On Collision-free Reinforced Barriers for Multi Domain IoT with Heterogeneous UAVs

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***Abstract*—Thanks to advancement of vehicle technologies, Unmanned Aerial Vehicle (UAV) now widely spread over practical services and applications affecting daily life of people positively. Especially, multiple heterogeneous UAVs with different capabilities should be considered since UAVs can play an important role in Internet of Things (IoT) environment in which the heterogeneity and the multi domain of UAVs are indispensable. Also, a concept of barrier-coverage has been proved as a promising one applicable to surveillance and security. In this paper, we present collision-free reinforced barriers by heterogeneous UAVs to support multi domain. Then, we define a problem which is to minimize maximum movement of UAVs on condition that a property of collision-free among UAVs is assured while they travel from current positions to specific locations so as to form reinforced barriers within multi domain. Because the defined problem depends on how to locate UAVs on barriers, we develop a novel approach that provides a collision-free movement as well as a creation of virtual lines in multi domain. Furthermore, we address future research topics which should be handled carefully for the barrier-coverage by heterogeneous UAVs.**

I. Introduction

Nowadays, Unmanned Aerial Vehicles (UAV) networks attract lots of attention of researchers as one of emerging research branches because it can be dramatically used for various purposes such as military, civil and public safety and more specific applications including traffic monitoring in smart city, rescue operation in extensive ocean, border surveillance, construction of rapid communication framework for disaster and harsh encironment, etc [1], [2]. Basically, it has been known that a system with multiple small-scale UAVs (ex. drones) should be much better than the system using a single large for cost, scalability, system maintenance, speed-up in several application scenarios. [1], [3], [4].

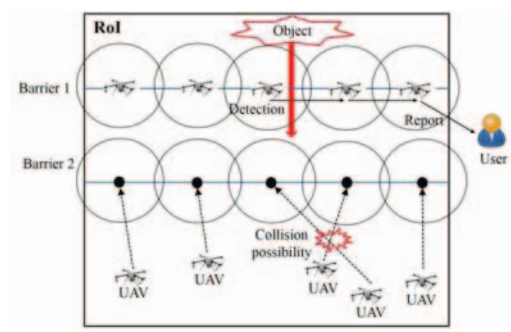


Fig. 1. An example of barrier application by UAVs.

Also, in recent years, several researchers have focused on *barrier-coverage* since it has been introduced initially at the areas of robots and wireless sensor networks (WSN) [5], [6]. As a special type of partial-coverage that a reduced number of sensors is necessary to cover an given area but some event could be missed, the barrier-coverage has been proved as a notable concept for security applications such as border surveillance, intrusion detection by many studies [5], [6], [7], [8]. In order to detect any object for given Region Of Interest (ROI) in WSN, a subset of wireless sensors can build a barrier over ROI if the sensors divide the area into two regions on condition that any penetration passing through those regions is detected by at least one sensor [6]. Then, Kim et al. recently has devised a new type of barrier called as *reinforced barrier* that senses any variation of penetrations by intruders [9], [10].

It is possible that we utilize multiple UAVs with small-scaled to monitor ROI by constructing reinforced barrier. Whenever the network topology and the ROI to be monitored are changed often by emergent events, UAVs can rapidly move to target locations so as to generate the reinforced barrier. However, if multiple UAVs participate in the construction of the barrier, those UAVs need to move from initial or current locations to specific target positions which result in building the barrier finally. Because these movements also may cause potential collisions among multiple UAVs that is currently one of key issues in applications using UAVs [11], a collision avoidance is managed very critically for reinforced barrier by UAVs [12], [13]. Furthermore, because energy resource of UAV is limited [1], [3], the cost-effective movement of UAVs should be handled to reduce an energy consumption as well as to maximize the lifetime of the system with UAVs. Fig. 1 shows an example of barrier by UAVs. Given square-shaped RoI, a barrier can be generated by UAV with a sensing range and any mobile objects should be detected if it is within sensing range of the UAV. If we plan to construct another barrier Barrier 2, it is required that UAVs move to the positions on Barrier 2. At that time, we may have collision possibility of movement among UAVs as shown as in Fig. 1.

