On Construction of Collision-free UAV Reinforced Barrier

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***Abstract*—Recently, Unmanned Aerial Vehicle (UAV) networks attracts a lot of interest as one of promising research areas since it can be used for a large portfolio of relevant applications. Among several issues in UAV networks, a collision avoidance among multiple UAVs should be addressed due to its significance. Furthermore, a barrier-coverage is considered as an important coverage concept because it is also appropriate for various applications such as intrusion detection and border surveillance. In this paper, we introduce a barrier-coverage system in UAV networks to construct collision-free UAV reinforced barrier. Then, we formally define a problem whose objective is to minimize total moving distance of UAVs such that collision-free is guaranteed among multiple UAVs when they move from initial locations to positions of constructing a reinforced barrier. To solve the problem, we introduce a novel strategy based on dividing a region into zones and describe our proposed approach. Moreover, we discuss future issues for barrier-coverage of UAV networks.**

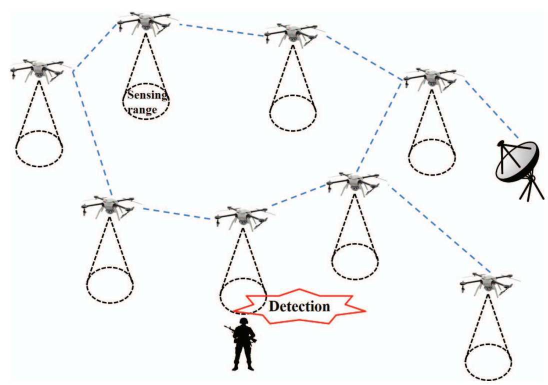

Fig. 1. An example of UAV networks.

I. Introduction

Due to recent technological advances, Unmanned Aerial Vehicle (UAV) networks are emerging and are attracting lots of attention because of its enormous potential. The UAV networks can be used in a wide variety of applications such as military, civil, public applications, search and rescue operations, border and area protection, wildfire and disaster monitoring, traffic monitoring, etc [1].

Basically, UAV networks can be considered as a special form of Mobile Ad-hoc Network (MANET) and Vehicular Ad-Hoc Network (VANET). But, there are several differences from those networks. For example, UAV networks has higher mobility degree than MANET and VANET. So, the topology of UAV networks can be changed more frequently than MANET and VANET. Also, though MANET nodes move on a certain area and VANET nodes move on the highways, UAV can fly in the sky. Therefore, it is appropriate for the application that requires dynamic, quick topology construction [2].

Although single large UAV can be used for the application, multiple UAVs networks can provide several advantages for cost, scalability, survivability, speed-up, compared with the single UAV system [1], [2]. Fig. 1 shows an example of UAV networks with multiple UAVs. Each UAV can be connected with other UAVs and any mobile objects should be detected if it is within sensing range of the UAV.

Recently, many researchers studied a special form of coverage, *barrier-coverage* in wireless sensor networks (WSN), because it can be used for important applications such as intrusion detection and border surveillance [3], [4], [5]. A subset of nodes in the given field can construct a barrier over the region of interest if the nodes divide the region into two areas such that any moving intruders or objects from one region to another can be sensed by at least one node. Especially, Kim et al. introduced *reinforced barrier*, which can detect any penetration types of intruder [8].

To monitor a region of interest (ROI), it is highly desirable that multiple UAVs can be used for barrier-coverage of ROI because UAV has a high moving speed in the sky and so it is possible that UAVs move to the target positions promptly whenever the required network topology by current system is dynamically changed. So, if we use multiple UAVs whenever we construct a reinforced barrier of ROI, the reinforced barrier should be formed quickly by UAVs and it can monitor ROI immediately after a creation of the reinforced barrier.

