Topology Control and Mobility Strategy for UAV Ad-hoc Networks: A Survey [⋆]

Zhongliang Zhao, Torsten Braun

Institute of Computer Science and Applied Mathematics, University of Bern
Neubrückstrasse 10, 3012 Bern, Switzerland
Email: {zhao, braun} @iam.unibe.ch

Abstract. Advances in electronics and software are allowing the rapid development of small unmanned aerial vehicles (UAVs), capable of performing autonomous coordinated actions. Developments in the area of lithium polymer batteries and carbon fiber-reinforce plastic materials let UAVs become an aerial platform, that can be equipped with a variety of sensors such as cameras. Furthermore, it is also possible to mount communication modules on the UAV platform in order to let the UAVs work as communication relays to build a wireless aerial backbone network. However, the cooperative operation between multiple autonomous unmanned aerial vehicles is usually constrained by sensor range, communication limits, and operational environments. Stable communication systems of networked UAVs and sensing nodes will be the key technologies for high-performance and remote operation in these applications. The topology of the UAV ad-hoc network plays an important role in the system performance. This paper discusses the state-of-art schemes that could be applied as the topology control of the UAV ad-hoc networks.

Keywords: UAVs, connectivity, coverage, mobility, topology control

1 Introduction

Recent developments of autonomous unmanned aerial vehicles (UAVs) and wireless sensor networks (WSNs) allow automated approaches to surveillance with minimal human intervention. A feasible solution is to deploy a set of UAVs, each mounted with a communication module like a wireless mesh node. In this way a wireless backbone can be built, over which various entities on the ground such as rescue teams, relief agencies, first responders can communication with each other. A system of aircrafts would provide mobile ad-hoc networks (MANETs) connecting ground devices with flying UAVs, as well as the inter-connection between different UAVs, as shown in Figure 1. One plausible approach to achieve this is to maintain a fully connected network of UAVs at all time, so that a given UAV can talk with any other UAVs using multi-hop ad hoc routing. However, oftentimes there are not enough UAVs to establish a continuous path between two points on the ground and this is a huge problem for solutions that require a fully connected UAV mesh. The notion of continuous path between end-points

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only makes sense when the relay nodes are stationary. When the nodes are capable of moving, especially in UAV ad-hoc networks that include nodes moving in a highly mobile way, it becomes extremely difficult to maintain continuous connectivity. Therefore, a decentralized agent-based motion planning approach is usually applied for UAV controlling. Compared with the centralized approach, autonomous agents are more robust against wireless link failures which might happen due to poor coverage and reliability of cellular technologies in higher altitudes. Since UAVs have to fly with a certain formation to keep connectivity with each other, topology control plays a crucial role. In this paper we give a review of existing typical swarm models proposed in the literature that could be applied for deploying and controlling groups of unmanned aerial vehicles. Three approaches are presented: Boids Flocking, Potential Fields and Virtual Spring.

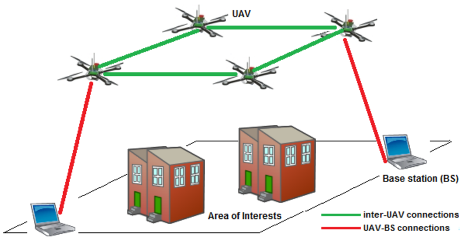

Fig. 1. UAV Ad-hoc Networks Scenario.

The remainder of the paper is organized as follows. In section 2, we describe the latest developments and essential problems of UAV ad-hoc networks. Different application scenarios will be introduced within the section. In section 3, we focus on the topology control of the UAVs ad-hoc networks and three different approaches are described, which can be regarded as the possible solutions for decentralized UAVs topology control. Based on these concepts, our proposed approach is also discussed in this section. Finally, section 4 concludes the paper.

2 UAV Ad-hoc Networks

A mobile ad-hoc network (MANET) is a wireless network that is formed by a collection of self-organizing mobile nodes. Each node communicates with its neighbors over a shared wireless medium. Due to the lack of central management, nodes in MANETs are designed to act as end systems and routers for other nodes. The network is established dynamically and does not rely on any pre-existing network infrastructure. In MANETs, nodes are free to move and have the capability of deliver messages in a decentralized manner. UAVs have the potential of creating an ad-hoc network in the air, namely UAV ad-hoc networks. Most UAVs used in communication networks are equipped with wireless transceivers using omni-directional antennas. In UAV ad-hoc network communication environments, due to the fast mobility of UAVs, network topology may change rapidly and unpredictably. As a result, UAVs are expected to act cooperatively to establish network connections for data routing. When UAVs perform a cooperative task by flying as a group, they can be considered flying in a formation. Formations must safely reconfigure in response to changing missions, UAV density and environment. Additionally, wireless links within a UAV ad-hoc network may alter in link quality over time due to a number of reasons, such as Doppler effects, changes in communication distance, etc. All these requirements make topology control more important in a UAV ad-hoc network environment.