On the other hand, it is expected that UAVs can play a key part as sensing and communication devices for Internet of Things (IoT) in smart cities where the heterogeneity is essential and IoT-based devices are major components [14], [15]. Hence, it is highly appropriate that we utilize multiple heterogeneous UAVs to design UAV-enabled applications and systems for IoT in smart cities. Also, we can imagine that the reinforced barrier with collision avoidance is applied to the IoT using heterogeneous UAVs to detect any movement of objects (or things) because those IoT-based UAVs can provide both a real-time detection and a ubiquitous monitor of objects within given ROI. In particular, it is adequate that we consider multi domain IoT where the requests of deciding multi domain can be changed frequently. It follows that reinforced barriers by UAVs can be built in multi domain and each domain provides a reinforced barrier to sense moving objects in IoT.

Based on the above observations, we introduce a barrier system in smart cities for multi domain IoT with heterogenous UAVs, *collision-free multi domain reinforced barriers*. Given multi domain in IoT environment, our system supports that a reinforced barrier with collision avoidance among heterogeneous UAVs is created within each domain such that it is guaranteed that any movements of objects of things passing through the domain are detected by at least one UAV. Also, with a consideration of heterogeneity, we formally define a problem whose goal is to minimize a maximum movement of heterogeneous UAVs such that the collision-free property is satisfied when UAVs move among multi domain. Then, in order to solve the problem, we develop a novel approach which eventually forms *multi domain collision-free reinforced barriers* in IoT with heterogeneous UAVs.

The remainder of the paper is structured as follows. Section II investigates previous studies of barrier-coverage and UAV-based studies including an issue of collision avoidance. Also, we describe a collision-free reinforced barrier of UAVs and a reinforced barrier of WSN as a preliminaries in Section III. In Section IV, we present our collision-free reinforced barrier for multi domain IoT and formally define a problem with ILP formulation, followed in Section V by a novel approach we propose to solve the problem. We conclude this paper with a discussion of future issues in Section VI.

II. Related Work

Kumar et al. [6] first introduced a concept of k-barrier-coverage in WSN with static sensors that the penetration of the intruders is detected by at least k sensors and they also proposed optimal sleep-wakeup scheduling algorithms for k-barrier-coverage. In [16], Chen et al. developed a one-way barrier coverage which support differential detections between legal passengers and illegal attackers. Also, in [17] et al. proposed an energy efficient scheduling scheme based on probabilistic model to maximize the lifetime of barrier-coverage. Tao et al. [18] defined a problem of seeking optimal orientations of sensors with directional sensing ranges to provide a strong barrier-coverage. For WSN with mobile sensors, He et al. [19] investigated a barrier-coverage of sensor scarcity environment with a consideration of sensor patrolling and periodic monitoring. In [20], Wang et al. studied a barrier-coverage problem dealing with sensor location errors and deployment of mobile sensors so as to support the barrier-coverage if the barrier does not cover the given area by initial deployment.