But, whenever we construct such a reinforced barrier using multiple UAVs with a dynamic network requirement, each

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UAV may move to target position to support the reinforced barrier-coverage from initial or current location. At this case, we should consider a possibility of collisions among multiple UAV. Practically, a collision avoidance among multiple UAV is one of critical issues in UAV networks [6]. Moreover, for those movements of UAV, cost-effective movement also should be considered because UAV's energy resource is limited [1], [2]. It follows that minimizing moving distance of UAV should be considered to reduce a consumption of energy resource of UAV and to maximize the UAV networks eventually.

Based on the above observations, we introduce a new barrier system in UAV networks, *collision-free UAV reinforced barrier*. When the reinforced barrier in UAV networks is constructed, our system provides collision avoidance among multiple UAVs and it is guaranteed that any penetration types of intruders are detected by the UAV reinforced barrier. Also, we formally define a problem whose objective is to minimize total moving distance of multiple UAVs such that UAVs can avoid collisions when they move from initial locations to construct reinforced barrier. To solve the problem, we introduce dividing zones strategy and also propose a novel approach of UAV movements to support collision-free property.

The rest of the paper is organized as follows. The next section reviews related work for previous barrier-coverage and UAV networks and the issue of collision avoidance. We study a reinforced barrier of WSN as a preliminary in Section III. Then, in Section IV, we introduce our collision-free reinforced barrier using multiple UAVs and formally define a problem for minimizing total moving distance of UAVs with a creation of collision-free reinforced barrier in ROI, followed in Section V by a novel strategy and approach we propose to solve the problem. Also, in Section VI, we deal with several future issues of UAV barriers. Finally, we summarize the main contribution of this study in Section VII.

II. Related Work

The barrier-coverage problem has been studied by many researchers. At first, the notion of barrier-coverage was introduced by Gage [3] in the context of robotic sensors. In [4], Kumar et al. firstly introduced the notion of k-barrier-coverage that an intruder is guaranteed to be detected by at least k different sensors while moving from one side to the other in the region of interest. Then, in [5], Kumar et al. defined a sleep-wakeup scheduling problem for k-barrier-cover of wireless sensors, whose objective is to extend the lifetime to protect a region of interest using a series of alternating barrier-covers. They proposed optimal sleep-wakeup scheduling algorithms of k-barrier-coverage. Moreover, Li et al. [9] introduced the weak-k-barrier coverage problem and derived a lower bound on the probability of weak k-barrier-coverage. Also, in [10], Saipulla et al. studied barrier-coverage in harsh environment which is difficult for human to reach. They considered barrier-coverage with airdropped wireless sensors using line-based deployments and derived a lower bound for the coverage. Importantly, Kim et al. [8] introduced a new barrier type which can detect any penetration types of attackers.

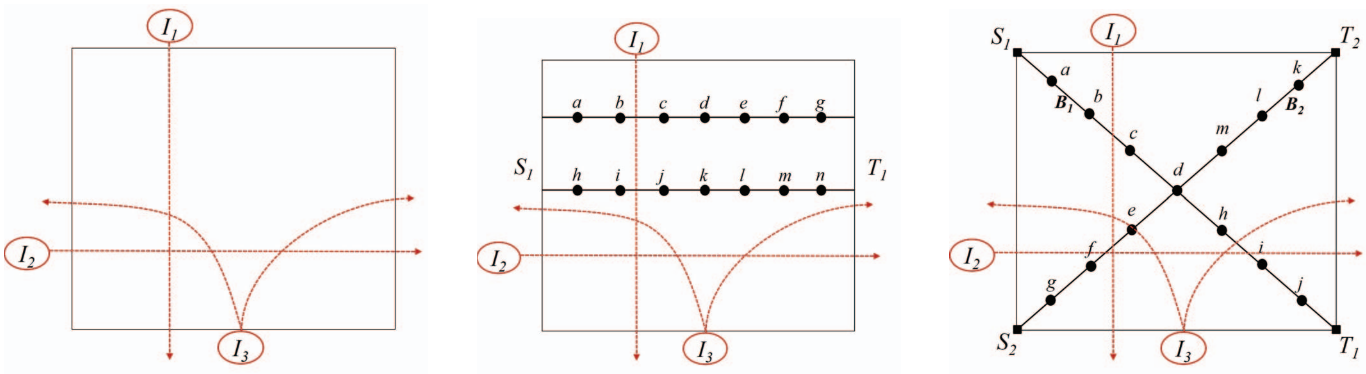
On the other hand, UAV networks has started to be targeted recently. Several works emphasized on its importance and applicability for various systems and also described challenging issues of UAV networks [1], [2], [7]. Also, several works studied path planning and collision avoidance for multiple UAV networks. In [11], authors addressed the path planning problem to maximize collected amount of information from desired regions with avoiding forbidden regions. In [14], authors investigated the cooperative collision-free trajectory planning of multi UAVs and proposed a cooperative approach based on differential flatness, B-spline curves and nonlinear programming. Then, in [12], authors considered a system for collision-free trajectory planning with multiple UAVs that find conflicts among them automatically. Also, Choi et al. [13] proposed an obstacle avoidance scheme which enables a group of UAV. Authors consider that UAV can avoid the obstacle by increasing and decreasing altitude for UAV with possible chance of collision.