Despite numerous design challenges, there are many application scenarios for UAV ad-hoc networks. Such UAV swarms have a wide variety of applications in both civil and military domains since they are rapidly deployable and highly survivable. There are many separate capabilities for use in addressing application-specific problems: (i) ground sensing; (ii) the ability to bridge communication, etc. Brief examples of these include: search and rescue; chemical/biological/radiological pollution monitoring; disaster recovery, e.g., flooding damage assessment; overflight of sensor fields for the purpose of data collection; and agriculture application[1]. A practical work about the autonomous deployment of a UAV ad-hoc network could be found in [2].

3 Topology Control of UAV Swarms

The absence of central infrastructure implies that an ad hoc network does not have an associated fixed topology. Indeed, an important task of an ad hoc network consisting of geographically dispersed nodes is to determine an appropriate topology over which high-level routing protocols are implemented. Topology control algorithms for wireless ad-hoc networks are mainly based on controlling and adapting the transmission power of nodes. Exploiting the high mobility of nodes, such as UAVs, will bring challenges.

In the following, we will first outline the relationship between coverage and connectivity in UAV ad-hoc networks. After that three mechanisms which might be applied for helping topology control in UAV ad-hoc networks are described.

3.1 Connectivity *versus* Coverage

The novelty of UAV ad-hoc network systems is that the movement of UAVs is controlled by fully autonomous algorithms with two objectives: first to maintain network connectivity to enable real-time communication between UAVs and ground devices; second, to increase sensing coverage to rapidly identify targets. The major resource constraints of using UAVs are battery power, communication bandwidth and processing capabilities. The life time of UAVs and the on-board radio transmission distance are limited. Thus, the behavior of UAV swarms regarding flight routes and communication has to be efficient. Therefore the global requirement of achieving spatial coverage and the local requirement of keeping connectivity could be regarded as contrary to each other. On one hand, high coverage in space is needed for gaining pertinent information from disjunct perspectives that cover a large region of interest. On the other hand, a disruption-free connectivity is indispensable, which mainly depends on the signal degradation due to propagation loss. Hence, the distances in the UAV ad-hoc network configuration must not exceed the receiver's sensitivity and need to be restricted to the boundaries of minimum signal-to-noise-ratio (SNR) or receive signal strength indicators (RSSI) respectively.

3.2 Boids Flocking

Boids flocking [3] is the first and major study on agent-based behaviors. It was the pioneering study where bio-inspired cooperative movements of agents have been developed. Due to its decentralized control mechanism, boids flocking could be considered as a basis to deploy aerial swarms in simulation.

[3] developed a computer animation model for coordinated motion of groups of animals such as bird flocks and fish schools. This flocking model consists of three steering rules that describe how an individual agent(so called “boid”) independently maneuvers based on the positions and velocities of its nearby flock-mates (as shown in Figure 2):

- **Separation**: steer to avoid crowding local flock-mates.
- **Alignment**: steer towards the average heading of local flock-mates.
- **Cohesion**: steer to move towards the average position of local flock-mates.

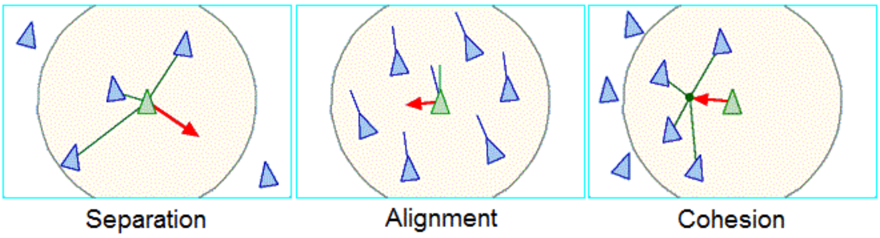

Fig. 2. Local separation, alignment and cohesion on the motion of flocking agents.

Separation could be regarded as collision avoidance, to enable agents be repulsed from neighboring agents to avoid collisions. Alignment enables agents to align their velocities(both speed and direction) to the average of neighboring agents. Cohesion empowers agents to be attracted to the average centroid of neighboring agents to stay close to neighbors. The superposition of these three rules results in all flying agents moving in a formation, with a common heading while avoiding collisions. An extension work of boids flocking is [6], which invented a discrete force model for pedestrian motion.

3.3 Potential Field

Potential field techniques for robotic applications were first described by Khatib in [4] and have been widely used in the mobile robotic community for tasks such as goal seeking and obstacle avoidance.

In this context, objects like goal area or obstacles will be occupied by artificial or virtual potential fields. There are mainly two different types of fields: an attractive potential field, and a rejective potential field. Attractive field corresponds to a seek-goal behavior, and rejective field corresponds to a collision/obstacle avoidance behavior. In general, the repelling forces decrease with distance and the attracting forces increase with distance. The calculation of the type and strength of the potential field created by obstacles, other UAVs or communication infrastructure is based on the agent’s sensors. Usually, it can be assumed that the strength of the potential field is inversely proportional to the distance between two objects, as shown in Figure 3⋆.

