On Differential Privacy-preserving Movements of Unmanned Aerial Vehicles

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***Abstract*—A recent proliferation of UAVs accompanies several critical issues to be considered for efficient, secure use of UAVs. One of those issues should be a privacy of people. Also, when the UAVs fly to perform specific objectives, minimizing movements of UAVs is a big issue to provide a minimum mission completion time and a maximum network lifetime. One intuitive solution is that UAVs may pass through private area of citizens whereas people do not want any penetration into own area without a permission. Then, we may take into account a compromise between those situations by giving a differential permission for each UAV to access citizens' areas depending on specific benefits by use of UAVs or emergent situation for public safety. In this paper, we introduce a framework for privacy-preserving movements of UAVs with differential UAVs' permissions given by citizens. Then, we formally define a problem whose objective is to minimize total movements of UAVs with preserving privacy of people. To solve the problem, we create a new graph type called as *UDiPP graph* and propose a novel priority-based approach. Furthermore, we discuss future issues and directions for differential privacy-preserving movements by UAVs.**

I. Introduction

With the rapid growth of recent mobile technology, unmanned aerial vehicles (UAVs) have become one of promising future technologies because of its potential with exponential growth. Basically, UAV is composed of several parts including body, power supply, thermal sensors, camera with night vision, actuators [1], [2], [3]. UAVs will be used in numerous applications such as border patrol, area surveillance, search and rescue operation, agriculture, wildlife tracking, traffic management, delivering items in both harsh environment and civil area operated by public institutions, industrial companies, ordinary individual user [1], [4], [6], [8]. Though a single large UAV can be utilized in those various applications, multiple small-scale UAVs (i.e. drones) can provide several advantages for cost, scalability, survivability, speed-up, compared with the single UAV system [4], [5]. Fig. 1 shows an example of UAV applications for security patrol and item delivery using multiple UAVs.

Because of a limited flight time of small-scale UAVs, a time critical issue should be addressed [9], [13]. So, we should give thought to potentially important problems in such a time critical limitation of UAVs. i.e. minimizing total movement of UAVs, minimizing maximum distance of UAVs, minimizing the final time to complete mission of UAVs, etc [12].

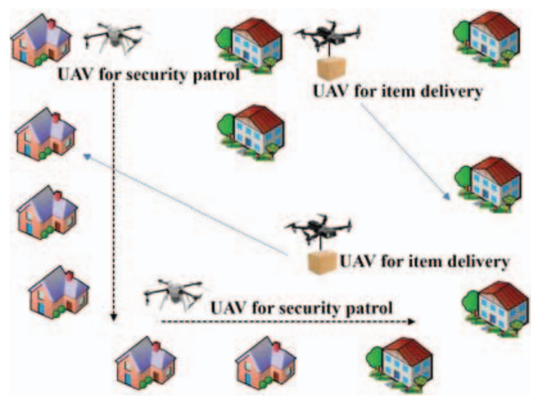

Fig. 1. An example of UAV application.

Although UAVs definitely have amazing capabilities and will give positive effects for future life of people, it will also cause additional critical issues which need to be addressed. One of those issues must be a privacy for citizens [8]. To perform time-sensitive objectives, it is expected that numerous number of small-scale UAVs will fly in the sky operated by public institutions, industrial companies or citizens, etc. By Federal Aviation Administration's regulations [7], [8], the small-scale UAVs must fly with relatively low altitude (i.e. no higher than 400 feet). Since UAVs are able to record photographs monitored by the equipped camera [1], [2], people in especially urban circumstance will be exposed to a serious exposure risk of unwanted private life by UAV's trespass into citizen's private area when UAVs perform emergent missions for a public safety. Hence, both unauthorized flights of UAVs over private area and unrecognized data collected by UAVs must be prohibited or be considered very carefully with strict regulations in order to protect privacy of citizens. On the

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other hand, citizens may give temporal admissions into their areas in certain circumstances requiring emergent measures. (i.e. collecting disaster information for fire-fighting, tracking terrorist trajectory). Also, citizens may allow trespass of UAVs selectively for industrial companies if people take benefits by permitting trespass of UAVs for a specific company into own private area. (i.e. approval of delivering the ordered items using UAVs). Hence, it is highly necessary to develop a new system of UAVs to be able to consider both the privacy of citizens and the time critical issue of small-scale multiple UAVs with a limited flight time.

