

# Optimal Trajectory Planning of Drones for 3D Mobile Sensing

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**Abstract**—Mobile sensing is usually limited in 3D space, as there are many inaccessible places where people rarely venture. Unmanned aerial vehicle (UAV), commonly known as drone, has greatly extends the scope of mobile sensing in 3D space, and pushed forward a variety of 3D mobile sensing applications, such as aerial photo- or video-graphy, 3D wireless signal survey, air quality monitoring. However, the limited battery life of drones has largely restricted the wide adoption of these applications; meanwhile, the flight between two locations consumes more of the drone's battery power than hovering over one location. To maximally expand the sensing scope of the drone, in this paper, we study the trajectory planning problem for optimizing its flight route in 3D space, given its limited battery life. Specifically, we divide the target 3D space into a network of observation locations formed by multiple 2D grids, formulate the minimum dominating path problem in each 2D grid to find the optimal trajectory that has the maximal coverage in 3D space, and then select necessary critical observation locations along the trajectory for the drone to hover and perform the measurement. Experimental results show that the proposed algorithm outperforms other approaches XXX.

## I. INTRODUCTION

Unmanned aerial vehicle (UAV), commonly known as drone, is an aircraft without a human pilot aboard, which is commonly used in measurement and sampling. Compared to manned aircraft, drones are more suitable for data collections and mobile sensing applications that capture different dimensions of signals in the environment that are beyond our sensing capability, such as aerial photography, 3D wireless signal survey, air quality index (AQI) measurement.

However, civilian drones are still not popular these days. Furthermore, a lot of drone companies were broken down. It could be a quite confusing problem if you have never come into attach with a drone. If you've actually tried using them, you could find that civilian drones do not really apply to daily life due to:

- Low battery available time.
- Great noise during flight.
- Wing rock and more battery drain caused by poor carrying capacity.

Therefore, in order to make more use of existing drones, we must consider the following problem: **How to complete flight in the shortest possible time? In other words, how to find the optimal trajectory? Furthermore, in the three-dimensional space?**

Similar to traditional sensor networks and mobile base station, we consider data collection in mobile environment. So total time consumption consists of two parts: **flight time**

and **measurement time**. While we also have the following difference:

- We consider optimal trajectory in three-dimensional space.
- We use the routing algorithm based on graph theory apart from traditional greedy algorithms.

In this paper, we consider optimal trajectory in three-dimensional mobile sensing. We divide three-dimensional space into a network of observation locations (OLs), and generate trajectory in two steps: select critical observation locations (COLs) from OLs to cover measurement space while find a OL-path(trajectory) that covers COLs. We formulate the problem as a constraint set coverage problem in graph theory. Specifically, we consider the following two special cases:

- 1) *Consider flight time only*: Under this condition, we assume measurement time negligible and consider flight time only. We choose the shortest OL-path in OL-network to minimize flight time and select all OLs in OL-path as COLs. Therefore, we could formulate problem as a minimum dominating path. In this paper, we solved this problem in grid which could extend to three-dimensional space.
- 2) *Consider total time consuming*: Under this condition, we consider total time consuming which is the sum of flight time and measurement time. Since flight time usually take up most of time consuming, we find the shortest OL-path first. Then in order to minimize measurement time, we select least OLs in OL-path to cover OL-network. Also, we solve this problem in grid.

Because of algorithms we use is based on graph theory, We could get size of COL and OL-path in  $O(1)$  time while select COLs and draw trajectory in  $O(n)$  time. We use drones to verify our simulation. We find out that the flight time we use is less than ordinary approach.

## II. RELATED WORK

### A. Drones in 3D mobile sensing

Conventional mobile sensing systems rely on the mobile devices or ground-vehicles to perform the environmental sensing in a 2D plane, e.g., the mobile data analysis using bikes [2] or cars [1].

Drones become more and more popular in 3D mobile sensing applications since they could capture different dimensions of signals in the 3D environment that are usually

beyond our sensing capability. Aerial photo or video-graphy applications [6] facilitate the collection of images, and the analysis over the collected data. For example, it is feasible to locate anomalies in image data, and link particular image data to an address of the property where the anomaly is detected. DroneSense is a system for 3D wireless signal survey [10], i.e., measuring wireless signals in the 3D space, which provides us with an efficient method to quickly analyze wireless coverage and test their wireless propagation models. SensorFly is designed for indoor emergency response or inspections in inaccessible places where people cannot reach [7], which forms aerial sensor network platform that can adapt to node and network disruptions in harsh environments.

However, these 3D mobile sensing applications of drones are constrained by the limited battery life, which motivates a more efficient measurement approach to better design the trajectory.

### B. Trajectory planning problem

To address the trajectory planning problem, the genetic algorithm [5], [11] and particle swarm optimization [3] are always proposed for real-time path planning, which could find an optimal or near-optimal path for robotics in both complicated static and dynamic environments. These approaches have been applied on the UAV platform which could ensure partial minimality between two nodes.

Meanwhile, the trajectory planning for a large scale mobile sensing scenario is usually formulated as an ordinary Traveling Salesman Problem (TSP) or a special TSP problem [9], [8]. Existing solutions take a two-step approach: (1) the first step is to find a minimum vertex cover in the underlying network graph (i.e., a number of measurement locations that cover the given sensing area); and (2) the second step is to find the shortest path connecting these vertices (locations), along which the mobile device can traverse to complete the mobile sensing task in space.

In this paper, we take a different approach by finding the optimal path first and then selecting the measurement locations, as the flight consumes more battery than hovering for drone operations.

## III. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we establish a multi-layer 3D network model that are formed by multiple 2D networks for mobile sensing in the 3D space. In the first case when the flight time is dominant, we formulate the trajectory planning problem as a minimum dominating path problem. In the second case, we consider both the flight time and hovering time of the drone, and formulate the problem as a combination of the minimum dominating path problem and the constrained minimum dominating set problem.

### A. 3D network model

**Dividing the 3D space into cuboids:** We divide a 3D space into cuboids with  $a$  meters long,  $b$  meters wide and  $h$  meters high. We define the center point of cuboid  $i$  as its observation

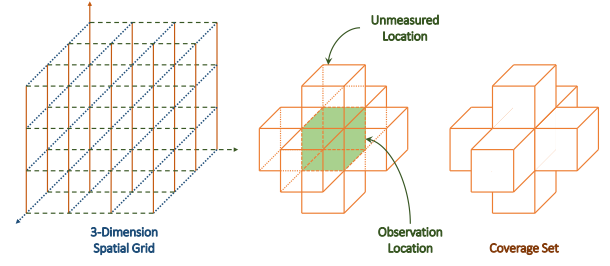


Fig. 1: The divided cuboids of a 3D space; a center OL in the cuboid in the green color; and the OLs and their cuboids in the coverage set of the center OL.

location (OL) (as shown in Figure 1), which is denoted by the 3-tuple (longitude, latitude, and altitude), i.e.,

$$OL_i = (x_i, y_i, z_i),$$

where  $x_i, y_i, z_i$  are 3D coordinates of OL  $i$ . Note that we call the OL at the center of cuboid  $i$  as OL  $i$ .

**3D network of observation locations (OLs):** OLs form a 3D network graph  $\mathcal{G} = (\mathcal{V}; \mathcal{E})$ , where  $\mathcal{V}$  denotes the set of vertices and  $\mathcal{E}$  represents the edges connecting neighboring vertices. Specifically, the OL inside each cuboid  $i$  is considered as a vertex in  $\mathcal{G}$ , and an edge  $(i, j)$  exists, if cuboid  $i$  is adjacent to cuboid  $j$  (i.e., they are the same in two coordinates and adjacent to each other in the third dimension coordinate). As a result, the OLs forms a 3D grid in the space.

**The coverage set of OL  $i$ :** We define the coverage set of OL  $i$  as the set of OLs including those located in the cuboids of the cuboid  $i$ , plus OL  $i$  itself, as shown in Figure 1.

**Critical OL (COL):** Given limited battery life, it is impossible for a drone to traverse all OLs in the space. Hence, we need to select a number of critical observation locations (COL) from OLs where the drone can perform the measurement.