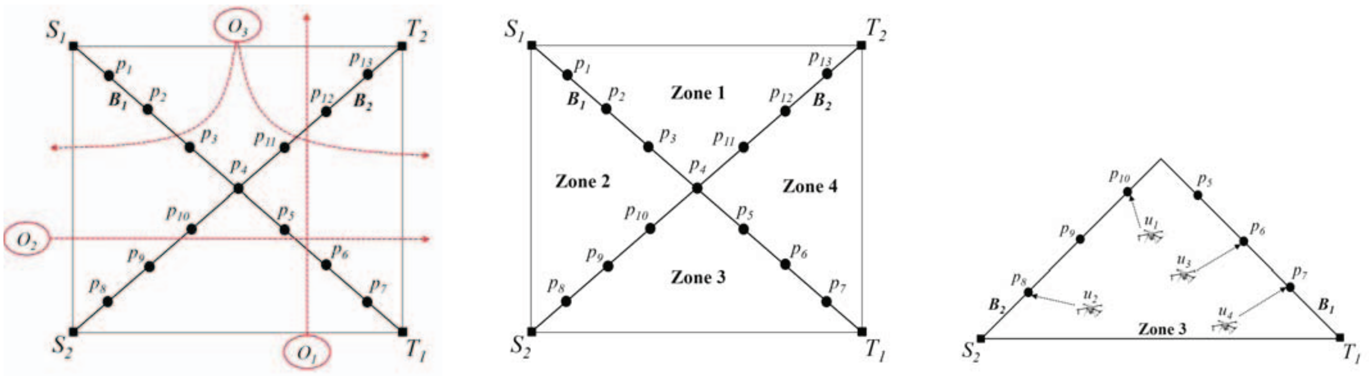
On the other hand, there exist various studies about path planning and collision avoidance of UAVs. Szczerba et al. [21] proved UAV path planning problem is NP-complete. In [22], Moon et al. proposed a hierarchical structure for task assignment as well as for path planning of UAVs in a dynamic environment. In [23], authors focused on the path planning problem to maximize the aggregated information for scheduled areas deliberating on avoidance of forbidden areas. Also, Choi et al. [24] developed an obstacle avoidance scheme that allows a fleet of UAVs to adjust altitudes to reduce any possibility of collision. Then, in [25], Zhang et al. developed an improved constrained differential evolution approach with a formal definition of a global route planning problem in 3-D environment.

III. Preliminaries

In this section, we first review the reinforced barrier in WSN as well as its applicability by multiple UAVs.

A. Reinforced Barrier of WSN

Previous studies of barrier-coverage concentrated on how to detect penetrations by attackers from top to down or from side to side within a given RoI. However, the penetration types of intruders may be various practically. For example, after entering RoI, attackers may turn right or left. Motivated by the observation, Kim et al. [9], [10] proposed a concept of reinforced barrier in WSN, which guarantees that any variation



(a) Reinforced barrier in WSN

(b) Divided zones for zone-based strategy

(c) An example of collision-free zone-based movement of UAVs

Fig. 2. Several penetration types of intruder and zone-based strategy for collision-free reinforced barrier.

of penetration by intruder is detected. Given a random deployment of homogeneous static sensors within square-shaped RoI, they tried to seek maximum number of reinforced barriers so that the system has a maximum network lifetime. Fig. 2(a) depicts the construction of reinforced barrier in WSN. Suppose that we identify each corner of RoI as S_1, T_1, S_2, T_2, respectively. Then, we look for at least one barrier B_1 between S_1 and T_1 and another barrier B_2 between S_2 and T_2 so that a combination of B_1 and B_2 returns a reinforced barrier that can detect various types of penetrations such as O_1, O_2, O_3 as it can be seen from Fig. 2(a).

B. Collision-free Reinforced Barrier of Homogeneous UAVs

It is possible that multiple small-scaled UAVs with homogeneous capability are utilized to support a reinforced barrier in RoI because UAVs can rapidly move from current positions to specific positions which result in the construction of the reinforced barrier. But, because potential collisions through those movements of multiple UAVs may occur, the issue of collision avoidance should be handled importantly. Also, since the resources of small-scaled homogeneous UAVs are limited, the total movement distance of UAVs should be minimized to maximize a lifetime of the reinforced barrier by UAVs.

