In: 2023 International Conference on Unmanned Aircraft Systems (ICUAS), 6-9 June 2023, Warsaw, Poland
DOI: 10.1109/ICUAS57906.2023.10156320

Dynamic Graph Propagation for Performance-based Tactical Conflict Resolution in Urban Air Mobility

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Abstract— **Tactical conflict management is a crucial issue for time-sensitive urban air mobility (UAM) operations, considering safety, security, and efficiency factors. To achieve real-time conflict resolution in structural UAM corridors, the operational environment is formulated as the graph structure, in which the edge connection is the available routes, and the node feature is collected from the flight states, e.g. arrival time, speed, arrival probability affected by uncertainties, and priority. To resolve the short-term conflict, the graph propagation solution is proposed to generate multiple augmented subgraph views based on the prescribed graph, where each subgraph represents one candidate action, e.g. speed adjustment, local re-routing. Information in each subgraph is then aggregated and assessed by the global cost metric. As the consequence, the final action is determined by ranking the cost values of all possible subgraph views. The study cases about the higher-priority intruder and non-cooperative intruder demonstrate the effectiveness of the proposed solution for eliminating the conflicts and reducing the additional cost.**

I. INTRODUCTION

With the development of air transportation techniques, the demand for air-based services increases dramatically, especially in crowded metropolitan regions. Urban Air Mobility (UAM) is an emerging technology for transiting passengers and delivering packages in urban areas. Considering the restriction of flight safety, security, and the morphology of metropolis in low-altitude airspace, the management of all flights is a crucial task for UAM operations to avoid potential conflicts and collisions between air-to-air and air-to-ground objects.

To improve flight safety and security efficiently, conflict management can be divided into three stages: strategic conflict management, separation provision, and collision avoidance [1]. The first strategic conflict resolution is able to solve the potential conflict in submitted flight schedules one day or several days before the execution of operations. In this stage, the flight states are nominal. The second component is separation provision, which is also the tactical conflict resolution to ensure the safe separation of all en-route flights in nearly real-time. The last resort to guarantee the safety is collision avoidance function, which relies on the onboard sensors and maneuvers to avoid short-term collisions.

In the paper, we focus on tactical conflict resolution, which needs cooperative information from en-route vehicles or non-cooperative information from surveillance techniques. According to the development of the UAM concept, the UAM aircraft are operating in the UAM corridors which connect different waypoints and aerodromes [2]. UAM aircraft need to adhere to specific regulations, performance, and procedure standards. In the meanwhile, the topology complexity of UAM corridors increases with the rising demand of air services. As the consequence, all en-route flights should be monitored for detecting off-nominal events and ensuring safe separation.

In traditional air traffic management (ATM), separation assurance is provided by air traffic controllers (ATCOs) and is typically achieved by tactically delaying aircraft through vectoring or speed control [3]. To avoid potential conflicts and ensure separation between two aircraft, conflicting protection zone [4] and discretizing airspace to 4D space-time grid [5] are common approaches. A potential conflict can be identified whether a cell is occupied by different aircraft or one of its neighbors is occupied by another aircraft [6].

Formulating mathematical models is always the first measure for resolving this issue. Commonly, a mathematical model can be formulated to minimize the total deviation from flight schedules that needs to avoid loss of pairwise separation. The deconfliction can also be achieved by both airborne adjustments (through speed changes) and ground delays (holds relative to the scheduled take-off) [7]. In the meanwhile, a non-linear program (NLP) was used for agent-based UAM conflict resolution, offering improved solution flexibility relative to other work [8]. Existed software such as NASA's Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) software also have the potential to apply the current rules of the road to the UAM environment to resolve multi-aircraft encounters [9].

And learning-based methods can further reduce the limitation of static models. The flight operation in UAM which was formulated as a Markov Decision Process, and the Monte Carlo Tree Search was able to perform real-time decision-making for collision avoidance and guidance to destination [10]. And this method was then extended to a multi-agent system, and the coordination mechanism was designed to manage multiple cooperative aircraft [11]. Instead of the centralized operation, a federated speed-control-based conflict resolution algorithm is established including rules of the road, data exchange requirements, and critical parameters. The federated structure is better than "centralized" if there are many aircraft in the same area [12]. Finally, AutoResolver [13] and Prediction-based Conflict-free Adaptive Navigation [14] can predict the trajectory and the occurrence of the conflict, then avoid it by modifying the velocity vector of the UAVs involved.