III. Preliminary: A Reinforced Barrier of WSN

When an intruder enters the ROI, the penetration of the intruder simply may not be top-down movement in practical applications. So, it should be desirable to consider and to develop a construction of the barrier to be able to detect any penetration variations of intruder including top-down, side-to-side, turning from one side to another.

Based on the motivation, Kim et al. [8] introduced a reinforced barrier of WSN, which can detect any penetration types of intruders. Sensors are static after initial random deployment and each sensor has an equal resource. To maximize the network lifetime, they considered to find the maximum number of possible barriers and to apply sleep-wakeup scheduling algorithm by activating barriers alternatively.

Let us consider Fig. 2, where a square-shaped field is given. Each sensor is depicted as a small circle. If a sensing range of two sensors overlaps, there exists an edge between the sensors. Fig. 2(a) shows possible penetration types of intruders I_1, I_2, I_3. I_1 passes through from top side to bottom side. I_2 passes through from left to right. I_3 turns to the left or the right after it enters the field. Also, Fig. 2(b) shows a barrier by Kumar et al. [4], [5]. Two barriers are constructed between source S_1 and destination T_1. Even though a penetration of intruder I_1 is detected by at least two sensors in the barriers, they can not detect the penetrations by I_2 and I_3. Then, Fig. 2(c) describes a reinforced barrier by Kim et al. [8]. Assume that we add four additional virtual nodes, S_1, T_2, S_2, T_2 and each virtual node is located at each corner of the field. Then, we can construct a barrier B_2 between S_2 and T_2 as well as a barrier B_1 between S_1 and T_1. So, a reinforced barrier by a combination of B_1 and B_2 can be formed. Such a reinforced barrier guarantees that the penetrations by any intruders are detected.



(a) Possible penetration types by intruders in ROI

(b) A scenario of missed penetrations by the basic barrier

(c) A formation of reinforced barrier to detect various penetration types

Fig. 2. Various penetration types of intruder and construction of reinforced barrier.

IV. Collision-free UAV Reinforced Barrier using Multiple UAVs

In this section, we describe our proposed application with an applicability of a barrier using multiple UAVs. Differently from previous work, the proposed system provides not only a construction of collision-free UAV reinforced barrier by UAVs' movements but also a minimization of UAVs' movement trajectories to maximize a lifetime of UAV network.

A. Assumption

At our proposed system, the following assumptions are considered.

- Region of Interest (ROI) is a square-shaped area.
- We use multiple UAVs instead of single UAV.
- Each UAV is equipped with a sensing device with a limited sensing range.
- Each UAV has an identical sensing range.
- Each UAV has a same moving speed.
- Each UAV's altitude is same. (It is less than 400 feet usually by [6]).
- The number of UAV is equal to the number of potential locations of UAV.
- Each UAV has a straight line-based movement when they move between initial location and potential location.