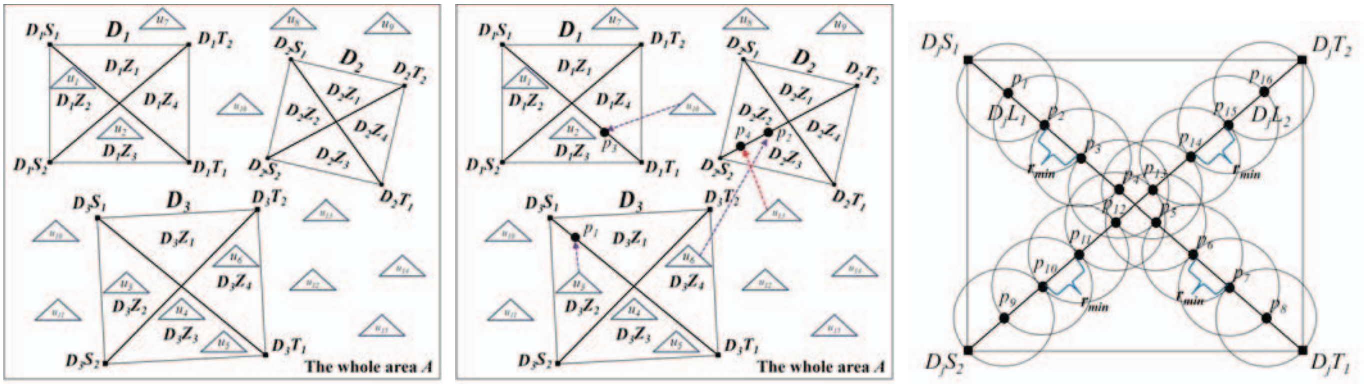
With those observations, Kim et al. [12], [13] introduced a collision-free reinforced barrier that allows homogeneous UAVs to generate a reinforced barrier supportable by UAV movements with collision avoidance given square-shaped RoI. Also, they developed a zone-based strategy to support those movements of multiple UAVs. Fig. 2(b) describes the zone-based strategy. Given RoI with identified four corners S_1, T_1, S_2, T_2, suppose we first create potential positions $\{p_1, p_2, p_3, ..., p_{13}\}$ on lines between S_1 and T_1 and between S_2 and T_2 where an interval between positions is equal. If so, a concern is to fill all potential positions on lines using UAVs so that a reinforced barrier is formed. To do so, they first divide the RoI into four different zones: Zone 1, 2, 3, 4 as shown in Fig. 2(b). With these settings, zone-based movement strategy with collision avoidance can be applied. It follows that UAVs within a specific zone can movable to only potential positions meeting the specific zone. Fig. 2(c) shows an example of the zone-based movement. Suppose that four UAVs such as u_1, u_2, u_3, u_4 have been verified within Zone 3. For collision-free movements, those UAVs can be matched with potential positions touching with the Zone 3. As it can be seen in Fig. 2(c), u_1 can move to p_{10} and u_2 is movable to p_8 and so on.

IV. Collision-free Reinforced Barriers for Multi Domain by Heterogeneous UAVs

In this section, we introduce the proposed framework, *collision-free reinforced barriers for multi domain IoT with Heterogenous UAVs* followed by the system setting and assumption within the section. Then, we formally define an original problem that we consider in this paper and also present it as Integer Linear Programming (ILP) formulation.

A. Collision-free Reinforced Barriers for Multi Domain IoT with Heterogeneous UAVs

For future IoT in smart cities, it is highly desirable to use multiple heterogeneous UAVs as sensing and communication devices. Also, because IoT-based UAVs can support both a real-time detection and a ubiquitous monitor of objects (or things), it is imaginable that the concept of reinforced barrier with collision avoidance is applied to the IoT environment to guarantee that any movement of objects is detected by at least one UAV given initially deployed heterogeneous UAVs within a whole area. Different from [12], [13], we expand collision-free reinforced barriers into multi domain IoT environment supportable by heterogeneous UAVs in smart cities. It follows that we particularly deliberate on multi domain IoT where the multi domain regions with different sizes can be changed frequently and each domain not only satisfies the complete construction of the reinforced barrier by heterogeneous UAVs but also allows UAVs to transfer both between domain and domain and between non-domain and domain.



