of each other can communicate with infinite bandwidth. If they are further away no communication is possible. Hence we do not model communication protocols at packet level and focus on the results of successful communication (no lost packets, no contention, no overloads). In later extensions of this work, we will return to these limitations, studying the impact of limited bandwidth within the chosen mobility models.

3.3 Reconnaissance Scan

For the reconnaissance mission an image resolution of 0.5 meters is assumed. With an 8 megapixel camera and the image proportions 2:1 (width:length) the scan area becomes 2000x1000 meters. See Figure 2 for an illustration. The camera is assumed to always be directed downwards, even when the UAV is turning.

3.4 Random Mobility Model

The first proposed model, the random mobility model, is a Markov process [6]. Every other second[1] a UAV decides on its actions according to Table 1. If the UAV moves outside the search area then it turns towards the centre of the search area until it has reached a randomly chosen direction -45° to 45° related to the normal of the edge of the search area. Compared to the Gauss-Markov model in [1] this model has no mean direction and the directional change is given as three discrete values, not a continuous distribution.

Table 1. UAV random action table.

Last action	Probability of action		
	Turn left	Straight ahead	Turn right
Straight ahead	10%	80%	10%
Turn left	70%	30%	0%
Turn right	0%	30%	70%

3.5 Distributed Pheromone Repel Mobility Model

To produce a mobility model that is robust and random, we further propose a distributed pheromone repel model. In natural systems the agents place the pheromones in the environment, something that is not possible in a system of UAVs. For this reason each UAV maintains its own pheromone map. The pheromone map is a grid with element size 100*100 meters where each element contains a timestamp representing the last time the element was scanned. As a UAV moves, it marks the areas that it scans on the map. To share this information with the other UAVs each UAV regularly broadcasts (every 10 seconds) a local area pheromone map (a square 5000*5000 meters centered at its current position). All UAVs within the broadcast range merge this information into their pheromone map. The reason for not broadcasting more frequently and only broadcasting a local map is to limit the size of data transferred over the wireless medium (requirement 6 in section 2.2).

As with the random model a UAV decides to turn left or right or go straight ahead every other second. But instead of making this decision with fixed probabilities, the probabilities are based on the pheromone smell in three areas; see Figure 2. Since a UAV should go to places not recently visited it should prefer areas with a low pheromone smell. For that reason the probability of action is defined as specified

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[1] Chosen based on the UAV movement parameters and to produce manageable amounts of data.

in Table 2. Left, Center and Right are the pheromone smells of the areas in Figure 2 and Total is their sum. If no pheromone smell is reported for any direction then a random direction is chosen as in the random model. If the center and either the left or right has no smell then a random direction is chosen between these two. The area outside the search area is given a high pheromone smell for the UAVs to avoid it. A special rule has been added to handle the case when a UAV flies directly into a corner of the area.

Figure 2. Pheromone search pattern

Table 2. UAV pheromone action table.

Probability of action		
Turn left	**Straight ahead**	**Turn right**
(Total – Left) / (2 * Total)	(Total – Center) / (2 * Total)	(Total – Right) / (2 * Total)

4   Evaluation

The three reconnaissance requirements on the system were to scan the entire area at least once every hour, to have a random scanning pattern and to maintain communication paths to C&C for all UAVs (requirements 2, 3 and 4 in section 2.2). The compatibility of the mobility models with respect to the above characteristics will now be evaluated in a number of studies.

The mobility models were tested by performing 10 independent runs per model. Each run simulates 10 UAVs for 2 hours. At the start of a simulation all UAVs are at the command and control center.

4.1   Scan Coverage

The initial goal is to scan the area as fast as possible. When the initial scan is completed the UAVs need to continuously monitor the area by rescanning every part at least once per hour. The absolute maximum scan

speed is 0.083 km²/second/UAV according to equation (1) and the data from section 3.

Scan speed = UAV speed * scan area width   (1)

Given the area of 900 km² the fastest time to cover the whole area (which is in practice impossible) is 18 minutes (1080 seconds). Adding the overhead of turning and additional requirements like randomness a coverage time of 40 minutes (2400 seconds) should be feasible.

The coverage data from the two mobility models can be found in Figure 3 and Figure 4. The graphs plot all the coverage curves from the 10 simulation runs.
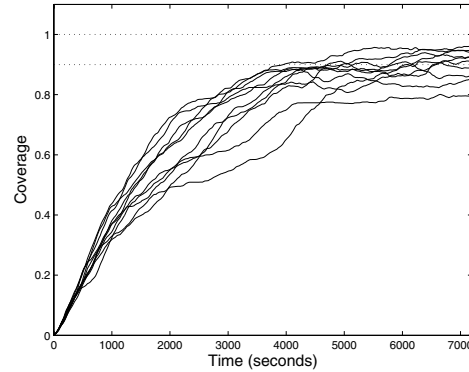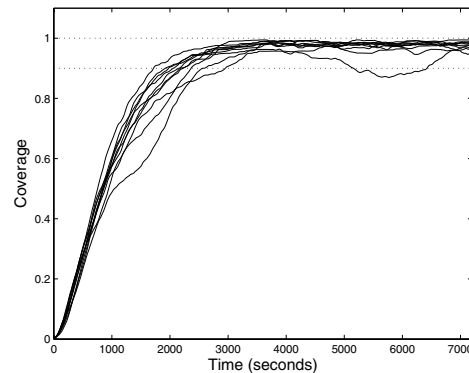

Figure 3. Random mobility coverage

Figure 4. Pheromone mobility coverage.