B. Minimal Movement of UAV Reinforced Barrier with Collision Avoidance

Specially, a collision-free movement is one of the most critical issues in multiple UAVs networks [6]. Also, cost-effective movement of UAVs should be addressed because each UAV's energy is limited and excessive movements of UAVs will cause depletion of the energy [1], [2]. It follows that minimizing movement distance of UAVs is highly desirable to reduce energy consumption of UAVs and to maximize the network lifetime ultimately.

Fig. 3 shows a possibility of collisions among UAVs. Suppose we have a set of UAVs, $U = \{u_1, u_2, ..., u_7\}$ and each UAV has own location initially. Also, assume that barrier can be constructed by a set of points, $P = \{p_1, p_2, ..., p_7\}$. To minimize energy consumption, it is appropriate for each UAV to choose the closest position of the barrier. For example, u_1 moves to p_1, u_2 moves to p_3, u_3 moves to p_2 and so on. However, as it can be seen from Fig. 3, we may have a collision possibility between u_2 and u_3 and between u_5 and u_6 since their moving trajectories are crossing at each other if each UAV is simply matched with its closest position on the barrier. Thus, if UAV reinforced barrier is formed, collision-free movement of UAVs should be considered to maintain current UAV network successfully.

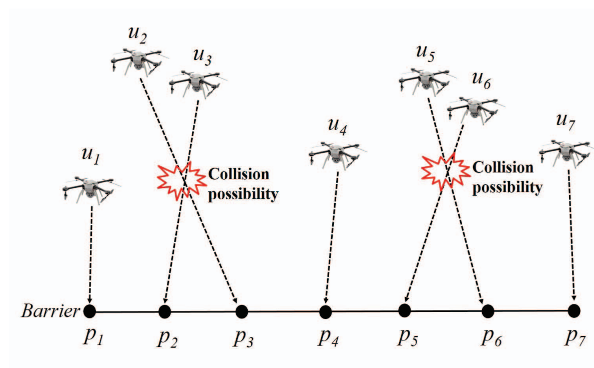


Fig. 3. Possibility of collisions among multiple UAVs when a barrier is formed by UAV.

C. Problem Definition

We describe two important definitions in our system.

Definition 4.1 (Collision-free UAV reinforced barrier): Given a set of potential positions P and a set of UAVs U over a square-shaped area, *collision-free UAV reinforced barrier* is a barrier which guarantees collision-free movements of multiple UAVs from initial locations to construct the reinforced barrier detectable any penetration types of intruders.

Definition 4.2 (MUCofRE): Given a set of potential positions P and a set of UAVs U over a square-shaped area A, *the minimum total moving distance of UAVs with collision-free reinforced barrier (MUCofRE) problem* is to minimize total moving distance of multiple UAVs when UAVs move from initial locations to form collision-free UAV reinforced barrier.

D. ILP Formulation

The notations used in the ILP formulation as follows.
U: set of UAVs.
P: set of potential positions for UAVs.
k: total number of deployed UAVs.
n: total number of potential positions ($n = k$).
i: index of the deployed UAV ($1 \leq i \leq k$).
p: index of the location in P ($1 \leq p \leq n$).
$\delta_{i,p}$: distance from initial location of UAV i to the position p.