**Correlation between OLs:** We assume that the sensed data at two OLs in the same 3D space may have certain correlation. Intuitively, the more distant two OLs are located, the less correlation they may have. That is, two adjacent OLs have the strongest correlation in their sensed data; the sensed data at two adjacent OLs are almost the same if the distance between them is small. Hence, if the drone has sensed at one OL, it can skip sensing at its adjacent OLs.

**Multiple layers of 2D grids:** The 3D grid can be divided into multiple layers of 2D grids at different heights. If the drone has sensed at OLs in one layer of 2D grid, it can skip sensing at OLs in its adjacent layers of 2D grids (i.e., the one upper layer and the one lower layer). Let  $G = L_{m,n} = (V; E)$  denote a 2D grid with  $m$  rows and  $n$  columns.

### B. Time consumed

The time consumed by the 3D mobile sensing of drones consists of two parts: (1) the flight time, and (2) the measurement time.

Let  $V_C \subseteq V$  denote the set of COLs, and  $v_{C_i}$  is  $i$ -th vertex in  $V_C$ . Let  $V_P \subseteq V$  denote the set of vertices in the

drone's trajectory which forms a path in  $\mathcal{G}$ . We have  $V_C \subseteq V_P$  since the trajectory should contain the COLs, i.e., vertices in  $V_C$ .

**Flight time:** the flight time  $T_F$  is time consumed by the drone's flight. In the formed 3D grid, we use Hamiltonian distance to characterize the distance between OLs. So the flight time is proportion to the length of the trajectory, which is written as  $T_F = t_F|V_P|$ , where  $t_F$  is the flight time for a unit length in the coordinate system of the 3D grid.

**Measurement time:** the measurement time  $T_M$  is time consumed by the drone for hovering and measurement. For the same sensing task (e.g., WiFi signal survey), we could assume that measurement time is the same for all OLs. So the total measurement time is proportion to the number of COLs, which can be written as  $T_M = t_M|V_C|$ , where  $t_M$  is the measurement time at each OL.

Therefore, the total time  $T$  consumed by the drone is

$$T = T_F + T_M.$$

### C. Problem formulation

We formulate the following two problems based on two observations: (1) the flight mode consumes more battery per unit time than the hovering mode for a drone; (2) the flight time much more than the measurement time in the trajectory for most sensing applications.

1) *Case 1: Considering flight time only:* In this case, we assume the flight time is dominant, and the measurement time at each OL can be negligible. Then, we formulate the problem as a minimum dominating path problem in multi-layer 2D grids.

**Problem 1** (Trajectory planning by flight time only). *Given a 3D grid  $\mathcal{G}$  divided into multi-layer 2D grids, for each 2D grid  $G = L_{m,n} = (V; E)$  where  $V = \{v_0, v_1, \dots, v_{|V|-1}\}$ , assume the time required for completing a drone's trajectory is only relevant to the drone's flight time, and let  $C(v_i)$  be the coverage set of vertex  $v_i$  in  $V$ .*

*Since  $V_C = V_P$ , we seek to find the minimum dominating path  $V_P \subseteq V$  which contains COLs in  $V$  and covers all OLs in the 3D grid.*

$$\begin{aligned} & \text{minimize} && |V_P| \\ & \text{subject to} && \bigcup_{v \in V_P} C(v) = V, \quad V_P \text{ is a path.} \end{aligned}$$

2) *Case 2: Considering both flight time and measurement time:* In this case, we assume the measurement time at each OL is not negligible. As the flight mode consumes more power per unit time, we first search for the shortest path that has the maximum coverage, and then select the least number of OLs along the path as COLs for measurement. We formulate this problem as a combination of a minimum dominating path problem and a constrained minimum dominating set problem in multi-layer 2D grids.

**Problem 2** (Trajectory planning by both flight time and measurement time). *Given a 3D grid  $\mathcal{G}$  divided into multi-layer 2D grids, for each grid  $G = L_{m,n} = (V; E)$  where*

$V = \{v_0, v_1, \dots, v_{|V|-1}\}$ , *assume the time required for completing a drone's trajectory is dependent on the drone's flight time and measurement time, and let  $C(v_i)$  be the coverage set of vertex  $v_i$  in  $V$ .*

*We seek to find the minimum dominating path  $V_P \subseteq V$  which covers all OLs in the 3D grid, and then select a set  $V_C$  of COLs from  $V_P$  as the dominating set.*

$$\begin{aligned} & \text{minimize} && |V_P|, |V_C| \\ & \text{subject to} && \bigcup_{v \in V_P} C(v) = V, \quad \bigcup_{v \in V_C} C(v) = V, \\ & && V_P \text{ is a path}, \quad V_C \subseteq V_P. \end{aligned}$$

Therefore, we will discuss these two problems in the next section and give corresponding certifications.

## IV. CONSTRUCTION OF THE MINIMUM DOMINATING PATH IN 2D GRIDS

In this section, we first extend the well-known concept of the dominating set to define the dominating path in a graph. Then, we address Problem 1 by proposing an optimal algorithm to find the minimum dominating path in the 2D grid. We can concatenate the discovered paths (trajectories) in 2D grids to construct the one in the 3D grid.

### A. From the dominating set to dominating path

**Our definition of dominating path:** Recall that a dominating set for the graph  $G = (V, E)$  is a subset  $D \subset V$  such that every vertex not in  $D$  has a neighbor on  $D$ . A connected dominating set  $D$  for graph  $G = (V, E)$  is a special dominating set such that any vertex in  $D$  can reach any other node in  $D$  by a path that stays entirely within  $D$ . Similarly, we have the following definition.

**Definition 1.** A dominating path  $L$  for graph  $G = (V, E)$  is path  $L \subset V$  such that every vertex not in  $L$  has a neighbor on  $L$  which is a special connected dominating set. In a dominating path  $L$ ,

- there exists a dominating set  $D_L$  of  $G$ , and vertices in  $D_L$  are called *dominating vertices* of path  $L$ ;
- and the other vertices in  $L \setminus D_L$  are called *connecting vertices* of path  $L$ .

**Start from the trivial cases:** The goal is to find the minimum dominating path in a 2D grid  $L_{m,n}$ , where  $m, n$  are positive integers.

- *Step 1: trivial cases.* When  $m \leq 3$  and  $n \leq 3$ , it is easy to find the minimum dominating path;
- *Step 2: adding more columns to trivial cases.* When  $m \leq 3$  and  $3 < n \leq 6$ , we seek to construct the minimum dominating path in the 2D grid  $L_{m,n}$  by extending the the minimum dominating path in the 2D grid  $L_{m,(n-3)}$  that has been found in Step 1;
- *Step 3: adding more rows to trivial cases and transposing the grid.* When  $3 < m \leq 6$  and  $n \leq 3$ , we first transpose the grid—swap the rows and columns of the grid, and construct the minimum dominating path in the 2D grid  $L_{n,m}$  by following Step 2;

Any bigger-size grid  $L_{m,n}$  when  $3 < m \leq 6$  and  $3 < n \leq 6$  can be expended by adding three more rows and/or three more columns from one of the grids in trivial cases. The minimum dominating path in the bigger-size grid  $L_{m,n}$  can be also found by repeating above Steps 2 and 3.

Next, we show the correlation between the smaller grid  $L_{m,n}$  and the expanded grid  $L_{m,(n+3)}$ ; note that the latter is expanded by adding three columns to the former.

We give notations of variables.