The random mobility model does not seem to have reached steady state after the two hour run, but from the data is seems reasonable that a coverage level of about 80% should be achieved. The pheromone model on the other hand has a much better coverage curve. After about one hour a steady state is reached and a coverage level of over 90% can be expected.

Comparing the two models the pheromone model has a much higher coverage rate and it can maintain a significantly higher steady state level than the random model.

4.2 Scan Characteristic

Both mobility models have been designed to produce unpredictable scanning patterns, but patterns that should fulfill the desired application properties. The randomness of the scanning can be investigated by looking at the probability distribution of the time between scans. In Figure 5 and Figure 6 the probability distributions of the two models are shown by the solid lines (average and 95% interval). After the end of a scan (at time 0 in the graph) the area under the curve for a particular interval gives the probability of the next scan appearing in that interval.
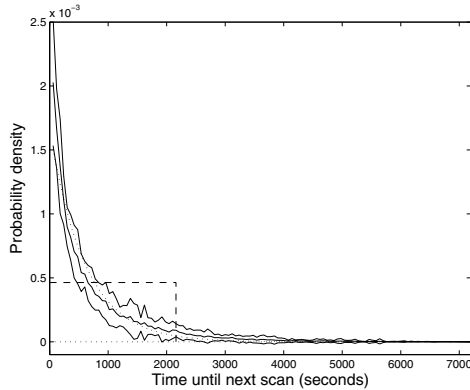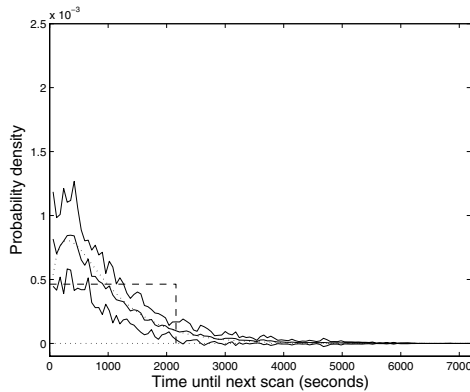

Figure 5. Random mobility

Figure 6. Pheromone mobility

The question is then; what is the desired distribution? To this question there is no definite answer, but a uniform distribution (dashed line in the graphs) should be an attractive result. This would mean that the probability of the next scan is evenly distributed over some time period. The only firm requirement on the distribution function is that it shall be zero after one hour to meet the one hour rescan requirement. What is very obvious from these two graphs is that the pheromone model manages quite well to avoid rescanning a recently scanned area. As we saw in the scan coverage graph no model manages

to achieve 100% coverage. This is seen by the fact that the function is not zero after one hour.

Comparing these two distributions to the chi-square distribution (after scaling) the random distribution is close to the chi-square distribution with two degrees of freedom and the pheromone to the one with three degrees of freedom (the dotted line close to the simulated results). These approximations could be used in further analyses of the scan characteristics.

The limitation of the probability distribution graphs is that they do not include the areas never scanned or only scanned once. To see the capability of the models to scan the complete area at least once the maximum, median and minimum uncovered area for the ten runs are shown in Table 3 for the two models. These numbers clearly show the ability of the pheromone model to cover the complete area.

Table 3. Never scanned area

	Max	Median	Min
Random	16.2%	3.2%	0.5%
Pheromone	0.21%	0.03%	0.01%

4.3 Communication

Reconnaissance data has no value if it cannot be transmitted to where it is needed. For this good connectivity is required. The connectivity metric shown here is the maximum possible connectivity. In a real environment routing protocol behavior and transmission disturbances will make these results worse (an aspect that we will study in later work).