Based on the above observations, we introduce a new framework to provide privacy-preserving movements of small-scale multiple UAVs by allowing differential access for those UAVs. We design a fundamental architecture of UAVs, which is applicable for the practical scenario and situation with various components such as a group of citizens (or private area), a set of UAVs, public area. Also, we formally define a problem whose objective is to minimize total movements of multiple UAVs with differential permissions. Then, in order to solve the defined problem, we propose a novel approach as well as create a new graph model, referred as *UDiPP graph*.

The rest of the paper is organized as follows. Next, we review related works for UAVs. In Section III, we introduce our system to support privacy-preserving movements of multiple UAVs by differential permissions and also define a new problem. In Section IV, we create a *UDiPP graph* to solve the defined problem and then propose a novel approach using *UDiPP graph*. Finally, we conclude this paper in Section V with possible future works.

II. Related Work

For coordination of multi-vehicles and future challenges, many works had been studied by researchers previously. In [10], authors considered a classical traveling salesman problem setting is used for making decisions with different levels of autonomy in a multi-UAV system. Then, in [11], authors proposed an architecture which allows the deployment of a group of heterogeneous UAVs with operational autonomy and also supports a possibility to create the decisional scheme based on the available robots dynamically. In [12], a method for optimizing cooperative heterogeneous multi-vehicle systems with connectivity features was proposed. Moreover, in [13], authors designed a modular architecture to construct an autonomous system with small-scale UAVs for search and rescue missions. Authors considered a coordination of multiple UAVs based on a distributed control system. In [14], authors designed an overview of UAV-aided wireless communications to consider on-demand systems based on low altitude UAVs which provide more faster to deploy and more flexible to reconfigure.

For planning trajectory of UAVs, there exist various previous works. UAV path planning problem is proved to be NP-Complete in [15] and authors presented a novel route planning scheme to create mission-adaptable paths. In [16], author developed an approximate model of aircraft dynamics using linear constraints for aircraft collision avoidance. In [17], authors introduced an evolutionary algorithm and a combination of modified breeder genetic algorithms is used to to develop an offline and online path planner for autonomous navigation of UAVs. The path planner considers a curved path line in a three-dimensional (3-D) terrain circumstance. In [18], authors considered a hierarchical framework for task assignment and path planning of multiple UAVs in a dynamic environment. They proposed an intersection-based path generation algorithm and a negotiation-based task assignment. They simulated their algorithms using a fixed wing UAVs. Also, in [19], authors proposed a scheme for comparing the planners performance by the combined use of several general and problem-specific quality indexes and then they showed the performance indexed with three graphic representation of their results which includes the comparison of various UAV planners. In [20], authors deal with a path planning problem whose goal is to maximize collected amount of information from desired regions with requirement of avoiding restricted areas. In [21], authors proposed an improved constrained differential evolution algorithm and formulated a global route planning problem of UAVs in the 3-D environments. Authors considered multiple constraints with practical scenarios such as maximum turning angle, terrain, forbidden flying areas, etc. Moreover, in [22], authors presented UAVs path planned based on a separate evolution scheme and considered the decomposed constraints and objective functions. The waypoints of candidate paths are evolved separately.

On the other hand, privacy issues in UAV system are addressed in [23], [24], [25], [26], [27]. Those articles and reports represent that UAVs may have potential privacy challenges since they have capabilities to be able to collect information using the equipped sensor and video camera on the board of UAVs. Also, UAVs with the collected information have a possibility to be hijacked by attackers, which will cause an interruption of the service they support. Hence, the private issue should be considered very critically to prevent intrusions into a privacy and a liberty of citizen.

III. A Framework for Differential Privacy Preserving Movements of UAVs

In this section, we introduce a framework to support privacy-preserving movements of multiple UAVs with differential permissions. After representing the assumptions which are used in the system, we depict practical scenarios and describe how to detect privacy violation in the framework. Then, we formally define a problem to consider both privacy of citizen and efficient movements of UAVs.

A. Assumptions

Based on Federal Aviation Administration's regulations [7], [8], the following assumptions are considered in the proposed framework of UAVs.