- $G_i^c$ : Leftmost  $i$ -th column in grid  $G$ .
- $G_i^r$ : Topmost  $i$ -th row in grid  $G$ .
- $G_{i,j}^c$ : Columns between  $G_i^c$  and  $G_j^c$ .
- $G_{i,j}^r$ : Rows between  $G_i^r$  and  $G_j^r$ .
- $v_{i,j}$ : Vertex of intersection of  $G_i^r$  and  $G_j^c$  in grid.
- $N[y] = \{v, y \in V : yv \in E\} \cup \{y\}$ : Coverage set of vertex  $y$ .
- $N[S] = \bigcup_{v \in S} N[v]$ : Coverage set of vertex set  $S \subset V$ .
- $L$ : Vertex set of dominating path.
- $L_i^c = L \cap G_i^c$ : Intersection between  $L$  and  $G_i^c$ .
- $L_i^r = L \cap G_i^r$ : Intersection between  $L$  and  $G_i^r$ .
- $L_{i,j}^c(G) = L \cap G_{i,j}^c$ : Intersection between  $L$  and  $G_{i,j}^c$ .
- $L_{i,j}^r(G) = L \cap G_{i,j}^r$ : Intersection between  $L$  and  $G_{i,j}^r$ .
- $D(L)$ : Dominating vertices in  $L$ .
- $C(L)$ : Connecting vertices in  $L$ .
- $D_i^c(L)$ : Dominating vertex in  $L_i^c$ .
- $D_i^r(L)$ : Dominating vertex in  $L_i^r$ .
- $D_{i,j}^c(L)$ : Dominating vertices in  $L_{i,j}^c(G)$ .
- $D_{i,j}^r(L)$ : Dominating vertices in  $L_{i,j}^r(G)$ .
- $C_{i,j}^c(L)$ : Connecting vertices that connect vertices in  $D_{i,j}^c(L)$ .
- $C_{i,j}^r(L)$ : Connecting vertices that connect vertices in  $D_{i,j}^r(L)$ .
- $C_i^{cccon}(L)$ : Connecting vertices that connect vertices between  $D_{1,i}^c(L)$  and  $D_{i+1,n}^c(L)$ .
- $\gamma(G)$ : The size of minimum dominating set of  $G$ .
- $\gamma_c(G)$ : The size of minimum connected dominating set of  $G$ .
- $\gamma_l(G)$ : The size of minimum dominating path of  $G$ .

**B. The size of the minimum dominating path in the expanded grid  $L_{m,n+3}$**

1) *Decomposing the minimum dominating path in  $L_{m,n+3}$* : In the following lemmas and theorems, we derive the lower bound for the number of vertices needed to add into the minimum dominating path of  $L_{m,n}$  so as to find the minimum dominating path in the expanded grid  $L_{m,n+3}$ .

Since vertices in  $L$  consists of dominating vertices and connecting vertices, we split dominating path in  $L_{m,n+3}$  into 5 parts:  $L = D_{1,n}^c(L) \cup D_{n+1,n+3}^c(L) \cup C_{1,n}^c(L) \cup C_{n+1,n+3}^c(L) \cup C_n^{cccon}(L)$ .

**Lemma 2.** *Let  $L^*$  denote minimum dominating path of  $L_{m,n}$ , and  $L$  denote a minimum dominating path of  $L_{m,(n+3)}$ . Then there exists at least one minimum dominating path  $L$  in  $L_{m,(n+3)}$ , such that the number of dominating vertices of path  $L$  is no less than the number of dominating vertices of path  $L^*$ . That is,  $|D_{1,n}^c(L)| \geq |D(L^*)|$ .*

*Proof:* We have  $|D_{1,n}^c(L)| \geq |D(L_{m,n})|$  if all vertices in  $G_{1,n}^c$  is dominated by  $D_{1,n}^c(L)$  since  $G_{1,n}^c = G^*$ . Therefore, if  $|D_{1,n}^c(L)| < |D(L^*)|$ , some vertices in  $G_n^c$  must be dominated by  $D_{n+1}^c(L)$  and do not have neighbors in  $D_{1,n}^c(L)$ .

Consider there are  $k$  continuous vertices  $v_k$  in  $G_n^c$  dominated by  $D_{n+1}^c(L)$ .

If  $k \geq 2$ , since these  $k$  vertices are not dominated by  $D_{1,n}^c(L)$ , the corresponding  $k$  vertices  $v_{k'}$  which are in the same row with  $v_k$  in  $G_{n-1}^c$  can not belong to  $D_{1,n}^c(L)$ . Therefore,  $k$  vertices  $v_{k''}$  in  $G_{n-2}^c$  should belong to  $D_{1,n}^c(L)$  to dominate  $v_{k'}$  because only two endpoints in  $v_{k'}$  could be dominated by its top and bottom vertex instead, but their right neighbors could not belong to  $L$  which makes  $L$  irregular. So we could use the corresponding vertices in  $G_{n-2}^c$  to replace them so as to shorten  $L$ . Then, we could use  $v_{k''}$  to construct. As shown in .

Since  $L_{n+1,n+3}^c$  may have multiple connected components,  $L$  may step into  $G_{n+1,n+3}^c$  and then move out  $G_{n+1,n+3}^c$  or just move to the end point.

In the first case, since  $L$  may move out from  $G_{n+1,n+3}^c$ , we could construct as Fig and add connecting vertex to corresponding position.

In the second case, when  $D_{n+1}^c$  come from  $D_{n+2}^c$ , we have the following three cases. When  $|v_k| > 3$ ,  $L$  would need more vertices in  $G_{n+3}^c$  to dominate vertices in  $G_{n+2}^c$ . And we could use similar construct like the first case. When  $|v_k| < 3$ ,  $L$  will need more connecting vertices which could also use the same construct. When  $|v_k| = 3$  and vertex in  $v_k$  do not reach  $G_m^r$ , then vertex below  $v_{k'}$  must belong to  $L$ . So vertices in Fig is a dominating path for  $L_{6,n+3}$  partial but can not reach the minimum so that  $L$  could not be the minimum dominating path because the form of minimum dominating path for has same start pointing as  $L$ .

When  $D_{n+1}^c$  do not come from  $D_{n+2}^c$ ,  $L$  would step into  $G_{n+1,n+3}^c$  in the first row, move down to  $v_{m-1,n+1}$  and use vertices in  $G_{n+3}^c$  to dominate remain vertices. Since  $v_{1,n+1} \in L$ ,  $v_k$  starts from  $G_3^r$ . Therefore, we could use similar construct before in Fig to replace  $L$  to another dominating path  $L^*$  where  $|L^*| = |L|$

If  $k = 1$ , then the vertex must lay in boundary otherwise it will need extra connecting vertices between  $G_{n+1}^r$  and  $G_{n+2}^r$ . Therefore, we assume  $v_{1,n+1} \in L$ . Then  $v_{1,n}, v_{1,n-1} \notin L$  and one of  $v_{1,n-2}$  and  $v_{2,n-1}$  must belong to  $L$  to dominate  $v_{1,n-1}$ . If  $v_{1,n-2} \in L$ ,  $L$  will turn to  $G_{n-1}^r$  to dominate vertices in  $G_n^r$  and it will bring more vertices than the following condition. If  $v_{2,n-1} \in L$ , we will have  $L$  like Fig (like  $L_{4,11}$ ). This case could only exist once. We transform  $L_{m,n+3}$  symmetrical. Then,  $|D_{1,n}^c(L)| \geq |D(L_{m,n})|$ . ■

Given  $L$  as the minimum dominating path of the grid  $L_{m,n+3}$ , let  $D_{n+1,n+3}^c(L)$  denote the set of dominating vertices of path  $L$  from the  $n+1$ -th column to the  $n+3$ -th column of grid  $L_{m,n+3}$ ; and let  $C_n^{cccon}(L)$  denote the set of connecting vertices of path  $L$  between the  $n$ -th column and the  $n+1$ -th column. Then, we have the following lemma.



Fig. 2: The viewing distribution of a hot message originated from Beijing.



Fig. 3: The change of modularity towards Information Increment.



Fig. 4: Performance of UDM on WM dataset- on WM and Gowalla dataset- s.



**Lemma 3.** *The number of dominating vertices of path  $L$  from the  $n+1$ -th column to the  $n+3$ -th column of grid  $L_{m,n+3}$ , plus the number of connecting vertices of path  $L$  between the  $n$ -th column and the  $n+1$ -th column is no less than  $m$ . That is  $|D_{n+1,n+3}^c(L)| + |C_n^{cccon}(L)| \geq m$ . Further, if  $3 \nmid m$ , then  $|D_{n+1,n+3}^c(L)| + |C_n^{cccon}(L)| \geq m+1$ .*

*Proof:* Since  $G_{n+1}^c$  might be dominated by  $D_{1,n}^c(L)$ , we consider the coverage problem of  $G_{n+2,n+3}^c$  only.

