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Molecular geometry inspired positioning for aerial networks

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ABSTRACT

The advances in unmanned aerial vehicle (UAV) and wireless sensor technology made it possible to deploy aerial networks and to collect information in three dimensional (3D) space. These aerial networks enable high quality observation of events as multiple UAVs coordinate and communicate for data collection. The positioning of UAVs in aerial networks is critical for effective coverage of the environment and data collection. UAV systems have their characteristic constraints for node positioning such as dynamic topology changes or heterogeneous network structure. The positioning methods for two dimensional (2D) scenarios cannot be used for aerial networks since these approaches become NP-hard in 3D space.

In this paper, we propose a node positioning strategy for UAV networks. We propose a wireless sensor and actor network structure according to different capabilities of the nodes in the network. The positioning algorithm utilizes the Valence Shell Electron Pair Repulsion (VSEPR) theory of chemistry, which is based on the correlation between molecular geometry and the number of atoms in a molecule. By using the rules of VSEPR theory, the actor nodes in the proposed approach use a lightweight and distributed algorithm to form a self organizing network around a central UAV, which has the role of the sink. The limitations of the basic VSEPR theory are eliminated by extending the approach for multiple central data collectors. The simulation results demonstrate that the proposed system provides high connectivity and coverage for the aerial sensor and actor network.

1. Introduction

The advances in unmanned aerial vehicle (UAV) systems made it possible to use autonomous or remotely operated UAVs in various applications such as environmental monitoring and battlefield surveillance. UAV solutions are cost effective and flexible compared to traditional aerial applications with personnel. The range of UAV applications has been increasing as UAVs have been equipped with multiple sensors for collecting different types of data such as thermal, visual or chemical observations. Although current approaches mostly use UAVs in solo flight, there are emerging concepts for employing multi-UAV systems as flying ad hoc networks (FANETs) [1]. Compared to a single UAV application, FANETs have several advantages such as scalability and survivability.

In a coordinated FANET, the capabilities and sizes of UAVs change according to their communication types to form a wireless sensor and actor network (WSAN) [2]. UAVs acting as sensor nodes are generally smaller and they only collect data from the environment. These small UAVs cannot carry heavy long distance communication hardware due to their limited weights and they are inexpensive compared to fully equipped research aircrafts, which act as actor nodes. Actor or sink UAVs require stronger communication hardware to communicate with an infrastructure or to communicate through longer distances. In addition

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to data collection, actor nodes also act on the environment by using actuators such as servo-mechanisms. For instance, low-flying helicopter platform by Thrun et al. [3] provides ground mapping and air-to-ground cooperation of autonomous robotic vehicles. Besides acting on the environment and collecting data, actor nodes perform networking functionalities such as processing or relaying of data in multi-UAV solutions. Therefore, these aerial networks are heterogeneous in terms of UAV types.

The application areas of FANETs expand continuously as the UAV technology is improved. We focus on application scenarios, in which the FANETs are used to cover the three dimensional (3D) space to execute the tasks of the system such as observation, monitoring or measurement. Volcanic plume sampling is one of these applications, where coordinated teams of UAVs are used to sample the airspace and provide an accurate mapping of distributed particles from recent volcanic eruptions [4]. These applications are time-critical since the maximum volume of the 3D space, where the plume is observed, must be covered and reported by the FANET. The efficient coverage of 3D space also plays an important role in atmospheric measurements. The Atmospheric Radiation Measurement (ARM) program [5] used UAV measurements to understand cloud and radiative processes. The FANETs provide expanded access to the atmosphere and clouds beyond what piloted aerial vehicles allow [6]. Therefore, FANETs allow studying 3D space for applications that are impossible with conventional aerial vehicles. In most of these applications, UAVs are deployed in regular topologies as they are deployed in an unrestricted aerial space and the main goal is the optimal coverage of 3D volume. However, they can also be integrated with obstacle avoidance approaches [7] for the cases where the UAV deployment is required to follow contours of the monitored area.

In this paper, an actor positioning strategy for aerial WSANs is presented to achieve 3D coverage while preserving 1-hop connectivity from each actor UAV to the central UAV in unprecedented settings of the scenario. The actors use a lightweight and distributed algorithm based on the Valence Shell Electron Pair Repulsion (VSEPR) theory [8] to form a self organizing actor network. VSEPR theory is originally used in chemistry for the prediction of peripheral atom alignments around a central atom. This concept is adopted to define the rules of the algorithm designed to determine the actor positions. The basic VSEPR theory has limitations on the number of central and surrounding nodes. These limitations are eliminated by extending the adopted theory for multiple sinks to improve the scalability of the approach.

The main contributions of this paper are twofold. First, VSEPR theory is applied to the actor positioning based on the correlation between the molecular geometry and the number of atoms in a molecule. The approach creates a mapping between the actors and the electron pairs. Then the locations of actors are formalized according to the location of the sink and the properties of the VSEPR theory geometries. This positioning strategy is also extended for geometries up to 50% more actors. Second, an approach for the definition of multiple sink topologies is presented. For multiple sink scenarios, the capabilities of sink nodes are used to form a mesh network and to avoid a central coordinator node. The actors are shared by the sinks either in a balanced fashion or by using a preferential attachment based approach.

The rest of the paper is organized as follows. Section 2 summarizes the related work. We provide a detailed description for our approach in Section 3. We present the simulation results in Section 4 and finally conclude in Section 5.

2. Related work

Although there is an increasing interest in applications of sensor networks in 3D space such as space exploration or airborne surveillance, most of the literature on dynamic node positioning and routing strategies is limited to two dimensional (2D) space (see [9–11]). In the conventional 2D scenarios, the maximal coverage problem is mapped to a circle packing formulation which has a polynomial time solution. This problem turns into the sphere packing problem in three dimensions and the strategies designed for two dimensions become NP-hard in 3D space. The optimization strategies for 3D setups mostly focus on coverage problems.

Most of the 3D applications include assumptions such as homogeneous node types or a priori knowledge of every location in the network for node positioning. These assumptions are not applicable in real life environmental monitoring scenarios, which have two important challenges. First, the problem of coverage in 3D space is a critical part of the scenario for the observation of an environment. The number of nodes and their locations are restricted by the investigated environment and the reception ranges of nodes. Second, the dynamic UAV network topology and flight must be handled efficiently considering the communication constraints of the vehicles. Ravelomanana [12] studies the properties of network topologies that result from random deployment of nodes in a 3D region of interest to provide the theoretical bounds. The study derives conditions for the node transmission range r required for achieving a degree of connectivity d, where every node has at least d neighbors. Li et al. [13] obtained the lower and upper bounds for capacities of both 3D regular and heterogeneous ad hoc networks. Akkaya and Newell [14] proposed a distributed node deployment scheme for underwater acoustic sensor networks. The nodes in this approach are relocated at different depths based on a local agreement in order to reduce the sensing overlaps among the neighboring nodes. Peppas and Turgut [15] has developed a hybrid routing algorithm for a specialized scenario consisting of a network of flying UAVs executing reconnaissance missions. Three different types of UAVs with various speeds, altitudes, and paths are considered for coordination of terrain identification process. Alam and Haas [16] argue that space filling polyhedrons would be more suitable for 3D coverage and aim to fill the 3D application space with the least number of polyhedrons for maximal coverage. Zhou et al. [17] present two algorithms for discovering boundary nodes and constructing boundary surfaces in 3D wireless networks. Bai et al. [18] designed and proved the optimality of one and two connectivity