- A two dimensional square-shaped area is considered as a region of interest (ROI).
- We use multiple small-scale UAVs instead of a single large UAV.
- Each UAV has a same moving speed (It is no faster than 100 mph.)
- Each UAV flies with two modes of altitude: a low altitude mode (i.e. 5 meters) over permitted private area and a high altitude mode (i.e. 100 meters) over an unpermitted private area and public area.
- Each UAV has a straight line-based movement. We define an euclidean distance $EucDist(a, b)$ between a and b.
- An UAV can move between permitted customers with a low altitude. But, an UAV should maintain a flight with a high altitude when a trajectory of UAV includes the unpermitted private area and the public area.
- Each UAV has one trespasser type.
- Each UAV can take multiple items with a light weigh.
- A distance between public points in public area is equal.
- At least, each customer has a path to one public point.
- A private area of each customer is a square-shaped area with an equal size.

B. System setup

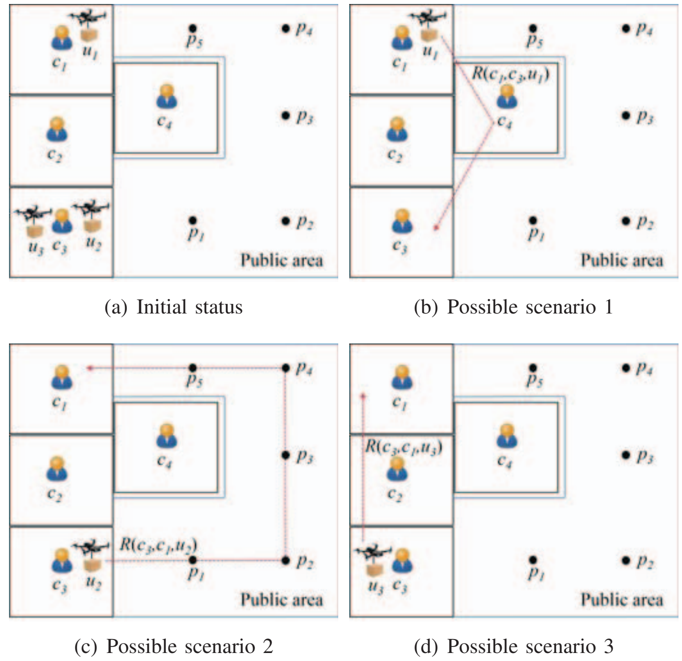
In our system, we consider a square-shaped area A. The area A includes n number of customer locations $C = \{c_1, c_2, ..., c_n\}$ which requires a permission for UAVs' access into own area. Also, A has q number of public points in public area as $P = \{p_1, p_2, ..., p_q\}$ which are accessible by any UAVs. Then, k number of UAVs, $U = \{u_1, u_2, ..., u_k\}$, have initial random locations on public points. And we have m number of trespasser types $T = \{t_1, t_2, ..., t_m\}$, which is simply considered as the number of companies or institutions operable UAVs. Each customer c_i, $1 \leq i \leq n$, can choose several permitting trespasser types by own decisions. Also, into own private area, c_i only allows access of UAVs which are operated by those permitted trespasser types by c_i.

For the flight mode of UAV, we consider each UAV has an initial location over a permitted customer with a low altitude mode and then a difference between a height at low altitude mode and a height at high altitude mode is given as h_{dalay}. Also, each customer has own permission lists for different trespasser types. (i.e. c_1 has $\{t_1, t_2, t_3\}$, c_2 has $\{t_1, t_2\}$, etc). For each trespasser type, the assignment of UAVs is given initially. (i.e. t_1 has $\{u_1, u_2\}$, t_2 has $\{u_3, u_4\}$, etc.)

Furthermore, each customer c_i considers own area as a virtual square with four points, $c_iv_1, c_iv_2, c_iv_3, c_iv_4$. Also, the virtual square includes four segments, $c_is_1, c_is_2, c_is_3, c_is_4$.

C. Applicable scenarios with a plan view

Let us consider an application for delivering items using multiple UAVs in the area A which includes a public area as Fig. 2. Within the public area, we have several public points p_1, p_2, p_3, p_4, p_5 and any UAV can fly over those public points.



(a) Initial status
(b) Possible scenario 1
(c) Possible scenario 2
(d) Possible scenario 3

Fig. 2. Various movement scenarios of UAVs with a plan view.