Before formal proof, we will prove that expect for one single case,  $G_{n+2,n+3}^c$  is dominated by rows. Specifically, every row in  $G_{n+2,n+3}^c$  is dominated by one connected component in  $L_{n+1,n+3}^c$ .

If  $G_i^r$  in  $G_{n+2,n+3}^c$  is dominated by two connected components in  $L_{n+2,n+3}^c$ , then we assume  $v_{i,n+2}$  is dominated by a component above and  $v_{i,n+3}$  is dominated by the other component beneath.

Therefore, there are two different scenarios. Under the first scenery,  $G_i^r$  is dominated by two end vertices like Fig which can be transformed by extending one vertex to dominate all vertices dominated by two components. Under the second scenery,  $G_i^r$  is dominated by one end vertex and one intermediate vertex. This is the unique case that could not be replaced. But we could take them as one part since the union of two components follows the result.

Then, we prove the lemma by induction. Obviously, when  $m = 1$ ,  $|D_{n+1,n+3}^c(L) \cup C_n^{cccon}(L)| \geq 2$ , when  $m = 2$ ,  $|D_{n+1,n+3}^c(L) \cup C_n^{cccon}(L)| \geq 3$  and when  $m = 3$ ,  $|D_{n+1,n+3}^c(L) \cup C_n^{cccon}(L)| \geq 3$ .

Now assume the result holds for  $m = k$ . When  $m = k+1$ , if there is only one connecting component in  $L_{n+1,n+3}^c$ ,  $|\gamma_c(G_{n+2,n+3}^c)| \geq m$ . Adding 1 connecting vertex in  $G_{n+1}^c$ ,  $|D_{n+1,n+3}^c(L) \cup C_n^{cccon}(L)| \geq m+1$ . If there are multiple connecting components in  $L_{n+1,n+3}^c$ , we assume  $G_{n+2,n+3}^c$  is dominated by rows. If  $a$  rows and  $b$  rows are dominated by two connected components  $L_a$  and  $L_b$  respectively. If  $3 \mid m$ , then at most two of  $a$  and  $b$  could be divided by 3 so that  $|(D_{n+1,n+3}^c(L) \cup C_n^{cccon}(L)) \cap (L_a \cup L_b)| \geq a+b$ . If  $3 \nmid m$ , then at most one of  $a$  and  $b$  could be divided by 3 so that  $|(D_{n+1,n+3}^c(L) \cup C_n^{cccon}(L)) \cap (L_a \cup L_b)| \geq a+b+1$ . Therefore, multiple connected components can finally reduce to one component which also holds the result. ■

2) *How many vertices are needed for finding the minimum dominating path in  $L_{m,n+3}$ :* Based on the results of Lemma 2 and Lemma 3, we decompose a minimum dominating path in  $L_{m,n+3}$  into two parts: (1) the left part from 1st column to the  $n$ -th column of  $L_{m,n+3}$ ; and (2) the right part from  $n+1$ -th column to the  $n+3$ -th column of  $L_{m,n+3}$ .

Since the left part is a grid  $L_{m,n}$ , the following theorem tells the relationship between the minimum dominating paths of  $L_{m,n+3}$  and  $L_{m,n}$ .

**Theorem 4.** *The minimum dominating paths of  $L_{m,n+3}$  contains at least  $m$  more vertices than that of  $L_{m,n}$ . That is  $\gamma_l(G) \geq \gamma_l(G^*) + m$ . Further, when  $3 \nmid m$ ,  $\gamma_l(G) \geq \gamma_l(G^*) + m+1$ .*

*Proof:* In Lemma 2 and Lemma 3, we know that there exist at least one minimum dominating path  $L$  in  $G = L_{m,n+3}$ ,  $|D_{n+1,n+3}^c(L) \cup |C_n^{cccon}(L)| \cup |D_{1,n}^c(L)|$  could fulfill additive part in result. Therefore, if the result is false,  $|C_{1,n}^c(L) \cup |C_{n+1,n+3}^c(L)|$  in  $G$  must be less than  $C(L^*)$  of a minimum dominating path  $L^*$  in  $G^*$ .

**Connectivity on the boundary:** Because connectivity depends on structure of  $G_n^r$  and there are only two start vertices in  $L$ , we have structures in  $G_n^r$  like Fig. We will consider different structures of  $L$  in  $G_n^r$ .

If there are only one connecting vertex  $v_{i,n}$  in connected component, we have following two cases. In the first case, like Fig , we have  $v_{i-1,n+1}, v_{i-1,n+2}, v_{i+1,n+1}, v_{i+1,n+2}, v_{i,n+2} \in L$ . In this case, although  $v_{i-1,n+1}, v_{i+1,n+1} \in C_n^{cccon}$  which decreases  $|C_{1,n}^c(L) \cup |C_{n+1,n+3}^c(L)|$ , but  $|C_n^{cccon}(L) \cup |D_{n+1,n+3}^c(L)| = 5$  which still use 4 vertices addition to dominate 3 rows. In the second case, we have  $v_{i-1,n+1}, v_{i-1,n+2}, v_{i-1,n+3}, v_{i+1,n+1}, v_{i+1,n+2}, v_{i+1,n+3}, v_{i,n+3} \in L$  where  $|C_{1,n}^c(L) \cup |C_{n+1,n+3}^c(L)| = |C(G^*)|$ .

If there are two connecting vertices in connected component, when we consider them separately, result is the same as one connecting vertex. If we consider them together, the size of  $L$  in  $G_n^r$  must be 4 as shown in Fig . We assume two vertices are  $v_{i,n}$  and  $v_{i+1,n}$ . Also, we have two cases. In the first case, we have  $v_{i-1,n+1}, v_{i-1,n+2}, v_{i-1,n+3}, v_{i,n+3}, v_{i+1,n+3}, v_{i+2,n+1}, v_{i+2,n+2}, v_{i+2,n+3} \in L$ , also  $|C_{1,n}^c(L) \cup |C_{n+1,n+3}^c(L)| = |C(L^*)|$ . In the second case,  $|C_{1,n}^c(L) \cup |C_{n+1,n+3}^c(L)|$  decreases 2,  $|C_n^{cccon}|$  add 2 and  $|D_{n+1,n+3}^c|$  add 4 which use only 4 vertices addition to dominate 4 rows. It is less than additive part in result. However, this kind of structure could exist when  $n$  is small since to reach that structure,  $G_{i-2}^r$  and  $G_{i+3}^r$  must be dominated by other components and this destroy the 3 periodic structure which will add more vertices in dominating path. Specifically, if there are two 2-period extends, the dominated rows will decrease more than gain in the dominating vertices. And if there are two 3-period extends, it could be replaced by similar structure which move two start points to  $G_{n+3}^r$ . Therefore, there are only two possibilities that the structure could exist. In the first possibility,  $m \equiv 2 \pmod{3}$  and  $m \geq 11$ , as shown in Fig , we have the structure. Consider the structure in  $L_{m',n'}$ .

We assume the structure first appear when  $n' = b$ . Since  $|L_{n'-2,n'}^c| = m'$ , minimum dominating path  $L'$  in  $n' = b - 3$  must hold the same structure which drop  $m' + 1$  vertices in origin  $L'$ . And this structure will hold till  $n' \leq 3$ . Except for  $n' = 1$  which is out of range,  $n' = 2$  or  $n' = 3$  do not have the same structure which makes contradictions. In the second possibility,  $m' \equiv 1 \pmod{3}$ . However, we could simplify this case, since when  $n' \equiv 0 \pmod{3}$  or  $n' \equiv 2 \pmod{3}$ , we could change  $m'$  and  $n'$ . Therefore, we consider  $m' \equiv 1 \pmod{3}$  and  $n' \equiv 1 \pmod{3}$  only. Then, we could simplify to  $L_{m',n'}$  to  $L_{m',1}$  with the same approach like the first possibility which is also out of range.