(a) Initial status for multi domain IoT with heterogeneous UAVs

(b) Possible movements of UAVs in multi domain environment

(c) Creation of potential positions

Fig. 3. Collision-free reinforced barriers for multi domain IoT environment and creation of potential positions.

Let us see Fig. 3 which depicts our collision-free barriers for multi domain and possible movements of UAVs among domains. An example of initial status is represented in Fig. 3(a). Suppose that a set of UAVs $U = \{u_1, u_2, u_3, ..., u_{15}\}$ are located within the whole area A and each UAV is capable of sensing any objects or things if they are within own sensing range. Then, as multi domain, we have three domains with different sizes: D_1, D_2, D_3. For each domain, four corners and four zones should be verified. For example, for corner points of D_1, we should identify D_1S_1, D_1T_1, D_1S_2, D_1T_2, respectively. Also, within D_1, four zones D_1Z_1, D_1Z_2, D_1Z_3, D_1Z_4 are also created by two virtual lines, one is between D_1S_1 and D_1T_1 and another is between D_1S_2 and D_1T_2. On the other hand, Fig. 3(b) shows possible movement types of UAVs in our multi domain IoT environment. As the first movement type, u_3 in D_3Z_2 is able move to specific position p_1 on the virtual line between D_3S_1 and D_3T_1 to construct the reinforced barrier of the domain D_3. Also, u_6 within D_3 may fly toward p_2 in another domain D_2 to support the construction of the barrier in D_2. And, u_{10} which is positioned at outer domain is movable to p_3 in D_1. However, it is not possible that u_{13} travels to p_4 in D_2 because the trajectory may have conflict with the movement of u_6 as shown in 3(b).

B. Assumption

For the proposed system, we take into account the below assumptions.

- Any IoT devices including multiple heterogeneous UAVs can be located within a whole area A.
- Within A, the system simultaneously can handle the requests of generating several domains where all domains are different square-shaped regions and may have frequent changes.
- Each UAV has heterogeneous capabilities such as different sensing ranges and batteries.
- Each UAV is capable of detecting objects within own sensing range whose shape is a circle.
- The altitude of each UAV is equal where it is less than 500 feet by [11].
- Each UAV basically follows a straight line-based movement if it travels between two specific positions.

C. Problem Definition

Now, we describe several definitions which are considered in the proposed system critically.

Definition IV.1 (multi domain collision-free UAV reinforced barriers) *Given a set of domains D and a set of heterogeneous UAVs U which are within a whole area A, multi domain collision-free UAV reinforced barriers is a barrier system that every domain constructs reinforced barrier by movements of UAVs without conflicts such that any penetration of objects in each domain is detected.*

Definition IV.2 (minmaxMultiUR) *Given a set of domains D and a set of heterogeneous UAVs U which are within a whole area A, the minimum maximum movement of UAVs for multi domain collision-free UAV reinforced barriers (minmaxMultiUR) problem is to minimize the maximum moving distance of UAVs from current positions to specific points on reinforced barriers such that a system has multi domain collision-free UAV reinforced barriers.*

D. ILP Formulation

Then, we formulate *minmaxMultiUR* problem using ILP. We represent the notations of ILP formulation as follows.
n: the number of deployed UAVs in A.
k: the number of domains.
m: the number of potential positions.
U: a set of heterogeneous UAVs, $U = \{u_1, u_2, ..., u_n\}$.
R: a set of sensing range of UAVs, $R = \{r_1, r_2, ..., r_n\}$.
D: a set of domains, $D = \{D_1, D_2, ..., D_k\}$.

P: a set of potential positions in D, $P = \{p_1, p_2, ..., p_m\}$.
i: index of the deployed UAV and sensing range ($1 \leq i \leq n$).
j: index of the domain in D ($1 \leq j \leq k$).
p: index of the position in P ($1 \leq p \leq m$ and $m \leq n$).
$\lambda_{i,p}$: distance from current location of u_i to the position p.