Suppose that there exist u_1, u_2, u_3 operated by three different industrial companies, t_1, t_2, t_3. Each UAV is only operated by the related company. Then, suppose u_1 is only operated by t_1, u_2 is by t_2 and u_3 is by t_3, respectively. Also, we have four customers c_1, c_2, c_3, c_4 which are located within A.

With these settings, suppose that both customer c_1 and c_3 have a membership of all companies t_1, t_2, t_3. And a customer c_2 has a membership of t_3 only and a customer c_4 has a membership of t_1 only. Also, let us suppose that c_1 is a neighbor with c_2, c_4 and also c_2 is a neighbor with c_1, c_3, c_4. Also, let us suppose u_1 flies over c_1 and both u_2 and u_3 fly over c_3 currently. Fig. 2(a) shows the initial status.

If a customer c_1 ordered some items through t_1, t_2, t_3, then the customer definitely will allow u_1, u_2, u_3 to access to own house and to drop the items at a low altitude. And if another customer c_3 ordered some items through t_1, t_2, t_3, then c_3 will receive the ordered items by allowing penetration of u_1, u_2, u_3 for delivery of the items.

Suppose u_1 has delivered an item to c_1 and tries to deliver an item to c_3 in Fig. 2(b). To reduce a delivery delay, u_1 may want to pass through the house of c_2 in the air if the trajectory is a short-cut from current location of u_1. But, to protect own privacy, c_2 may not want the penetration of u_1 operated by t_1 because c_2 is not a member of t_1. So, u_1 should find an alternate route $R(c_1, c_3, u_1)$ through c_4 with an increased delivery time because c_4 allows UAVs of t_1 as its member as Fig. 2(b). Otherwise, u_1 at low altitude mode should move up to reach the high altitude and it may pass through the area of c_2 with high altitude. Then, u_1 moves down for a low altitude to deliver the item at the area of

c_3. But, this case also increases a delivery time due to the increased movement by excessive altitude conversion.

On the other hand, suppose that after delivering to c_3, u_2 needs to deliver an item of t_2 to c_1 in Fig. 2(c). Similarly, to reduce delivery delay, u_2 also may want to pass through a house of neighbor c_2 or c_4 if the movement trajectory is a path with the shortest distance from current location of u_2. But, since both c_2 and c_4 are not a member t_2, they will not approve any penetration of u_3. So, u_2 only may choose a route $R(c_3, c_1, u_2)$ in order to deliver the item through public road with a long distance with a high altitude mode. Finally, c_1 will receive the ordered item from u_2 with the delayed time.

Next, suppose we have u_3 which is over the house of c_3 as a current location as Fig. 2(d). To deliver an item of t_3 to c_1 as the next customer, u_3 can use the shortest route $R(c_3, c_1, u_3)$, which passes through the house of c_2, because c_2 will permit the penetration u_3 as a member of t_3.

D. Detection of privacy violation

Now, we explain how to decide whether UAVs penetrate into private areas in the proposed framework.

Assume that we create a virtual square based on a customer location. So, a customer location must be a center of the virtual square with four same-length segments between each corner point of the square. Also, assume we consider each virtual square has equal size. Based on the virtual squares, we decide if an UAV penetrates into unpermitted private area by checking if UAV's route is crossing with any line segment in the square where is located between two permitted customer locations.

Then, we define a privacy violation of UAV as follows.

Definition 3.1 (Privacy violation of UAV): Given a set of customers C and virtual squares with a line segment length r, the privacy violation of UAV is occurred if UAV's route between two customers who gave access permission to the UAV is crossing with any line segment of virtual squares of unpermitted customer.

Fig. 3 shows an example of the privacy violation by UAV and its detection. Suppose we have UAV u_1 and four customers, c_1, c_2, c_3, c_4. Then, a virtual square is created by generating four corner points with distance d from a customer location as well as four segments. For example, using c_2 and given distance d, we can generate a virtual square with four points, $c_2v_1, c_2v_2, c_2v_3, c_2v_4$. Also, the virtual square will include four segments, $c_2s_1, c_2s_2, c_2s_3, c_2s_4$ with a length r. Suppose that u_1 is located at c_1 and u_1 is able to move to c_3 or c_4 since u_1 has an access permission for c_1, c_3, c_4. If u_1's route between c_1 and c_3, $R(c_1, c_3, u_1)$, will cross with two segments c_2s_3, c_2s_4 within the virtual square of unpermitted c_2. So, by these crossed segments, UAV u_1's penetration into c_2 can be detected. On the other hand, another route between c_1 and c_4, $R(c_1, c_4, u_1)$, has no privacy violation because the route has no crossing segments.