**Connectivity in the middle:** In this case, we split  $L_{1,n}^{*c}$  on middle and connect two connected components in  $L_{n+1,n+3}^c$  and generate  $L$ . We assume the origin endpoints in  $L^*$  lay in  $G_n^{*c}$ , otherwise we need more connecting vertices between  $L_{1,n}^c$  and  $L_{n+1,n+3}^c$ . If  $C_{1,n}^c(L) \cup C_{n+1,n+3}^c(L)$  could be less than  $|C(G^*)|$ , we consider  $L_{1,3}^c$ . In Lemma 1,  $|L_{1,3}^c| \geq m$  and if  $3 \nmid m$ ,  $|L_{1,3}^c| \geq m + 1$ . Therefore, we could move connecting vertices from  $C_{1,3}^c$  to  $C_{4,n}^c$  if necessary without add more vertices since there are no start point in  $G_4^{*r}$  and we could reduce the extend from minimum dominating path in  $L_{m,n-3}$  to  $L^*$ . Then, we could construct a minimum dominating path  $L^{**}$  from  $L_{4,n+3}^c$  and  $|L^{**}| < \gamma_l(G^*)$  and this makes contradiction.

Therefore, since  $|C_{1,n}^c(L) \cup C_{n+1,n+3}^c(L)|$  is no less than  $C(L^*)$ , we could prove the result. ■

From Theorem 4, we could also know that when  $n = 1$ ,  $\gamma_l(G) \geq \gamma_l(G^*) + m$ .

3) *Meta structs for constructing the minimum dominating path in  $L_{m,n+3}$ :* Although we have proof the lower bound for minimum dominating path in  $L_{m,n}$ , in many cases we can not reach it. Therefore, we consider structures of minimum dominating path instead and give **meta structs** to construct them.

**Struct 1:**  $\gamma_l(L_{m,n+3}) - \gamma_l(L_{m,n}) = m$ . There are two cases for meta struct 1.

- 1) When  $m \equiv 0 \pmod{3}$ , we could select vertexes in  $G_2^r, G_5^r, \dots, G_{m-1}^r$  in  $G_{n+1,n+3}^c$  into minimum dominating path with connecting vertices shift from  $G_n^c$  to  $G_{n+3}^c$ , as shown in Figure 6. And this structure is scalable.
- 2) When  $n = 1$ , when  $m \equiv 3 \pmod{1}$  we could construct as Figure 7 and when  $m \equiv 3 \pmod{2}$  we could construct as Figure 8. Both cases could only exist once.

**Struct 2:**  $\gamma_l(L_{m,n+3}) - \gamma_l(L_{m,n}) = m + 1$ .

There are five cases for meta struct 2.

- 1) When  $m \equiv 2 \pmod{3}$ , we could construct minimum dominating path using similar struct like Figure 10 as shown in Figure ?? which is also scalable.
- 2) When  $v_{1,n}$  belong to minimum dominating path in  $L_{m,n}$ , we could construct as Figure 11.
- 3) When  $G_n^c \setminus v_{1,n}$  belong to minimum dominating path in  $L_{m,n}$ , we could construct as Figure 12.
- 4) When  $n \equiv 0 \pmod{3}$ , we could rotate direction of minimum dominating path of  $L_{m,n}$  and construct with

meta struct 1. If rotation only bring one extra vertex, we could have construct as Figure 13 and  $\gamma_l(L_{m,n+3}) - \gamma_l(L_{m,n}) = m + 1$ .

- 5) When  $n \equiv 2 \pmod{3}$  and  $n \geq 8$ , we could use structure in Figure 14 once to construct minimum dominating path in  $L_{m,n+3}$ .

**Struct 3:**  $\gamma_l(L_{m,n+3}) - \gamma_l(L_{m,n}) = m + 2$ .

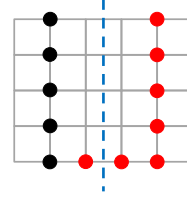


Fig. 16: Typical case of meta struct 3.

Since there are several cases for meta struct 3. We consider the most common and useful case.

When there are no vertices in  $G_n^c$  belong to minimum dominating path  $L$  in  $L_{m,n}$ , vertices in  $G_{n-1}^c$  must belong to  $L$ . Then, we could construct minimum dominating path in  $L_{m,n+3}$  with structure shown in Figure 16.

### C. Optimal Trajectory Planning Algorithms

We have four cases to construct minimum dominating path  $L$  in grid  $G = L_{m,n}$ : (1)  $m < 4$  and  $m < n$ ; (2)  $m \equiv 0 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$  or  $m \equiv 2 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ ; (3)  $m \equiv 0 \pmod{3}$ ,  $n \equiv 0 \pmod{3}$  or  $m \equiv 0 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$  or  $m \equiv 2 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$ ; and (4)  $m \equiv 1 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ .

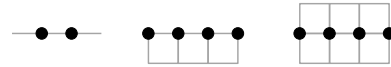


Fig. 17: Minimum dominating path for  $L_{1,n}$ ,  $L_{2,n}$  and  $L_{3,n}$

1) *Case 1:* Since connected dominating set is also dominating path when  $m < 4$  and  $m < n$ , we have the same structure as shown in Figure 17 of [4]. Therefore, we have

- 1)  $\gamma_l(L_{1,1}) = \gamma_l(L_{1,2}) = 1$ , and if  $3 \leq n$ ,  $\gamma_l(L_{1,n}) = n - 2$
- 2)  $\gamma_l(L_{2,2}) = \gamma_l(L_{2,3}) = 2$ , and if  $4 \leq n$ ,  $\gamma_l(L_{2,n}) = n$
- 3)  $\gamma_l(L_{3,n}) = n$

2) *Case 2:* Since minimum dominating path in  $L_{m,1}$  contains  $m - 2 - \lceil \frac{m}{3} \rceil$  connecting vertices, when  $m \equiv 0 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ , we could use meta struct 1 to construct  $L_{m,n}$ . we have the following structure as shown in Figure 18.

Therefore, when  $m \equiv 0 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ , we have  $\gamma_l(L_{m,n}) = 3ab + 3a - 2$ .

Similarly, when  $m \equiv 0 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ , we use meta struct 1 when  $n = 1$ , then we use meta struct 2 as  $n$  increases. We have the following structure as shown in Figure 19.



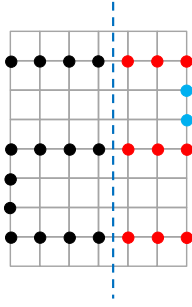


Fig. 6: (a)

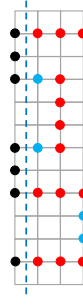


Fig. 7: (b) 1

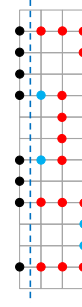


Fig. 8: (b)

Fig. 9: Different cases of meta struct 1. Red vertices are extra vertices in minimum dominating path of  $L_{m,n+3}$ , blue vertices are shifted connecting vertices, Black vertices are vertices in minimum dominating path of  $L_{m,n}$ . The dashed line separates  $G_{1,n}^c$  and  $G_{n+1,n+3}^c$ .

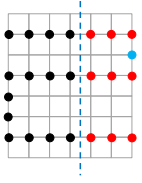


Fig. 10: (a)

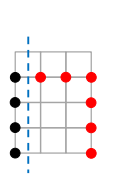


Fig. 11: (b)

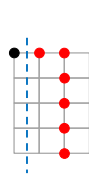


Fig. 12: (c)

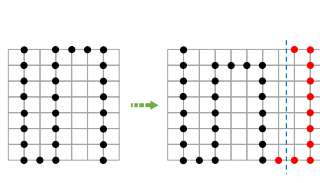


Fig. 13: (d)

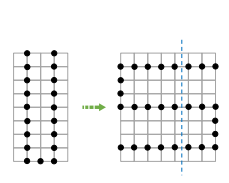


Fig. 14: (e)

Fig. 15: Different cases of meta struct 2.

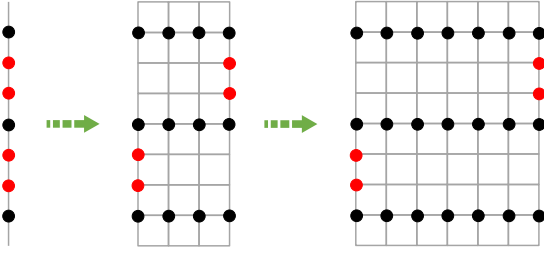


Fig. 18: Minimum dominating path when  $m \equiv 0 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ .

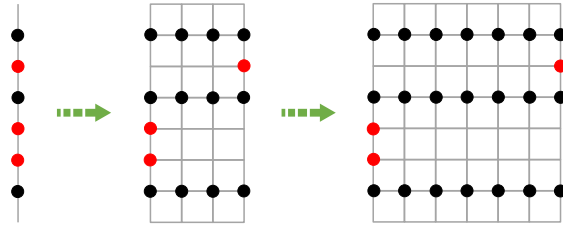


Fig. 19: Minimum dominating path when  $m \equiv 2 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ .

Therefore, when  $m \equiv 2 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ , we have

$$\gamma_l(L_{m,n}) = \begin{cases} 3ab + 3a + 3b & a \leq 2 \\ 3ab + 3a + 3b - 1 & \text{otherwise} \end{cases}$$

3) *Case 3:* We could use reduction on the structure to construct minimum dominating path of  $L_{m,n}$  in this case.

When  $m \equiv 0 \pmod{3}$ ,  $n \equiv 0 \pmod{3}$ , if  $m = 6$ , we could construct  $L_{6,n}$  using meta struct 1. Assume the result hold for  $m = k$ , then we could get minimum dominating path for  $L_{k+3,k}$  from  $L_{k,k+3}$ , since none of meta struct 1 and meta struct 2 fit the structure, we could use meta struct 3 to get minimum dominating path for  $L_{k+3,k+3}$ . Then, we could use meta struct 1 to get  $L_{k+3,n}$  when  $n \geq k + 3$  as shown in Figure 20 which hold the structure for  $k + 3$ . We could use the same approach to construct when  $m \equiv 2 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$  as shown in Figure 21.

When  $m \equiv 0 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$ , we have two structures (a) and (b) as shown in Figure 22 and for different  $n$  we also have two structures shown in 21. Assume result hold for  $m = k$ , and the critical point between structure (a) and structure (b) is  $n = l$  when  $m = k$ . Specifically, when  $n \leq l$ ,  $L_{k,n}$  has structure (a) and otherwise,  $L_{k,n}$  has structure (b). For  $L_{k,n}$  with structure (a), we could construct from  $L_{k+3,l}$ . Since structure (a) could only use meta struct 3 or meta struct 2, we use meta struct 3 on  $L_{k+3,l}$  until it satisfies the condition of meta struct 2. And we hold result for  $m = k + 1$ .

Therefore, we have following results.

When  $m \equiv 0 \pmod{3}$ ,  $n \equiv 0 \pmod{3}$ , assume  $m \leq n$ , we have  $\gamma_l(L_{m,n}) = 3ab + 2a - 2$ . When  $m \equiv 2 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$ , assume  $m \leq n$ , we have

$$\gamma_l(L_{m,n}) = \begin{cases} 3ab + 4a + 3b + 1 & a \leq 2 \\ 3ab + 4a + 3b & \text{otherwise} \end{cases}$$

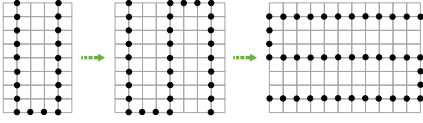


Fig. 20: Minimum dominating path when  $m \equiv 0 \pmod{3}$ ,  $n \equiv 0 \pmod{3}$ .

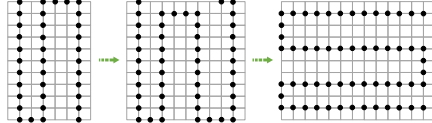


Fig. 21: Minimum dominating path when  $m \equiv 2 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$ .

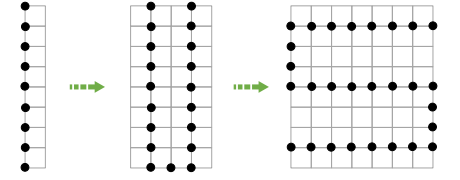


Fig. 22: Minimum dominating path when  $m \equiv 0 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$ , middle one with structure (a) and right one with structure (b).

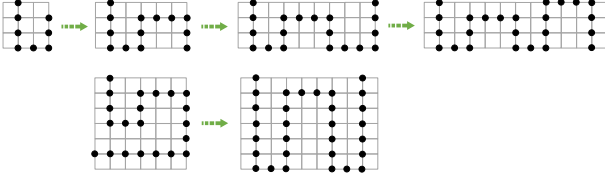


Fig. 23: Minimum dominating path when  $m \equiv 1 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ .

. When  $m \equiv 0 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$ , we have

$$\gamma_l(L_{m,n}) = \begin{cases} \min(3ab + 4a - 2, 3ab + 3a + 2b - 1) & b \leq 2 \\ \min(3ab + 4a - 2, 3ab + 3a + 2b - 2) & \text{otherwise} \end{cases}$$

4) *Case 4:* We could get minimum dominating path of  $L_{4,4}$  in Figure 23. Therefore, we could use two meta structs 2 to construct minimum dominating path of  $L_{4,7}$  and we could use meta struct 2 to construct minimum dominating path of  $L_{7,7}$ . And we could construct minimum dominating path of  $L_{4,n}$  when  $n \geq 10$  from  $L_{1,n}$  with a meta struct 1. Finally, for  $m \geq 7$ ,  $n \geq 10$ , we could only use meta struct 3 to construct minimum dominating path of  $L_{m,n}$  from  $L_{m-3,n}$  which get the result in Figure 23.

Therefore, when  $m \equiv 1 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ , we have

$$\gamma_l(L_{m,n}) = \begin{cases} 3ab + 3a + 3b - 3 & a + b \leq 4 \\ 3ab + 2a + 2b + 1 & \text{otherwise} \end{cases}$$

#### D. How to concatenate 2D trajectories to a 3D one

In actual scenery, 3D space might be irregular. Therefore, we give a approach to concatenate 2D trajectories to a 3D trajectory.

First, we divide 3D space into cuboids and we divide gotten 3D irregular grid into multiple layers of 2D irregular grids. Then, for each irregular grid, we could divide it into regular 2D grids in which we could use proposed algorithm to construct minimum dominating path. Finally, we could simple connect minimum dominating path for regular grids since the start points of minimum dominating path always lay in the boundary.

## V. FINDING THE COLS FROM THE MINIMUM DOMINATING PATH

### A. Consider total time consuming

From last subsection, we know how to find the minimum dominating path in  $L_{m,n}$ . Therefore, we just have to find the set of COLs  $V_C$  in dominating path  $L$ . However, since we have already discussed dominating vertices in last subsection, we only need to add all dominating vertices into  $V_C$ . In general, we only have 1 case for COL which is *standardextendrow* and in this case, we just take the entire row into  $V_C$  and add

Therefore, for the 6 different cases, we have the following result.

#### Proposition 1.

- 1)  $\gamma_l(L_{1,n}) = \lfloor \frac{n+2}{3} \rfloor$
- 2)  $\gamma_l(L_{2,2}) = \gamma_l(L_{2,3}) = 2$ , and if  $4 \leq n$ ,  $\gamma_l(L_{2,n}) = n$
- 3)  $\gamma_l(L_{3,n}) = n$

**Proposition 2.** Assume  $m \geq 4$ ,  $n \geq 4$ . When  $m \equiv 0 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ , we have  $|V_C| = 3ab + a$ . When  $m \equiv 2 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ , we have

$$|V_C| = \begin{cases} 3ab + a + 3b + 1 & a \leq 2 \\ 3ab + a + 3b + 2 & \text{otherwise} \end{cases}$$

**Proposition 3.** Assume  $m \geq 4$ ,  $n \geq 4$ . When  $m \equiv 0 \pmod{3}$ ,  $n \equiv 0 \pmod{3}$ , we have  $|V_C| = 3ab$ . When  $m \equiv 0 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$ , we have

$$|V_C| = \begin{cases} 3ab + 2a & b \leq 2, 3ab + 4a - 2 \leq 3ab + 3a + 2b - 1 \\ 3ab + 3a & b \leq 2, 3ab + 4a - 2 > 3ab + 3a + 2b - 1 \\ 3ab + 2a & b > 2, 3ab + 4a - 2 \leq 3ab + 3a + 2b - 2 \\ 3ab + 3a + 1 & \text{otherwise} \end{cases}$$

. When  $m \equiv 2 \pmod{3}$ ,  $n \equiv 2 \pmod{3}$ , assume  $m \leq n$ , we have

$$|V_C| = \begin{cases} 3ab + 2a + 3b + 2 & a \leq 2 \\ 3ab + 2a + 3b + 3 & \text{otherwise} \end{cases}$$

. Besides, the results have a same structure.