3.4 Virtual Spring

A virtual spring-based model is proposed by [5]. According to the model, within a specified neighborhood radius, each vehicle forms a virtual connection with

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⋆ http://students.cs.byu.edu/ cs470ta/goodrich/fall2004/lectures/Pfields.pdf.

each neighbor vehicle by a virtual spring. As the vehicle changes its position, speed and altitude, the total resulting forces on each virtual spring try to equal zero by moving to the mechanical equilibrium point. The agents then add the simple total virtual spring constraints to their movements to determine their next positions individually. Together, the multi-agent vehicles reach a group behavior, where each of them keeps a minimal safe-distance with others. A new safe behavior thus arises in the group level. When the spring forces are applied to an agent, the total applied force is defined[⋆] as:

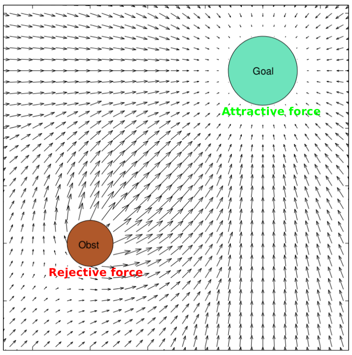

Fig. 3. Potential fields of attractive, rejective and combined.

$$F_{x|y|z} = \sum_{i=1}^{n} \frac{\Delta L_i \times K_i \times (X_i|Y_i|Z_i - X_A|Y_A|Z_A)}{D_i}$$

in which X_A, Y_A, Z_A specify the present position of an agent, n is the number of factors the agent has spring connections with (for this case it is equal to the number of neighbors), L_i is the length of the spring with i^{th} factor, K_i is the constant of that spring, D_i is the distance to the i^{th} factor and (X_i, Y_i, Z_i) specify the position of the i^{th} point.

According to [5], vehicles need no direct communication with each other, require only minimum local processing resources, and the control is completely distributed. However, this is under the assumption that each vehicle knows the neighbors' position, which come from the messages exchange with neighbors.

As a summary, a comparison of three models could be found in Table 1, which lists the pros or cons, and the possible applications of different approaches.

Mechanism	**Pros or Cons**	**Applications**
Boids Flocking	*Cons:* Mostly for computer animation.	Connectivity
Virtual Spring	*Cons:* Only distance is utilized, not accurate.	Coverage
Potential Field	*Pros:* Both distance and RSSI are used.	Coverage & Connectivity

Table 1. Comparison of three approaches

3.5 Adaptation of Swarm Control Concepts for Topology Control in UAV Ad-hoc Networks

Since the possibility of connectivity losses can not be absolutely avoided in a UAV ad-hoc network environment, it is essential to ensure the viability of all UAVs and the fulfillment of the overall mission objectives. Subsequently, UAVs within the swarm are designed as autonomous agents, which are capable to react cognitively on environmental changes such as connectivity and sensor perception. On this basis, UAVs should adapt their motion to positions with channel characteristics to provide better network connectivity or coverage.

Based on the concepts described before, we propose to develop a topology control protocol inspired by the potential field approach, with some adaptation.

[⋆] $X|Y|Z$ means X or Y or Z.

The strength of the artificial field, which interconnects the UAVs, is calculated dependent on both the RSSI value and distance measured between two UAVs. Our assumption is that, due to the fact that each UAV is equipped with a GPS module, it can broadcast its position to inform the neighbors about their distance. A lower/upper distance bounds between UAVs will be defined. Within these bounds, RSSI signal is utilized to adapt the movements of UAVs. If the RSSI is too low, the force for attracting two UAVs becomes higher, two UAVs will fly close to each other to keep the connectivity. If the RSSI is too high, UAVs are too close and therefore they need to be pushed away from each other. In case of temporary invalid recognition of RSSI, as an alternative, GPS information might still be available and utilized for controlling the movement of UAVs. Besides, to avoid obstacle collisions, in which UAVs can not retrieve any RSSI value from the obstacle, GPS information of the obstacle (i.e., derived from a leading UAV with cameras) will enable UAVs to calculate the distance to steer their movements. Another important design issue is that, in general the inter-reactions between agents of a swarm can only change the relative position of each other within the swarm, and can not modify the movement of the swarm itself. Without any external intervention, the motion of the swarm will keep its initial state, which is unknown in most cases. Therefore, in order to have the swarm moving in an expected manner, it is necessary to control the swarm in a way, i.e., to define a “leader-follower” structure and give commands to the “leader”. Interferences and impacts of cross flows will also be considered in the future.

4 Conclusions

In this work, we summarize the mechanisms that could be applied for controlling the movements of mobile ad-hoc UAV swarms. An adaptation of the potential field approach is also presented, which takes into account both distance and RSSI for UAV steering. As a conclusion, topology control in UAV ad-hoc networks must consider application requirements in terms of node density, e.g., when a certain sensing coverage is needed. Alternatively, transmission power can be changed depending on the application in terms of node density and area coverage.

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