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In addition, en-route flights are affected by many uncertainties, which may cause serious consequences in a short time. To some degree, wind and some conditions about aircraft can be predicted, but some factors like actual maneuver error and sudden storms are not always predictable over a long time, especially in urban regions. Many non-learning based methods [15] [16] [17] [18] are proposed to cope with different uncertainties. Learning-based methods such as Monte Carlo [19] and reinforcement learning [20] show their advantages of the realistic application. The nominal operations will be directly influenced by those unpredictable factors which may result in potential conflicts, so it needs to be taken seriously. Due to uncertainty in UAM flight trajectories, environmental conditions (e.g., wind), and other factors, tactical departure management, en-route separation management, and arrival management technologies may also be needed to mitigate the effects of uncertainty [21] [22]. Therefore, this research will resolve short-term interaction-free separation problems, meantime, involving the trajectory probabilities from uncertainties.

As UAM aircraft are operating in UAM corridors, it is convenient to model the problem as the graph problem. Some cases take the aircraft as the graph node, and the interaction between aircraft is viewed as the edge connection [7]. As for the resolution actions, most of the cases utilize speed vector change and delay, whereas, it is not safe to fly outside of UAM corridors when revising the heading of aircraft. Restricted by the structure, the proposed action should not deviate from the bounds of corridors. As a result, those solutions for changing heading are not applicable to UAM corridors.

In this paper, we model the UAM corridors as a graph structure, in which the node is the crosspoint or waypoint, and the edge is the corridor connecting two waypoints. Then the flight information of each aircraft about the arrival data at each node, e.g. arrival time, speed, probability, and priority, is collected as the node feature. The conflicts are detected with the node features. To solve the detected conflicts, graph augmentation and graph propagation are applied to generate candidate actions in speed change and local replanning. The final action is determined by the global cost of all subgraph views.

The contributions of this paper are summarized as follows:

- A dynamic graph propagation scheme is proposed for solving the tactical conflict in UAM.
- The flight priority and probability of arrival at each waypoint are involved in formulating the graph features.
- Performance-based operation is enabled for improving the operational efficiency.

The rest of the paper is organized as follows: Section II introduces the graph structure for UAM corridors and tactical conflict definition. The proposed graph propagation solution is illustrated in Section III. Section IV analyses the results of some study cases. Section V concludes the paper.

II. PROBLEM STATEMENT

In this section, fundamental elements in tactical conflict resolution are described.

A. *Tactical Conflict*

The strategic conflicts and demand-capacity balancing (DCB) issues have been resolved by the Provider Providers of Service to UAM (PSU) before executing the flight schedule, which means that the provided flight plan is expected to be nominal and conflict-free. However, there is an issue that strategic trajectory management only uses scheduled plans and estimated information for optimization without accurate environmental effects involved. In the process of actual operation, short-term uncertainties such as wind effects or intruders will have a great impact on flight states, as a result, the nominal schedule will suffer deviations and new conflicts are possible to be generated in the tactical stage. In this way, to detect short-term conflicts, tactical trajectory management for conflict resolution needs real-time and relatively accurate states of flights such as velocities and positions. When the distance between any pairwise aircraft is less than the separation minima, the tactical conflict appears to be solved.

B. *Graph Structure*

We assume that all UAM vehicles should fly within the designated corridors or routes, whether the corridor network is prescribed or dynamic. In this work, we design flight corridors as undirected graphs. The nodes in the graph represent the en-route waypoints and the connected edges are available routes.

To formulate the tactical conflict resolution solver, the necessary information should be given as follows:

- Nominal schedule about the arrival time t and speed v at each waypoint of all flights. For non-cooperative intruders, t and v should be detected and predicted by the surveillance system.
- Possibility p of each aircraft to reach the waypoint according to the trajectory prediction considering contingencies. Especially, we only consider the possibility value here, as for the prediction approaches, it is possible to apply linear models or neural networks to predict this value.
- The priority o of all flights to avoid emergency flights or non-cooperative intruders.

We need to employ this kind of information to detect potential conflicts in real time and propose solutions. A flight in the tactical stage is represented by a probabilistic spatiotemporal trajectory, in general, written as $a_i = \left\{ \left(wpt_0, t_0^{a_i}, v_0^{a_i}, p_0^{a_i}, o_0^{a_i}\right), \ldots, \left(wpt_n, t_n^{a_i}, v_n^{a_i}, p_n^{a_i}, o_n^{a_i}\right) \right\}$, where i and n are indices of aircraft and waypoints, respectively.