Also, we define the following integer variables.

$$X_{i,p} = \begin{cases} 1, & \text{if a UAV } i \text{ moves to position } p \\ 0, & \text{otherwise.} \end{cases}$$

$$Y_{i,p} = \begin{cases} 1, & \text{if there is no confliction with other UAVs} \\ & \text{when UAV } i \text{ moves to position } p \\ 0, & \text{otherwise.} \end{cases}$$

$$Z_{p} = \begin{cases} 1, & \text{if location } p \text{ is selected} \\ 0, & \text{otherwise.} \end{cases}$$

Our objective function is to minimize the total movement distances between the initial and the final positions for UAVs without any collision among UAVs to construct a reinforced barrier. Therefore, the objective function is as follows.

$$\textbf{Minimize} \sum_{i=1}^{k} \sum_{p=1}^{n} \delta_{i,p} \cdot X_{i,p} \cdot Y_{i,p} \quad (1)$$

Subject to:

$$\sum_{p=1}^{n} X_{i,p} \leq 1, (\forall i) \quad (2)$$

$$\sum_{p=1}^{n} Y_{i,p} \geq 1, (\forall i) \quad (3)$$

$$X_{i,p} \leq Z_{p}, (\forall i, \forall p) \quad (4)$$

$$\sum_{p=1}^{n} Z_{p} = k \quad (5)$$

From constraint (2), each UAV i is allowed to move to at most one potential position p. By constraint (3), it follows that we should guarantee there is no confliction with other UAVs when an UAV moves to the position p. Also, constraint (4) forces that if an UAV chooses some location, the location must be among potential positions. Finally, constraint (5) requires that the number of selected positions should be k.

Algorithm 1 ***Potential-Positions***
Inputs: r, k, S_1, T_1, S_2, T_2, Output: P

set a potential position set $P \leftarrow \emptyset$;
draw a virtual line L_1 between S_1 and T_1;
draw a virtual line L_2 between S_2 and T_2;
set $p_p = S_1$;
while True **do**
  if $EucDist(p_p, T_1) \leq r$ **then**
    set $P \leftarrow P \cup T_1$;
    break;
  end if
  find a location p_t onto L_1 with a distance of r from p_p;
  set $P \leftarrow P \cup p_t$;
  set $p_p = p_t$;
end while
set $p_p = S_2$;
while True **do**
  if $EucDist(p_p, T_2) \leq r$ **then**
    set $P \leftarrow P \cup T_2$;
    break;
  end if
  find a location p_t onto L_2 with a distance of r from p_p;
  set $P \leftarrow P \cup p_t$;
  set $p_p = p_t$;
end while
return P

V. Proposed Approach

A. Creation of potential positions of UAVs

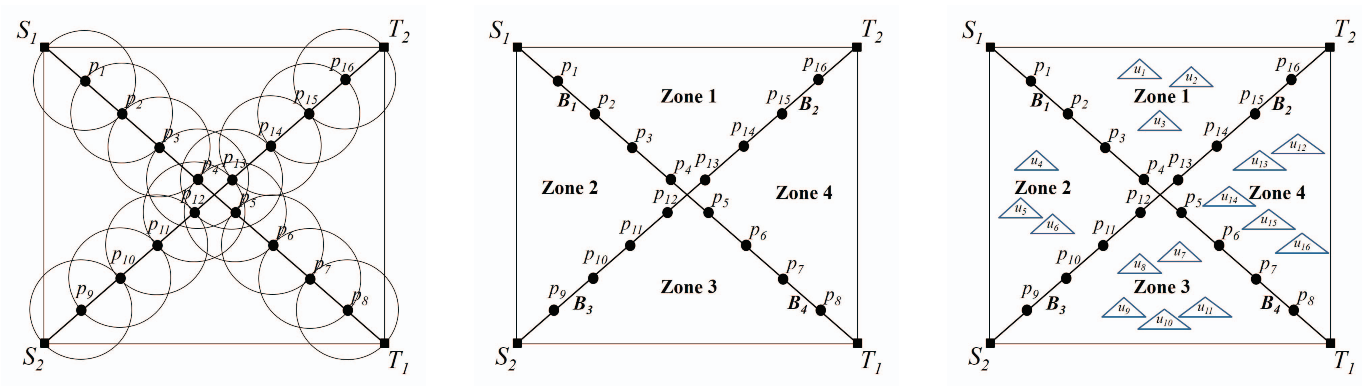
To construct a reinforced barrier using UAVs, we first generate potential positions of UAVs, which is referred as *Potential-Positions*.