**Proposition 4.** Assume  $m \geq 4, n \geq 4$ . When  $m \equiv 1 \pmod{3}$ ,  $n \equiv 1 \pmod{3}$ ,  $a \geq 1$  and  $b \geq 1$ , assume  $m \leq n$ , we have

$$|V_C| = \begin{cases} 7 & a = 1, b = 1 \\ 10 & a = 1, b = 2 \\ 17 & a = 2, b = 2 \\ 3ab + 3a + b - 1 & \text{otherwise} \end{cases}$$

## B. Optimal Trajectory Planning Algorithms

### VI. EVALUATION

#### A. Experiment Setup

**Prototype:** The prototype consists of two parts: (1) a drone with an API that can configure its trajectory; and (2) a measurement sensor board or a smartphone is installed into a plastic box with vent-holes made by a laser engraving machine, which is attached at the bottom of the drone. The drone we use is a DJI Phantom 3 Quadcopter, as shown in Figure ???. There is an intelligent flight mode that allows the customization of the trajectory by configuring a number of stop locations such that the drone will autonomously follow this trajectory to hover over each stop and complete the flight. The GPS sensor, ultrasonic sensor, and the motion sensors collectively determine the current observation location of the drone and guide the drone to the next stop in the trajectory. At each stop, the drone hover for a few seconds,  $T_M$ , to collect sufficient measurement data, before traversing to the next stop.

**Compared algorithms:** We compare the proposed algorithm with two other conventional algorithms. In the proposed algorithm, we choose the minimum dominating path in grids first, and then select COLs from path. In contrast, the conventional algorithms we considered will select COLs in grids first, and then choose a path to connect the selected COLs. The two conventional algorithms differ by the way of selecting COLs, as introduced below.

- 1) *Row-wise COL selection:* We select the minimum dominating set in grids first, and select an OL at boundary as start point. Then, we use a row-first COL selection strategy to find a row by row, along the longer side of the grid.
- 2) *Greedy COL selection:* We select the minimum dominating set in grids first, and then select a COL at boundary as start point. Then, we follow the greedy algorithm that chooses the next vertex  $v$  as the closest one that can lead to the maximum coverage, such as:

$$\min_{d(v, v')} \max_{|N[v] \setminus N[P]|} v,$$

where  $v' \in \mathcal{G}$  is the last vertex of path of  $P \subset \mathcal{G}$ .

**Performance metrics:** We use the following two metrics for evaluating the algorithm performance.

- *Time consumed:* The time consumed is defined as total time of flight and measurement of the drone to cover the space of the trajectory under a specific algorithm.

- *Coverage space:* The coverage space is defined as the maximum coverage area in the 3D space during entire battery life, by following the trajectory under a specific algorithm.

#### B. Experimental Results

We choose an open space in a university campus which has a size of 45 m in length, 35 m in width, and 10 m in height. It is divided into 3D grids formed by 5 by 5 by 5 m cuboids. Since the time consumed is the sum of flight time and measurement time, we consider the impact of different measurement times in experiments, which are set as 0, 1, 2, 5 seconds at each COL. Note that the case when the measurement time is 0 second is equivalent to the case when we consider the flight time only.

Figure ?? show the time consumed under compared algorithms with different granularity of the measurement time. The sensing area is a 2D grid of size 9 by 7 m. We observe that our proposed algorithm consumes less time when the measurement time is small. The gap between our algorithm and the row-wise COL selection algorithm decreases as the measurement time increases. When the measurement time is 5 seconds at each COL, the total time consumed by the proposed and the row-wise COL selection algorithms are equal.

Figure ?? show the coverage space in the 3D grid under compared algorithms with different granularity of the measurement time during the battery life. We fix the width of the grid as 6 m, we observe that our proposed algorithm could cover more space than other algorithms in all cases, during the whole battery life. As the measurement time increases, the coverage area by any of three algorithms decreases, since the measurement time consumes part of the battery. Meanwhile, the difference in the coverage space among three algorithms decreases when the measurement time is set greater.

In a real-world application, drones might be used to delivery packages or other goods. Hence, we also evaluate the time consumed and the coverage space with different loads when we only consider the flight time. Results in Figure ?? and ?? show that as the load increases, the time consumed of three algorithms to complete the sensing task of a given grid increases; meanwhile, the coverage space of three algorithms during the battery life decreases. Note that the proposed algorithm performs the best in all scenarios under different loads on the drone.

#### C. Simulation results in different-size spaces

In experiments, we only test the performance of compared algorithm in a give 3d space with the fixed size. In simulations, we can evaluate the algorithm performance in different-size spaces.

Figure ?? show the flight time in spaces with different width and length. We observe that our algorithm consumes less time to complete the sensing task in each grid. When fixing the width (or length) of the grid, the gap among algorithms increases as the length (or width) increases.

Similarly, we observe in Figure ??, our proposed algorithm has the maximum coverage space during the battery life; When

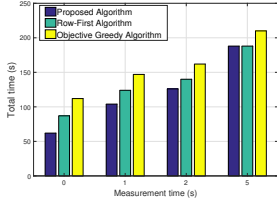


Fig. 24: Time consumed of three algorithms with different granularity of measurement time.

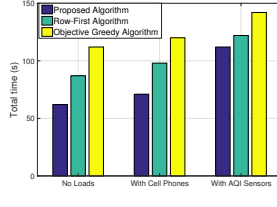


Fig. 25: Time consumed of three algorithms with different loads when considering flight time only.

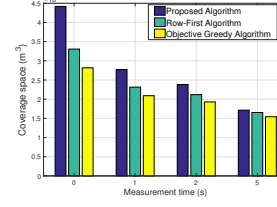


Fig. 26: Coverage space of three algorithms with different granularity of measurement time.

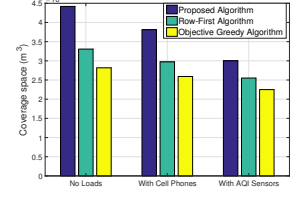


Fig. 27: Coverage space of three algorithms with different loads when considering flight time only.

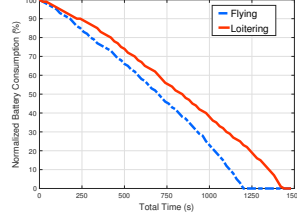


Fig. 28: Comparison of the Adaptive Monitoring Algorithm, Greedy Algorithm and Sequential Selection.

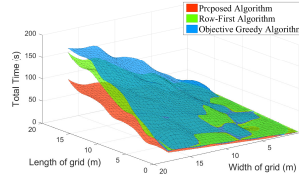


Fig. 29: Comparison of the Adaptive Monitoring Algorithm, Greedy Algorithm and Sequential Selection.

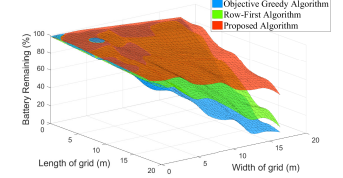


Fig. 30: Comparison of the Adaptive Monitoring Algorithm, Greedy Algorithm and Sequential Selection.

fixing the width (or length), our algorithm could cover more space than other compared algorithms.