An illustrative example used to explain the graph architecture is demonstrated in Fig.1. The node set is $\{wpt_1, \ldots, wpt_8\}$ and the edge set is $\{(wpt_1, wpt_2), (wpt_2, wpt_3), (wpt_2, wpt_6), \ldots, (wpt_7, wpt_8)\}$. To clearly explain the scheme, we introduce one ownship vehicle a_0 and one intruder vehicle a_1 in this scenario. According to the flight schedule and real-time prediction, we can estimate the expected arrival information $[t, v, p, o]$ at each node, which is also known as the node feature. Referring to the flight plan, the ownship will traverse waypoints $\{wpt_2, wpt_3, wpt_7\}$ and the intruder will arrive at the wpt_3. With the flight information at each node, the node feature can be constructed as follows:

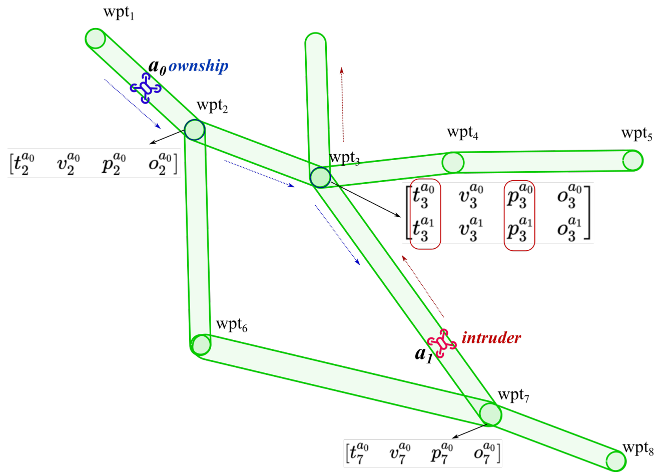

Fig. 1: Graph structure of UAM Corridors.

- For node wpt_2, only ownship a_0 traverse this point, and the feature is $f_{wpt_2} = \begin{bmatrix} t_2^{a_0} & v_2^{a_0} & p_2^{a_0} & o_2^{a_0} \end{bmatrix}$;
- For node wpt_3, both ownship a_0 and intruder a_1 will pass the node, then the feature is stacked by two aircraft: $f_{wpt_3} = \begin{bmatrix} t_3^{a_0} & v_3^{a_0} & p_3^{a_0} & o_3^{a_0} \\ t_3^{a_1} & v_3^{a_1} & p_3^{a_1} & o_3^{a_1} \end{bmatrix}$;
- For node wpt_7, only ownship a_0 is expected to travel this node, and the feature is $f_{wpt_7} = \begin{bmatrix} t_7^{a_0} & v_7^{a_0} & p_7^{a_0} & o_7^{a_0} \end{bmatrix}$;

According to the constructed node features, it is easy to notice that only one aircraft will pass the node wpt_2 and wpt_7, there is no other aircraft to produce possible conflicts at those points. As for wpt_3, there will be two aircraft arriving at this node from different headings. We then need to assess if these two aircraft can generate possible conflicts at this node. In this paper, we detect tactical conflict based on the arrival time difference and the probabilities as in Eq. (1):

$$\begin{cases} t_m^{a_0} - t_m^{a_1} < \Delta t \\ p_m^{a_0} * p_m^{a_1} > \Delta p \end{cases} \tag{1}$$

where $m = 3$ refers to information at wpt_3 in this sample. If the possibility of arrival time difference less than the separation minima Δt exceeds the limit value Δp, we define that the conflict will occur at this node.

III. GRAPH PROPAGATION SOLUTION

In this section, the graph propagation solution is proposed for generating candidate actions and then selecting the best option to reduce the global cost, as well as inducing conflicts.

A. Local Augmentation for Multi-view Graphs

With the detected short-term conflicts, an efficient and fast solution should be proposed to resolve the conflict immediately. As the node features are collected from en-routes flights, messages are passing along the graph edge. Inspired by graph augmentation for graph structure learning [23], the dynamic topology of the subgraph can be fully explored for providing candidate solutions.

The general workflow for generating valid actions is illustrated in Fig. 2. It consists of three major components: augmented views, graph propagation, and global cost ranking.