Suppose a square-shaped area is given and we consider four virtual nodes S_1, T_1, S_2, T_2 which is represented as a small rectangle in Fig. 4(a). Each virtual node is located at each corner of the area. Suppose that we have two virtual lines: One is between S_1 and T_1 and another is between S_2 and T_2. Given a sensing range r of UAV, calculate potential positions dotted in Fig. 4 and then a distance between two potential positions is r. In Fig. 4(a), we have eight potential positions $p_1, p_2, ..., p_8$ between S_1 and T_1 and also have eight positions $p_9, p_{10}, ..., p_{16}$ between S_2 and T_2. Then, a formation of those potential positions will guarantee a detection of any penetration types by intruders.

The pseudocode of *Potential-Positions* is described in Algorithm 1 in more detail.

B. A Strategy based on Dividing a ROI into Zones

Through the proposed *Potential-Positions*, we earn a set of potential positions, P, by which a reinforced barrier of UAVs can be formed. Given a set of UAVs, U, within ROI and each UAV has own initial location. To solve the defined problem,



(a) Creation of potential positions of UAV in ROI

(b) Dividing into zones

(c) A description of constructing collision-free UAV reinforced barrier using zone strategy

Fig. 4. A description of potential positions, zone strategy and collision-free reinforced barrier.

we should decide which UAV moves to some position in P. To do so, we simply may not choose the closest potential position from initial UAV location because the movement of UAV may have collision with other UAVs. So, we propose a zone-based movement strategy by diving ROI into several zones. Based on the strategy, UAVs within zone can move to potential positions related to the zone. By zone-based movements, we tries to reduce collision possibility to form UAV reinforced barrier.

Fig. 4(b) shows an example of dividing zones. Given ROI and P, divide ROI into four zones: Zone 1, 2, 3, 4. Then, identify a group of potential positions related to each zone. For example, Zone 1 is related to potential positions onto line B_1 and B_2 such as $p_1, p_2, p_3, p_4, p_{13}, p_{14}, p_{15}, p_{16}$ in Fig. 4(b). Also, Zone 2 is related to potential positions onto line B_1 and B_3, etc. Hence, each zone is correlated to own potential positions. In Fig. 4(c), assume we have a set of UAVs $U = \{u_1, u_2, ..., u_{16}\}$ initially. Then, UAVs within Zone 1, u_1, u_2, u_3, are able to move to the related positions $p_1, p_2, p_3, p_4, p_{13}, p_{14}, p_{15}, p_{16}$. Also, UAVs within Zone 2, u_4, u_5, u_6, can move to the positions $p_1, p_2, p_3, p_4, p_9, p_{10}, p_{11}, p_{12}$.

C. Greedy-Point-Movement Approach

Now, we describe our proposed approach, *Greedy-Point-Movement*, which includes the zone strategy.

The steps of *Greedy-Point-Movement* are as follows.

- Decide four zones, Z_1, Z_2, Z_3, Z_4.
- Identify potential positions for each zone. Hence, from P, we calculate a group of potential positions of each zone, $P_{Z_1}, P_{Z_2}, P_{Z_3}, P_{Z_4}$, respectively.
- We do iterate as follows.
  - From U, choose one UAV u_a and identify which zone covers u_a.
  - From the related potential positions, search for the closest a potential position p_c with u_a and calculate