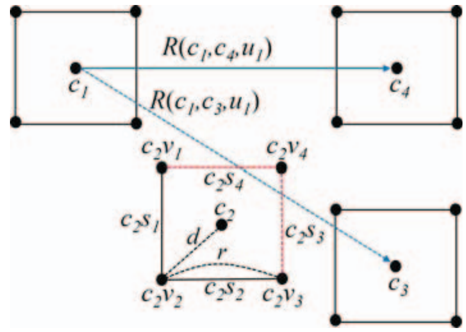


Fig. 3. An example of the penetration decision.

E. Problem Definition

Based on the proposed framework, we pursue to maximize a lifetime of UAVs network by minimizing total movement distance for multiple small-scale UAVs. Because we should address a preserved privacy for customers and each customer may give different permissions for UAVs into own area, we also should consider differential privacy-preserving movement of UAVs by verifying detection of privacy violation.

Then, we formally define our problem referred as *UDiPP-move* problem as well as *differential privacy-preserving movements* of UAVs as follows.

Definition 3.2 (Differential privacy-preserving movements): Assume that we have a set of UAVs U, a set of customers C with a set of trespasser type T deployed over an area A. Also, each UAV has differential access permissions into customers. *Differential privacy preserving movements* of UAVs are to support a guaranteed route of UAVs without any privacy violation by UAVs.

Definition 3.3 (UDiPPmove problem): Given the system setup information, *UDiPPmove* problem is to minimize total UAVs' differential privacy preserving movements such that the requested customers have guaranteed visits by UAVs.

To solve the *UDiPPmove* problem, we should consider to create a new graph type, *UDiPP graph*, based on system information including customer, UAV, public point information and the information for a low and a high altitude. Then, from those given information, we convert into *UDiPP graph* with the set of vertices, edges, virtual squares. Then, we also define *UDiPP graph* as follows.

Definition 3.4 (UDiPP graph): Given information for customer, UAVs, public points with the number and locations of each entity, *UDiPP graph* $\mathcal{G} = (V, E, S)$, is a graph which consists of the set of vertices V, edges E, virtual squares S.

IV. Proposed Approaches

In this section, we develop two algorithms: the first algorithm is to create *UDiPP-Graph*. The second algorithm is proposed using a *UDiPP-Graph* and a priority-based movement of UAVs.

Algorithm 1 ***UDiPP-Graph-Creation***

Inputs: A, C, P, T, d, r, Output: $\mathcal{G} = (V, E, S)$

set $V = \emptyset$;
set $E = \emptyset$;
set $S = \emptyset$;
identify C, P and their locations in A;
$V \leftarrow (C \cup P)$;
find a neighbor p_j for each public point p_i, where $p_i, p_j \in P$ for $\forall i$;
if there exists **then**
  create an edge $E(p_i, p_j)$;
  $E \leftarrow E(p_i, p_j)$;
end if
search for the closest public point p_j for each customer c_i, where $c_i \in C, p_j \in P$ for $\forall i$;
if it is found **then**
  create an edge $E(c_i, p_j)$;
  $E \leftarrow E(c_i, p_j)$;
end if
create four corner points $c_i v_j$ of virtual square s_i for each customer c_i, where $EucDist(c_i, c_i v_j) = r$, $c_i \in C, v_j \in \{v_1, v_2, v_3, v_4\}$ for $\forall i, j$;
if it is generated **then**
  $s_k \leftarrow c_i v_j$;
end if
$S \leftarrow s_k$, where $\forall k$;
return $\mathcal{G} = (V, E, S)$

A. Creation of UDiPP graph

To create a *UDiPP-Graph*, we perform *UDiPP-Graph-Creation* algorithm. It uses the following steps.

- Verify C, P and their locations in A and then add them to a set of vertices, V.
- For each public point, search for an edge between a public point and its neighbor. Then, add it to a set of edges, E.
- For each customer, find an edge between a customer and the closest public point. Also, add it to a set of edges, E.
- For each customer, create four corner points of the virtual square and add them to a set of virtual squares, S.