Also, we define integer variables as follows.

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

$$X_{i,p} = \begin{cases} 1, & \text{if there is no conflict with other UAVs} \\ & \text{when } u_i \text{ travels to position } p \\ 0, & \text{otherwise.} \end{cases}$$

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

Then, our objective function is to minimize the maximum movement distance between the initial and the final positions of UAVs to construct collision-free reinforced barriers for every domain. The objective function is formulated as follows.

$$\textbf{Minimize Max } \lambda_{i,p} \cdot W_{i,p} \cdot X_{i,p} \cdot Y_p \tag{1}$$

Subject to:

$$\sum_{p=1}^{m} W_{i,p} \leq 1, (\forall i) \tag{2}$$

$$\sum_{p=1}^{m} X_{i,p} \geq 1, (\forall i) \tag{3}$$

$$W_{i,p} \leq Y_p, (\forall i, \forall p) \tag{4}$$

$$\sum_{p=1}^{m} Y_p = m \tag{5}$$

It is forced that each UAV u_i can move to at most one potential locations p by constraint (2). By constraint (3), we satisfy the condition that there is no collision with other UAVs when an UAV travels to the position p. Constraint (4) imposes that if u_i selects some location, it must be from potential positions. Also, constraint (4) satisfies the selected total number of positions are no greater than equal to m. Constraint (5) forces that the number of chosen positions should be k and each domain eventually constructs a reinforced barrier by selected positions.

V. The Proposed Approach

Note that *minmaxMultiUR* problem depends on how to locate heterogenous UAVs so as to generate collision-free reinforced barriers for all domains. Then, to solve the *minmaxMultiUR* problem, we propose a *Multi-Domain-Combined-Movement* approach which returns a creation of potential positions and a construction of reinforced barriers for all domains by collision-free movements by UAVs. Fundamentally, the *Multi-Domain-Combined-Movement* approach is performed as follows.

- For each domain, identify zones as D_jZ_h and four corner points D_jS_1, D_jT_1, D_jS_2, D_jT_2 where $1 \leq j \leq k$ and $1 \leq h \leq 4$, $(\forall j, h)$.
- Recognize UAVs within each zone as UAV inner candidates. So, each zone should recognize inner candidates $U_{D_jZ_h}$ and outer candidates $U_{\neg D_jZ_h}$.
- For each domain, draw two virtual lines. So, D_jL_1 is created between D_jS_1 and D_jT_1 and D_jL_2 is drawn between D_jS_2 and D_jT_2.
- On D_jL_1 and D_jL_2 for each domain, generate a set of potential positions P with an interval distance r_{min} where r_{min} is a minimal sensing range in R as shown in Fig. 3(c). Verify a group of potential positions for each zone as inner position candidates $P_{D_jZ_h}$ and also set outer candidates as $P_{\neg D_jZ_h}$.
- We do the following iterations until every domain has a reinforced barrier.
  - Find a pair (u_c, p_a) with the closest distance $d_{closest}$ between inner UAV candidates $U_{D_jZ_h}$ and inner position candidates $P_{D_jZ_h}$ for every domain such that a movement trajectory $\overline{u_c, p_a}$ with a straight line between u_c and p_a is not crossing with already selected other trajectories in M.
  - if it is found, compare $d_{closest}$ with previous d_{minmax}. If $d_{closest}$ is greater than d_{minmax}, update $d_{closest}$ as a new d_{minmax}. Remove u_c from $U_{D_jZ_h}$ and p_a from $P_{D_jZ_h}$, respectively. Also, $\overline{u_c, p_a}$ is added to M.
  - if it is not found, look for the closest pair (u_c, p_a) between outer UAV candidates $U_{\neg D_jZ_h}$ and outer position candidates $P_{\neg D_jZ_h}$ on condition that $\overline{u_c, p_a}$ is not crossing with other trajectories in M.
    - if (u_c, p_a) is found, compare $d_{closest}$ with previous d_{minmax}. If $d_{closest}$ is greater than d_{minmax}, update $d_{closest}$ as a new d_{minmax}. Remove u_c from $U_{\neg D_jZ_h}$ and p_a from $P_{\neg D_jZ_h}$. Moreover, $\overline{u_c, p_a}$ is added to M.
    - if it is not discovered from outer candidates, we stop the search and return $false$.
- After the above steps, *Multi-Domain-Combined-Movement* finally returns d_{minmax}.

