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Survey Paper

Flying Ad-Hoc Networks (FANETs): A survey

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ABSTRACT

One of the most important design problems for multi-UAV (Unmanned Air Vehicle) systems is the communication which is crucial for cooperation and collaboration between the UAVs. If all UAVs are directly connected to an infrastructure, such as a ground base or a satellite, the communication between UAVs can be realized through the in-frastructure. However, this infrastructure based communication architecture restricts the capabilities of the multi-UAV systems. Ad-hoc networking between UAVs can solve the problems arising from a fully infrastructure based UAV networks. In this paper, Flying Ad-Hoc Networks (FANETs) are surveyed which is an ad hoc network connecting the UAVs. The differences between FANETs, MANETs (Mobile Ad-hoc Networks) and VANETs (Vehicle Ad-Hoc Networks) are clarified first, and then the main FANET design challenges are introduced. Along with the existing FANET protocols, open research issues are also discussed.

1. Introduction

As a result of the rapid technological advances on electronic, sensor and communication technologies, it has been possible to produce unmanned aerial vehicle (UAV) systems, which can fly autonomously or can be operated remotely without carrying any human personnel. Because of their versatility, flexibility, easy installation and relatively small operating expenses, the usage of UAVs promises new ways for both military and civilian applications, such as search and destroy operations [1], border surveillance [2], managing wildfire [3], relay for ad hoc networks [4,5], wind estimation [6], disaster monitoring [7], remote sensing [8] and traffic monitoring [9]. Although single-UAV systems have been in use for decades, instead of developing and operating one large UAV, using a group of small UAVs has many advantages. However, multi-UAV systems have also unique challenges and one of the most prominent design problems is communication. In this paper, Flying Ad-Hoc Network (FANET), which is basically ad hoc network between UAVs, is surveyed as a new network family. The differences between Mobile Ad-hoc Network (MANET), Vehicular Ad-hoc Network (VANET) and FANET are outlined, and the most important FANET design challenges are introduced. In addition to the existing solutions, the open research issues are also discussed.

Along with the progress of embedded systems and the miniaturization tendency of microelectromechanical systems, it has been possible to produce small or mini UAVs at a low cost. However, the capability of a single small UAV is limited. Coordination and collaboration of multiple UAVs can create a system that is beyond the capability of only one UAV. The advantages of the multi-UAV systems can be summarized as follows:

- Cost: The acquisition and maintenance cost of small UAVs is much lower than the cost of a large UAV [10].
- Scalability: The usage of large UAV enables only limited amount of coverage increases [11]. However, multi-UAV systems can extend the scalability of the operation easily.

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- Survivability: If the UAV fails in a mission which is operated by one UAV, the mission cannot proceed. However, if a UAV goes off in a multi-UAV system, the operation can survive with the other UAVs.
- Speed-up: It is shown that the missions can be completed faster with a higher number of UAVs [12].
- Small radar cross-section: Instead of one large radar cross-section, multi-UAV systems produce very small radar cross-sections, which is crucial for military applications [13].

Although there are several advantages of multi-UAV systems, when compared to single-UAV systems, it has also unique challenges, such as communication. In a single-UAV system, a ground base or a satellite is used for communication. It is also possible to establish a communication link between the UAV and an airborne control system. In all cases, single-UAV communication is established between the UAV and the infrastructure. While the number of UAVs increases in unmanned aerial systems, designing efficient network architectures emerges as a vital issue to solve.

As in a single UAV system, UAVs can also be linked to a ground base or to a satellite in a multi-UAV system. There may be variants of this star topology based solution [14]. While some UAVs communicate with a ground base, the others can communicate with satellite/s. In this approach, UAV-to-UAV communication is also realized through the infrastructure. There are several design problems with this infrastructure based approach. First of all, each UAV must be equipped with an expensive and complicated hardware to communicate with a ground base or a satellite. Another handicap about this network structure is the reliability of the communication. Because of the dynamic environmental conditions, node movements and terrain structures, UAVs may not maintain its communication link. Another problem is the range restriction between the UAVs and the ground base. If a UAV is outside the coverage of the ground base, it becomes disconnected. An alternative communication solution for multi-UAV systems is to establish an ad hoc network between UAVs, which is called FANET. While only a subset of UAVs can communicate with the ground base or satellite, all UAVs constitute an ad hoc network. In this way, the UAVs can communicate with each other and the ground base.

FANET can be viewed as a special form of MANET and VANET. However, there are also certain differences between FANET and the existing ad hoc networks:

- Mobility degree of FANET nodes is much higher than the mobility degree of MANET or VANET nodes. While typical MANET and VANET nodes are walking men and cars respectively, FANET nodes fly in the sky.
- Depending on the high mobility of FANET nodes, the topology changes more frequently than the network topology of a typical MANET or even VANET.
- The existing ad hoc networks aim to establish peer-to-peer connections. FANET also needs peer-to-peer connections for coordination and collaboration of UAVs. Besides, most of the time, it also collects data from the environment and relays to the command control center, as in wireless sensor networks [15]. Consequently, FANET must support peer-to-peer communication and converge cast traffic at the same time.
- Typical distances between FANET nodes are much longer than in the MANETs and VANETs [16]. In order to establish communication links between UAVs, the communication range must also be longer than in the MANETs and VANETs. This phenomenon accordingly affects the radio links, hardware circuits and physical layer behavior.
- Multi-UAV systems may include different types of sensors, and each sensor may require different data delivery strategies.

The main motivation of this paper is to define FANET as a separate ad hoc network family and to introduce unique challenges and design constraints. Although, there exists a few studies that address some specific issues of networked UAVs [17,18,14], to the best of our knowledge, this is the first comprehensive survey about FANETs.

The paper is organized as follows. In Section 2, we present several FANET application scenarios and introduce FANET design characteristics in Section 3. We provide an extensive review of the existing communication protocols and the open research issues in Section 4. We also present the existing multi-UAV test beds and simulation environments in Section 5. We conclude the paper in Section 6.

2. FANET application scenarios

In this section, different FANET application scenarios are discussed.

2.1. Extending the scalability of multi-UAV operations

If a multi-UAV communication network is established fully based on an infrastructure, such as a satellite or a ground base, the operation area is limited to the communication coverage of the infrastructure. If a UAV cannot communicate with the infrastructure, it cannot operate. On the other hand, FANET is based on the UAV-to-UAV data links instead of UAV-to-infrastructure data links, and it can extend the coverage of the operation. Even if a FANET node cannot establish a communication link with the infrastructure, it can still operate by communicating through the other UAVs. This scenario is illustrated in Fig. 1.

There are several FANET designs developed for extending the scalability of multi-UAV applications. In [19], a FANET design was proposed for the range extension of multi-UAV systems. It was stated that forming a link chain of UAVs by utilizing multi-hop communication can extend the operation area.

It should be noticed that the terrain also affects the communication coverage of the infrastructure. There may be some obstacles on the terrain, such as mountains, walls or buildings, and these obstacles may block the signals of the infrastructures. Especially in urban areas, buildings and constructions block the radio signals between the ground base and UAVs. FANET can also help to operate be-