The pseudocode of *UDiPP-Graph-Creation* is presented in Algorithm 1.

B. Proposed approach for UDiPP movement

UAVs have various movement types. With a consideration of both a low altitude mode and a high altitude mode of UAVs, we define the following movement priorities of UAVs, which can be used as the movement strategy of UAVs.

1) *Priority 1*: a movement between a permitted customer (location) and a permitted customer without any privacy violation, which allows to maintain the movement with low altitude after UAV finished its mission to the permitted customer. So, this is the best movement type of UAV since it only needs to consider a distance between two permitted customers without any change of altitude of UAV.
2) *Priority 2* has two cases.
   a) *Priority 2-1*: a movement between a permitted customer and a permitted customer with a privacy violation, which should consider the long distance of UAV between a low altitude and a high altitude as well as the distance between two permitted customers.
   b) *Priority 2-2*: a movement between a permitted customer and a permitted customer through public points, which consider the distances between public points.

Algorithm 2 ***Priority-UDiPP-Movement***

Inputs: $\mathcal{G} = (V, E, S), A, U, C, P, T, U_{locations}$

Output: $U_{totalmove}$

set $U_{totalmove} = 0$;
set $C' \leftarrow C$;
while $C' \neq \emptyset$ **do**
  set $found = false$;
  set $temp = 0$;
  while $found == false$ **do**
    find *priority 1* pairs without private violation for all pairs between c_i and UAV u_j, where $c_i \in C, u_j \in U_{locations}$;
    if there exist **then**
      select a pair (c'_i, u'_j) with the shortest distance from those pairs;
      $U_{totalmove} = U_{totalmove} + EucDist(c'_i, u'_j)$;
      $C' \leftarrow C' - c'_i$;
      update $U_{locations}$ by removing u'_j and adding c'_i;
      $found = true$;
      break;
    else
      find a shortest distance pair (c'_i, u'_j) with private violation;
      calculate a *priority 2-1* distance, $temp_1 = EucDist(c'_i, u'_j) + 2 \cdot h_{delay}$;
      find a path $\{c'_i, p_a, ..., p_b, u'_j\}$;
      calculate a *priority 2-2* distance of the path, $temp_2$;
      choose the path with smaller distance, $temp = min(temp_1, temp_2)$;
      $U_{totalmove} = U_{totalmove} + temp$;
      $C' \leftarrow C' - c_{min}$;
      update $U_{locations}$ by removing u_{min} and adding c_{min};
      $found = true$;
      break;
    end if
  end while
end while
return $U_{totalmove}$

To solve the *UDiPPmove* problem, we propose an approach, which is referred as *Priority-UDiPP-Movement*. The steps of *Priority-UDiPP-Movement* are as follows.

- Find pairs without private violation for all pairs between customers to be visited and current UAVs.
- If there exist those pairs, select a pair with the shortest distance and add the distance to total distance of UAVs, $U_{totalmove}$, and update a set of current UAV location information, $U_{locations}$ for the selected pair.
- If not, choose the pair with the shortest distance from pairs with private violations.
  - For the chosen pair, calculate a distance $temp_1$ to consider a high altitude mode by adding $2 \cdot h_{delay}$ to $EucDist(c_i, u_j)$.
  - For the chosen pair, search for a path through public points and calculate the distance $temp_2$.
  - Choose a smaller distance between $temp_1$ and $temp_2$ and add the distance to $U_{totalmove}$ and update $U_{locations}$ for the selected pair.

The above steps are iterated until the requested customers are visited completely by UAVs. The pseudocode of *Priority-UDiPP-Movement* is presented in Algorithm 2.

V. Concluding Remarks and Future Issues

In this paper, we introduced a framework for *UDiPP* movement. We defined a *UDiPPmove* problem whose objective is to minimize total movements of multiple UAVs by differential permissions. Then, we not only created a new type of graph, *UDiPP graph*, but also proposed a priority-based movement of UAVs to solve the defined problem. As a future work, we plan to analyze the performances of the proposed approaches by various practical scenarios and environments.

Also, as future research issues, we consider an application by UAVs for smart cities. Because smart cities have dynamic and dense properties, the collision-free, delay-sensitive movement issue with the privacy-preserving property by UAVs will be one of important issues. On the other hand, an application by UAVs for sparse areas such as extensive ocean is planned to be studied.

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