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Collision-free reinforced barriers in UAV networks

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ABSTRACT

Unmanned Aerial Vehicle (UAV) networks have gained a lot of interest because of their effectiveness and great potential. One of major challenges in UAV networks is a collision avoidance and should be addressed carefully. Also, a barrier-coverage has been studied widely since it can be utilized in promising applications for border surveillance and intrusion detection. In this study, we introduce a framework for constructing a collision-free UAV reinforced barrier, which provides a guaranteed detection for various penetration types by intruders. Formally, we define a problem whose goal is to minimize total movement distance of UAVs such that a collision-free reinforced barrier is constructed from initial locations of UAVs. To solve the problem, we create potential positions which can support flexible movements of UAVs. Then, a zone-based novel approach is proposed. Furthermore, we evaluate the performance of the proposed scheme through extensive simulations.

1. Introduction

Thanks to recent technological advances, Unmanned Aerial Vehicle (UAV) networks are considered as one of emerging research topics and also gain a lot of interest by researchers. The UAV networks can be utilized for various applications such as border patrol, emergent item delivery, public security, search and rescue operations, environment monitoring, traffic monitoring, etc [1].

Although UAV networks are similar to Mobile Ad-hoc Network (MANET) and Vehicular Ad-Hoc Network (VANET), they exhibit non-negligible differences and peculiarities. Basically, for mobility, UAV networks may have higher mobility than MANET and VANET. It follows that UAV networks should consider frequent network topology changes. In addition, MANET nodes may move on a specific region and VANET nodes may drive only on existing roads. On the contrary, UAV mobility is less constrained; therefore, UAVs are highly likely to be utilized for applications which require dynamic, rapid topology creation [2].

Also, it is possible that a single large UAV performs a specific mission in the application. However, compared with a single large UAV, the UAV networks with multiple small-scale UAVs have advantages for cost, survivability, scalability in several deployment environments and application scenarios [1–3]. For example, Fig. 1 depicts an example of UAV networks with multiple small-scale UAVs. Each UAV can sense objects within a specific range and also can communicate with other UAVs to send any detection or any sensed information.

On the other hand, a special type of coverage in Wireless Sensor Networks (WSN), *barrier-coverage*, attracts a lot of interest of researchers since it can be used for security applications such as battlefield surveillance [4,5,8]. To detect intruders, a subset of sensors in the given field should create a barrier if the sensors divide the area into two regions and any penetrations from one region to another are guaranteed to be monitored by at least one sensor. Recently, Kim et al. designed a new type of barrier, *reinforced barrier*, which detects any penetration types of intruder [9].

Surely, it is highly appropriate that multiple UAVs can support the barrier-coverage to monitor a Region Of Interest (ROI). Since UAVs' movements are fast, UAVs are able to relocate to the target locations promptly when the network topology to be requested is changed frequently. Hence, whenever a reinforced barrier should be constructed immediately by multiple UAVs, it is possible to monitor the given ROI promptly as well as to form the requested reinforced barrier.

But, when such a reinforced barrier is generated by multiple UAVs, it is necessary that multiple UAVs will move to the positions for constructing the reinforced barrier from initial or current location. This could generate the serious problem of collisions among those UAVs, which is currently one of major challenges

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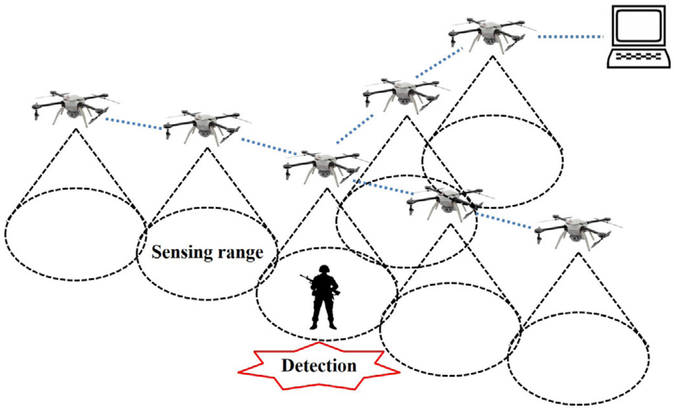

Fig. 1. An example of UAV networks with multiple UAVs.

in UAV networks. Furthermore, we should consider an energy-efficient movement of small-scale UAVs because the small-scale UAV's energy for flight might be limited. Therefore, minimizing total movement by UAVs to reduce a energy consumption must be considered in order to maximize the UAV network lifetime.

Based on the above observations, we introduce a new barrier system in UAV networks with multiple small-scale UAVs. Then, the main contribution of the paper can be summarized as follows.