1) Graph Augmentation: The graph augmentation is to generate several subgraphs from the global graph, in which each subgraph has various node features and edge connections. In this tactical deconfliction problem, the intruder is assigned with higher priority, only the ownship needs to take action. In this way, we consider building alternative graph views for the ownship to make decisions. As in the Augmented Views of Fig. 2, each candidate view is a possible option for resolving the issue. In View 1, the ownship follows the planned routes, and the node connections remain unchanged. Therefore, this subgraph view is directly extracted from the global graph to formulate nodes and connections, the node feature is revised, especially the speed component to avoid a collision. And in other subgraph views, such as the route changing in View 2, alternative routes are searched to avoid potential conflicts. In this case, both node connections and features are changed. In addition to directly extracting the route from the original schedule like View 1, other graph views are generated by finding all possible routes between the next available node and the terminal node.

In this process, one subgraph view will keep the original path, and it only changes the aircraft speed. But other generated subgraphs will change the traversed nodes and node feature at the same time.

2) Graph Propagation: After the augmented subgraph views are generated, we need to assess the influence and effectiveness of each candidate solution. To proceed with the process, we put the subgraph information back into the original graph, in this way, replanned schedules are propagated to the graph. Once the information is collected by the global graph, the node features are updated for each duplicated global graph while maintaining the topology.

3) Global Cost Ranking: The candidate operations are generated from the augmentation subgraphs and propagation. To select one effective option from all candidate subgraph views, we propose the global cost ranking to evaluate the importance or the cost of each possible action. The global cost G consists of the time delay to the scheduled node t_{delay}, the distance increment d_{incre} for route re-planning, and the inducing collision risk c_r as in Eq.(2).

$$G = t_{delay} + d_{incre}/v_{avg} + c_r \tag{2}$$

where the collision risk is set to $c_r = 100$ to enlarge the global cost when the inducing collision is unavoidable in the generated graph. And v_{avg} is the average speed of all aircraft in the scenario.

For speed change on the original route in View 1, the $d_{incre} = 0$ as there is no distance difference. Thus only speed

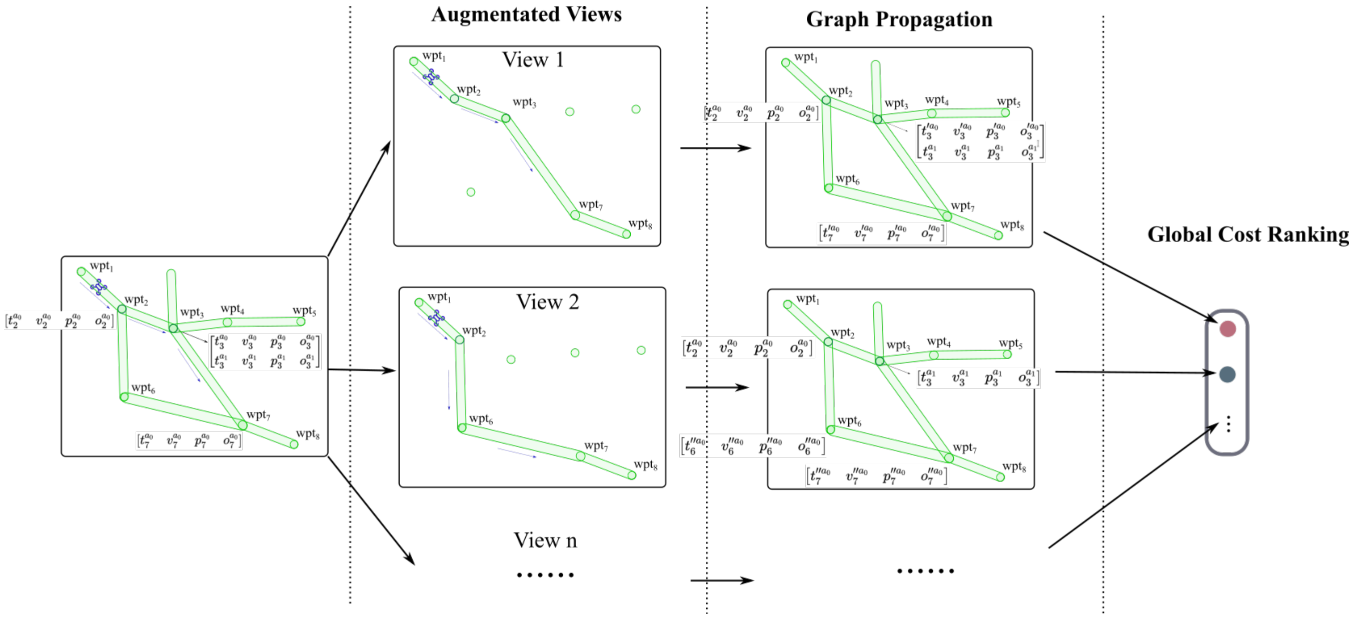

Fig. 2: Graph propagation workflow.