Algorithm 2 ***Greedy-Point-Movement***

Inputs: $U, r, k, S_1, T_1, S_2, T_2, P$, Output: $totalmove$

set total movement distance $totalmove = 0$;
set UAV's movement trajectory T = $\emptyset$;
set $U' \leftarrow U$;
divide ROI into four zones: Z_1, Z_2, Z_3, Z_4;
identify the related potential positions for each zone. Then, set them as $P_{Z_1}, P_{Z_2}, P_{Z_3}, P_{Z_4}$;
while True **do**
  choose one UAV u_a from U';
  identify the selected u_a's zone;
  set u_a's potential positions P_{Z_a};
  while True **do**
    find the closest a potential position p_c with u_a from P_{Z_a};
    calculate the distance d of movement trajectory $\overline{u_a, p_c}$ with straight line between u_a and p_c;
    if $\overline{u_a, p_c}$ is not crossing with any other trajectories in T **then**
      set $totalmove = totalmove + d$;
      set $U' \leftarrow U' - u_a$;
      set $P_{Z_a} \leftarrow P_{Z_a} - p_c$;
      set $T \leftarrow T \cup \overline{u_a, p_c}$;
      break;
    end if
  end while
  if U' is empty **then**
    break;
  end if
end while
return $totalmove$

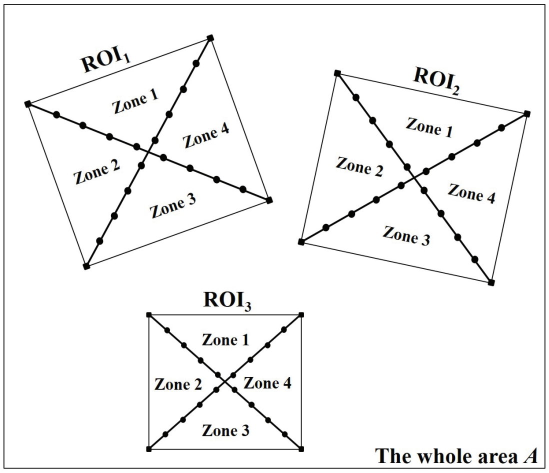


Fig. 5. Possible construction of UAV reinforced barriers for multiple, different ROIs in the given whole area.

the distance of movement trajectory by connecting u_a with p_c by a straight line.
  - Check whether current movement trajectory is crossing with previous other trajectories. That is, check whether there exists any confliction with other UAV movements.
  - If there is no confliction, update current movement distance as a part of total movement.
  - If there exists a confliction, try to find the next closest potential position of u_a.
- After the above steps, *Greedy-Point-Movement* finally returns a total movement of UAVs with the constructed reinforced barrier with collision-avoidance.

The pseudocode of *Greedy-Point-Movement* is described in Algorithm 2 in more detail.

VI. Discussion of Future Issues

As future issues, we will focus on UAV barrier with different environments. i.e. Each UAV has different sensing ranges, different moving speeds. Also, we may consider not only various topologies but also various shapes of ROI such as a convex hull. And it is a possible direction to apply the proposed UAV reinforced barrier to three-dimensional environment. In order to minimize the maximum delay of constructing a barrier, it also can be a critical issue to consider minimizing maximum movement distance of each UAV in various environments.

On the other hand, we may consider regions of interest with various sizes as Fig. 5. Given a whole area A, there are multiple regions with different sizes: ROI_1, ROI_2, ROI_3. To construct complete collision-free reinforced barriers with minimum movement of UAVs in the given area A, we can support that UAVs move to the positions in other regions as well as to the positions within current own region. i.e. Some UAVs in ROI_1 are movable to positions in ROI_3 to minimize total UAV movement distance. Also, as a future research issue, it is possible to consider the construction of event-driven partial barrier [15] using multiple UAVs to minimize total distance of UAVs without any collision.

VII. Concluding Remarks

In this paper, we introduced a problem whose objective is to minimize total moving distance such that collision-free is guaranteed among multiple UAVs when they move from initial locations to construct reinforced barrier. The difficulty of the problem is depending on decision a pair between each UAV and moving position to form a reinforced barrier without any collision among UAVs. To solve the problem, we have introduced the strategy based on dividing into zones and have created potential positions of UAVs on the reinforced barrier. Based on the strategy, we proposed a heuristic which solves the defined problem. Then, we discussed various future issues which should be addressed.

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