- We introduce a new barrier of UAV networks, *collision-free UAV reinforced barrier*, which allows UAVs to provide a reinforced barrier-coverage without any conflicts among multiple UAVs.
- We formally define the problem, whose goal is to minimize total moving distance of UAVs when they move from initial locations such that a collision avoidance among multiple UAVs is guaranteed.
- Different from our previous work [10], we generate adjustable potential positions that allow UAVs to have flexible movements to avoid conflicts with previously selected pairs between UAVs and potential positions. To solve the problem, we propose a new algorithm that uses not only a zone-based approach but also adjustable potential positions. Moreover, we evaluate the performance of the proposed scheme through extensive original simulations.

The remainder of the paper is organized as follows. The next section reviews related work. Then, we present a concept of the reinforced barrier in WSN in Section 3. In Section 4, we introduce a collision-free reinforced barrier by multiple small-scale UAVs and also give a formally defined problem to minimize total movement distance of UAVs with collision-free reinforced barrier, followed in Section 5 by the determination of potential positions and the corresponding original proposal of this paper. Then, in Section 6, we analyze the performance of the proposed scheme in various experiments. Conclusive remarks and directions of ongoing research work end the paper.

2. Related work

For barrier coverage in general, a significant amount of research work has been already published. By Gage [4], the concept of barrier-coverage was firstly introduced in robotic sensors. In [5], Kumar et al. firstly defined k-barrier-coverage in wireless sensor networks (WSN). A distributed algorithm for a construction of disjoint strong barriers is developed by Liu et al. [6]. Also, in [7], Saipulla et al. introduced a barrier-coverage with airdropped wireless sensors using line-based deployments and derived its lower bound. Then, in [8], Kumar et al. considered a sleep-wakeup scheduling problem for k-barrier-coverage. They developed optimal sleep-wakeup scheduling algorithms. Also, in [11], Zhang et al. investigated a strong barrier coverage problem in the system with directional sensors. Li et al. [12] introduced a weak-k-barrier coverage as well as a derivation of a lower bound about the probability of the coverage. Chen et al. [13] introduced a concept of local barrier coverage and developed localized optimal sleep-wakeup algorithms. Then, in [14], they designed a one-way barrier coverage to provide a different detection between legal intruders and illegal intruders. Li et al. [15] developed an energy efficient scheduling algorithm based on a probabilistic sensing model to extend the lifetime of barrier coverage. In [16], Tao et al. studied a problem to find optimal orientations of directional sensors in order to support a strong barrier coverage. Importantly, in [9], Kim et al. introduced a new barrier-coverage concept, reinforced barrier-coverage, which provides a guaranteed detection for various penetrations types by intruders. They proposed novel approaches to maximize the network lifetime with the reinforced barrier-coverage. Then, in [17], Kim et al. designed a new type of barrier which is called as event-driven partial barrier such that the barrier is able to detect movements of mobile objects among multiple hubs in an event-driven environment.

Furthermore, there are several studies about the barrier-coverage using mobile sensors. In [18], Keung et al. considered a problem to provide k-barrier coverage against moving intruders, which is related to the trajectories of sensors and intruders. They derived the number of mobile sensors to support k-barrier coverage. In [19], Kong et al. focused on a problem to construct a barrier surrounding the area automatically using mobile sensors. To solve the problem, they designed a fully distributed scheme using virtual force and convex analysis, which allows a relocation of mobile sensors on convex hull region. Also, a distributed and asynchronous algorithm of k-barrier coverage using mobile sensors, called as MobiBar, was developed by Silvestri [20]. In [21,22], He et al. considered a barrier coverage in the sensor scarcity environment by sensor patrolling. To solve the issue, they proposed a periodic monitoring scheduling algorithm. Based on the algorithm, they also developed a coordinated sensor patrolling algorithm to improve the coverage. Also, in [23], Kim et al. considered to maintain resilient k event driven partial barriers by recovering them continuously in case of failure sensors' occurrences. To solve the problem, authors developed a novel moving strategy to minimize the total movement distance of mobile sensors. In [24], Want et al. investigated the barrier coverage problem if sensors have location errors and deploy mobile sensors so as to provide the barrier-coverage when the given region is not barrier-covered by the initial deployment. They also evaluated how location errors affects the barriers in the region. And, in [25], Tian et al. considered the barrier coverage problem of a mobile survivability-heterogeneous WSN because sensors deployed outdoors are subject to environmental detriments and it may cause sensors to be failed. To solve the issue, authors proposed a grid-based barrier construction heuristic which is to keep the given area to be monitored continuously regardless of harsh environment.

On the other hand, UAV networks are attracting the interest of many researchers as one of emerging research topics. Several works addressed an importance and an applicability of UAV networks for numerous applications and also described challenging issues [1–3]. In [26], Gancet et al. designed a decisional architecture that can support different schemes of decision distribution with different levels of autonomy in multi-UAV systems. In [27], authors proposed a modular architecture to create an autonomous systems with multiple UAVs for the purpose of search and rescue missions. For UAV path planning and collision avoidance, there are various studies. First of all, UAV path planning problem was proved to be *NP-complete* by Szczerba et al. [28]. In [29], Richards et al.