In Figure 7 and Figure 8 the number of UAVs that can reach command and control directly or via neighbor peers is illustrated. The graphs show the maximum, average, and minimum number of UAVs in contact with C&C at any given time for the 10 runs. Neither the random nor the pheromone mobility model provides good connectivity. This indicates that the number of UAVs is not enough to naturally create a fully connected communication graph given the area, size, and communication link range. The pheromone logic pushes the UAVs away from each other which quickly gives a low constant connectivity. With the random model it takes more time for the UAVs to be evenly distributed over the area, but at the end of the simulation the random model has the same poor connectivity as the pheromone model.
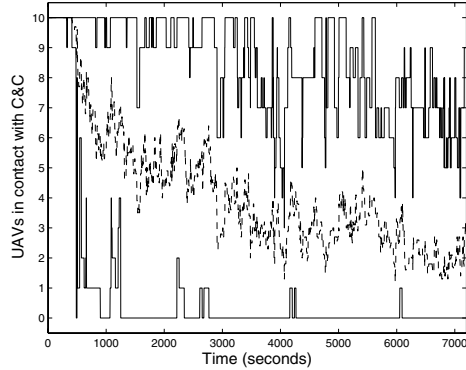
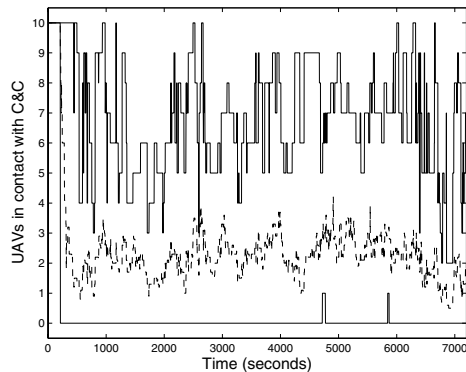**Figure 7. Random. Number of UAVs in contact with C&C (max, average, min).**

Figure 8. Pheromone. Number of UAVs in contact with C&C (max, average, min).

5   Related Works

The use of pheromones to guide UAVs and other vehicles in reconnaissance scenarios is not a new idea. The viability of the principle has been shown by simulation and practical tests [8][2][10]. The research in all the three referred papers was financed by the US military. For that reason the models used are not publicly available which makes it difficult to build on this research and verify the results. Additionally several design choices are not very well elaborated in the papers.

Sauter et al. [10] show by simulation that pheromone logic can be used for several types of surveillance and target acquisition and tracking scenarios. They have also shown by practical demonstration that the technique works in practice. To guide the vehicles several types of pheromones are used, both repulsive and attractive. For the basic surveillance scenario two types of pheromones are used, one repulsive and one attractive. In their scenario the area to be surveyed generates attractive pheromones. When an area is visited the attractive pheromones are removed and no new pheromones are

generated for some set time. To avoid that two vehicles try to survey the same area a vehicle places repulsive pheromones in the next place it plans to move to. The pheromones placed diffuse which create pheromone gradients that the vehicles use to guide their movement. There are two main issues with their model. The first is that there seems to be a global pheromone map that all agents can access. This might closely simulate the real-life insect pheromone systems, but in a mechanical system where pheromones need to be placed in a virtual map this means that there is a central node managing the map. This design makes the system sensitive to the failure of that node and all vehicles require good communication to this node. Another issue is that they do not discuss how a vehicle determines where to go. That it is based on the pheromone map is clear, but the areas evaluated in order to select where to go is not described.

Parunak et al. [8] propose two approaches to perform target localization and imaging. In the entity (individualistic) approach the UAVs use offline determined paths to guide their movement. In the group (team) approach visitation pheromones are used to deter UAVs from visiting areas recently visited. To produce a distributed and robust solution each vehicle maintains its own pheromone map. When a UAV passes through an area it updates its internal map and broadcasts its position, which makes it possible for all UAVs within communication range to update their maps. When a UAV shall decide on its movement it randomly selects a location, where the probability is inversely proportional to the distance to the location and the pheromone concentration in the location. A drawback of the paper is that it provides no evidence of the performance of the localization and imaging approaches, which makes them difficult to evaluate.

Gaudiano et al. [2] test several control principles for an area-coverage mission. From the tested approaches the pheromone one was the best. The problem with their pheromone strategy is that is seems to rely on a global pheromone map, giving the same problem as with the Sauter et al. solution. Additionally, there is no dissipation of the pheromones in the simple reconnaissance scenario, a property that they do use in a suppression mission scenario also presented in the paper. Further, they only run the system for a limited time and it never reaches more than 65% coverage.

6 Conclusions and Future Work

This study shows that our proposed pheromone repel logic works well to achieve scan coverage and randomness in a reconnaissance scenario. The down side is that the UAVs are forced away from each other, which gives poor networking characteristics. In the random model the coverage is worse and the connectivity at the end of the simulation is on par with the pheromone model. The conclusion is that coverage and connectivity of communication are two conflicting objectives.

Before MANET routing and networking functionality can be studied using the presented models, the problem with the connectivity properties needs to be addressed. One option would be to change the pheromone model to encourage the UAVs to stay in communication range of each other and of C&C. An alternative approach could be to relax the limited bandwidth requirement and permit temporary storage of data as it is moved towards C&C. Current work deals with the connectivity issue in a scenario in which C&C is replaced by several mobile ground-based subscribers.

Furthermore the robustness of the coverage properties (requirement 5) need to be evaluated. This can for example be done by randomly removing some UAVs during the runs.

The main goal for this study was to produce a mobility model that can be used for MANET research in the UAV domain. When the connectivity properties have been addressed the next step will be to detail the communication model and to simulate packet-based communication. Based on this foundation combined routing, resource allocation and security issues can be studied.

Acknowledgements

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