The pseudocode of *Multi-Domain-Combined-Movement* is represented in Algorithm 1 in more detail.

VI. Concluding Remarks and Future Works

In this study, we introduced a barrier system by collision-free reinforced barriers which are for multi domain IoT with heterogeneous UAVs. We formally defined the *minmaxMultiUR* whose goal is to minimize the maximum movements of UAVs without any conflicts when UAVs move from current locations to the positions of barriers such that all domains

Algorithm 1 ***Multi-Domain-Combined-Movement***

Inputs: U, R, D, Output: d_{minmax} or $false$

set $d_{minmax} = 0$;
set UAV's movement trajectory $M = \emptyset$;
identify D_jZ_h where $1 \le j \le k$ and $1 \le h \le 4$ $(\forall j, h)$;
verify $U_{D_jZ_h}$ and $U_{\neg D_jZ_h}$ where $U_{D_jZ_h}, U_{\neg D_jZ_h} \subset U$;
draw virtual lines D_jL_1, D_jL_2 for each domain;
create P with an interval r_{min} on D_jL_1, D_jL_2
identify $P_{D_jZ_h}$ and $P_{\neg D_jZ_h}$ where $P_{D_jZ_h}, P_{\neg D_jZ_h} \subset P$;
while True **do**
    find a pair (u_c, p_a) with the closest distance $d_{closest}$ between $U_{D_jZ_h}$ and $P_{D_jZ_h}$ such that a movement trajectory $\overline{u_c, p_a}$ is not crossing with trajectories in M;
    if $\overline{u_c, p_a}$ is found from $U_{D_jZ_h}$ **then**
        set $d_{minmax} = MAX(d_{minmax}, d_{closest})$;
        set $U_{D_jZ_h} \leftarrow U_{D_jZ_h} - u_c$;
        set $P_{D_jZ_h} \leftarrow P_{D_jZ_h} - p_a$;
        set $M \leftarrow M \cup \overline{u_c, p_a}$;
    else
        while True **do**
            search for a pair (u_c, p_a) with $d_{closest}$ between $U_{\neg D_jZ_h}$ and $P_{\neg D_jZ_h}$ such that $\overline{u_c, p_a}$ is not crossing with trajectories in M;
            if $\overline{u_c, p_a}$ is found from $U_{\neg D_jZ_h}$ **then**
                set $d_{minmax} = MAX(d_{minmax}, d_{closest})$;
                set $U_{\neg D_jZ_h} \leftarrow U_{\neg D_jZ_h} - u_c$;
                set $P_{\neg D_jZ_h} \leftarrow P_{\neg D_jZ_h} - p_a$;
                set $M \leftarrow M \cup \overline{u_c, p_a}$;
                break;
            else
                return $false$;
            end if
        end while
    end if
    if each domain has a reinforced barrier **then**
        break;
    end if
end while
return d_{minmax}

construct reinforced barriers. Also, we represented the problem using ILP. To solve the problem, we proposed *Multi-Domain-Combined-Movement* approach based on divided zones, which returns the system that every domain has a constructed reinforced barrier by UAVs. As future works, we will implement the proposed approach through extensive and will evaluate their performances thoroughly. Furthermore, we plan to apply collision-free UAV reinforced barriers in various shaped domains such as convex hull. And, it is planned that we design a barrier system by UAVs with hierarchical structure for future extensive ocean development.

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