## VII. CONCLUSIONS

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**Algorithm 1** Trajectory planning for UAV in grid when consider flight time only

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**Input:** The graph of trajectory planning,  $L_{m,n}$ ; The length of grid,  $m$ ; The width of grid,  $n$ ;

**Output:** The trajectory of two-dimensional coordinate of grid,  $V_P$ ;

```

1:  $a = \lfloor \frac{m}{3} \rfloor$ ,  $b = \lfloor \frac{n}{3} \rfloor$ ,  $ra \equiv m \pmod{3}$ ,  $rb \equiv n \pmod{3}$ ;
2: if ( $ra = 1$  and  $rb = 0$ ) or ( $ra = 1$  and  $rb = 2$ ) or
   ( $ra = 0$  and  $rb = 2$  and  $a > 2b$ ) or ( $ra = 2$  and  $rb = 0$ 
   and  $b \leq 2a$ ) or ( $ra \equiv rb \pmod{3}$  and  $a > b$ ) then
3:   swap( $m$ ,  $n$ ), swap( $a$ ,  $b$ ), swap( $ra$ ,  $rb$ );
4: end if
5: if  $m < 4$  or  $n < 4$  then
6:   if  $m > n$  then
7:     swap( $m$ ,  $n$ ), swap( $a$ ,  $b$ ), swap( $ra$ ,  $rb$ );
8:   end if
9:   if  $m = 1$  then
10:    put  $G_1^r$  except  $v_{1,1}$  into  $V_P$ ;
11:    if  $n = 1$ , then put  $v_{1,1}$  into  $V_P$ ;
12:   else if  $m = 2$  and  $n = 3$  then
13:     put  $v_{1,2}$ ,  $v_{2,2}$  into  $V_P$ ;
14:   else if ( $n = 2$ ) then
15:     put  $G_1^r$  into  $V_P$ ;
16:   else
17:     put  $G_2^r$  into  $V_P$ ;
18:   end if
19: else if  $m \equiv 0 \pmod{3}$  then
20:   put  $G_2^r$ ,  $G_5^r$  ...,  $G_{3a-1}^r$  into  $V_P$ ;
21:   put connecting vertices in  $G_1^c$  and  $G_n^c$  into  $V_P$ ;
22: else if  $m \equiv 2 \pmod{3}$  then
23:   if  $a > 2$  then
24:     put  $v_{2,1}$ ,  $v_{3,1}$ ,  $v_{6,2}$ ,  $v_{7,2}$  into  $V_P$ ;
25:     put  $G_2^r$ ,  $G_5^r$ ,  $G_8^r$  except vertices in  $G_1^c$  into  $V_P$ ;
26:     put  $G_1^r$ ,  $G_4^r$  ...,  $G_{3a+1}^r$  into  $V_P$ ;
27:     put connecting vertices in  $G_1^c$  and  $G_n^c$  into  $V_P$ ;
28:   else
29:     put  $G_2^r$  into  $V_P$ ;
30:     put  $G_4^r$ , ...,  $G_{3a+1}^r$  into  $V_P$ ;
31:     put connecting vertices in  $G_1^c$  and  $G_n^c$  into  $V_P$ ;
32:   end if
33: else
34:   if  $a \leq 2$  and  $b \leq 2$  then
35:     if  $a \geq 1$  and  $b \geq 1$ , then put  $v_{1,2}$ ,  $v_{2,2}$ ,  $v_{3,2}$ ,  $v_{4,2}$ ,
        $v_{4,3}$ ,  $v_{4,4}$ ,  $v_{3,4}$ ,  $v_{2,4}$  into  $V_P$ ;
36:     if  $a \geq 1$  and  $b = 2$ , then put  $v_{2,5}$ ,  $v_{2,6}$ ,  $v_{2,7}$ ,  $v_{3,7}$ ,
        $v_{4,7}$  into  $V_P$ ;
37:     if  $a = 2$ , then put  $v_{5,7}$ ,  $v_{6,7}$ ,  $v_{6,6}$ ,  $v_{6,5}$ ,  $v_{6,4}$ ,  $v_{6,3}$ ,
        $v_{6,2}$ ,  $v_{6,1}$  into  $V_P$ ;
38:   else
39:     put  $v_{1,2}$ ,  $v_{2,5}$ ,  $v_{2,6}$  into  $V_P$ ;
40:     put  $G_2^c$ ,  $G_4^c$ ,  $G_7^c$  except vertices in  $G_1^r$  into  $V_P$ ;
41:     put  $G_9^c$ ,  $G_{12}^c$ , ...,  $G_{3b}^c$  into  $V_P$ ;
42:     put connecting vertices in  $G_1^r$  and  $G_m^r$  into  $V_P$ ;
43:   end if
44: end if
return  $V_P$ ;

```

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---

**Algorithm 2** Trajectory planning for UAV in grid when consider total time consuming

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**Input:** The graph of trajectory planning,  $L_{m,n}$ ; The length of grid,  $m$ ; The width of grid,  $n$ ;

**Output:** The trajectory of two-dimensional coordinate of grid,  $V_P$ ; The COL set of two-dimensional coordinate of grid,  $V_C$ ;

```

1: do algorithm 1 and get  $V_P$ .
2:  $a = \lfloor \frac{m}{3} \rfloor$ ,  $b = \lfloor \frac{n}{3} \rfloor$ ,  $ra \equiv m \pmod{3}$ ,  $rb \equiv n \pmod{3}$ ;
3: if  $m < 4$  or  $n < 4$  then
4:   if ( $m = 1$  and  $n \leq 3$ ) or  $m \geq 2$  then
5:      $V_C = V_P$ ;
6:   else
7:     put  $v_{1,2}$ ,  $v_{1,5}$ , ...,  $v_{1,3b-1}$  into  $V_C$ ;
8:     if  $rb = 1$  or  $rb = 2$ , then put  $v_{1,3b+1}$  into  $V_C$ 
9:   end if
10: else if  $m \equiv 0 \pmod{3}$  then
11:   put  $G_2^r$ ,  $G_5^r$  ...,  $G_{3a-1}^r$  into  $V_C$ ;
12: else if  $m \equiv 2 \pmod{3}$  then
13:   if  $a > 2$  then
14:     put  $v_{2,1}$ ,  $v_{3,1}$ ,  $v_{6,2}$ ,  $v_{7,2}$  into  $V_C$ ;
15:     put  $G_2^r$ ,  $G_5^r$ ,  $G_8^r$  except vertices in  $G_1^c$  into  $V_C$ ;
16:     put  $G_1^r$ ,  $G_4^r$  ...,  $G_{3a+1}^r$  into  $V_C$ ;
17:   else
18:     put  $G_2^r$  into  $V_C$ ;
19:     put  $G_4^r$ , ...,  $G_{3a+1}^r$  into  $V_C$ ;
20:   end if
21: else
22:   if  $a \leq 2$  and  $b \leq 2$  then
23:     if  $a \geq 1$  and  $b \geq 1$ , then put  $v_{1,2}$ ,  $v_{2,2}$ ,  $v_{3,2}$ ,  $v_{4,2}$ ,
        $v_{4,4}$ ,  $v_{3,4}$ ,  $v_{2,4}$  into  $V_C$ ;
24:     if  $a \geq 1$  and  $b = 2$ , then put  $v_{2,5}$ ,  $v_{2,6}$ ,  $v_{2,7}$ ,  $v_{4,7}$ 
       into  $V_C$  and move  $v_{3,4}$  out from  $V_C$ ;
25:     if  $a = 2$ , then put  $v_{6,7}$ ,  $v_{6,6}$ ,  $v_{6,5}$ ,  $v_{6,4}$ ,  $v_{6,3}$ ,  $v_{6,2}$ ,
        $v_{6,1}$  into  $V_C$ ;
26:   else
27:     put  $v_{2,4}$ ,  $v_{2,5}$ ,  $v_{2,6}$ ,  $v_{2,7}$  into  $V_C$ ;
28:     put  $G_2^c$  into  $V_C$ ;
29:     put  $G_4^c$ ,  $G_7^c$  except for  $G_{1,3}^r$  into  $V_C$ ;
30:     put  $G_{10}^c$ ,  $G_{13}^c$ , ...,  $G_{3b}^c$  into  $V_C$ ;
31:   end if
32: end if
return  $V_P$ ,  $V_C$ ;

```

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