change can be applied. We need to delay the ownship to arrive at the conflict point wpt_n δt seconds after the intruder passes this point to obtain the expected arrival time t'^{a_0} as in Eq. (3). Then we need to check if the ownship can reach the node wpt_m after the conflict node wpt_n by comparing the expected speed (travel between wpt_n and wpt_m within $t_m^{a_0} - t_n'^{a_0}$) with the maximum speed as in Eq. (4). If this condition can be satisfied, it means that the flight can reach the scheduled node as planned by changing the speed within the flight performance range. Otherwise, the flight must be delayed and minimum t_{delay} can be obtained by flying with the maximum speed as in Eq. (5). The detailed workflow for generating the global cost of View 1 has been illustrated in Algorithm 1.

$$t_n'^{a_0} = t_n^{a_1} + \delta t \tag{3}$$

$$dist(wpt_m, wpt_n)/(t_m^{a_0} - t_n'^{a_0}) < v_{max}^{a_0} \tag{4}$$

$$t_{delay} = dist(wpt_m, wpt_n)/v_{max}^{a_0} + (t_n'^{a_0} - t_n^{a_1}) \tag{5}$$

For other views about the local replanning, the distance must be changed between the new route and the original one. To reach the terminal node wpt_k, the distance increment can be compared by the new route and the planned one from wpt_n to wpt_k as in Eq. (6). Then the reachability in the schedule range from the conflict node wpt_n to wpt_k can be examined by the Eq. (7). If the required flight speed is in the range of aircraft performance, it means that no delay is generated for the re-routing, otherwise, the time delay will be added with the flight distance change. The detailed workflow for generating the global cost of other views is described in Algorithm 2.

Algorithm 1: Speed change on the original route

```
Calculate the safe arrival time at the first conflict
  node $n$ with: Eq. (3);
Check the reachability at the node $m$ after conflict
  node $n$;
if $t_m^{a_0} > t_n^{a_0}$ then
    if Eq. (4) then
        New speed change between node $wpt_m$ and
          $wpt_n$;
    else
        Obtain delay when flying with the maximum
          speed as in Eq. (5)
else
    Obtain delay when flying with the maximum
      speed as in Eq. (5)
```

$$d_{incre} = dist'(wpt_n, wpt_k) - dist(wpt_n, wpt_k) \tag{6}$$

$$\frac{\sum_{i,j\in(n,k)} dist'(wpt_i, wpt_j)}{t_k^{a_0} - t_n^{a_0}} < v_{max}^{a_0} \tag{7}$$

IV. STUDY CASES

To evaluate the performance of the proposed graph propagation solution for resolving the tactical conflict, we simulate several study cases to demonstrate its effectiveness.

A. *UAM Aircraft Performance Dataset*

To enable performance-based operation, we need to propose an appropriate solution for various aircraft based on aircraft performance. It is not reasonable to require one aircraft to fly faster than its maximum speed range. And

Algorithm 2: Local replanning

```
Check the reachability from conflict node $n$ to the terminal node $k$: ;
if Eq. (7) then
    No additional delay cost.
else
    Compare the new schedule and the original schedule to obtain time delay and distance increment.
```

in this paper, the small UAVs for accomplishing the urban last-mile delivery task are presented in TABLE I.

Various-size aircraft have restricted flight time because of the limited amount of battery. Meanwhile, the speed range limits the fastest speed to avoid unreasonable action requirements.

TABLE I: Small Aircraft Performance Data.

Aircraft Type	**Size (m)**	**Max Hovering Time (min)** [*Full Payload*]	**Max Hovering Time (min)** [*Empty Payload*]	**Speed Range (m/s)**
DJI Matrice 600	1.668	16	35	[-18,18]
DJI Matrice 100	0.65	13	22	[-22, 22]
DJI Matrice 200	0.887	27	38	[-23, 23]
DJI Mavic pro	0.887	24	24	[-18, 18]
Horsefly Gen 5.3	1.1	25	50	[-22, 22]
DJI AGRAS MG-1S	1.47	10	22	[-15, 15]
DJI AGRAS T30	2.858	7.5	20.5	[-10, 10]
DJI AGRAS T16	2.509	10	18	[-10, 10]

B. Schduled Intruder with Higher Priority

The first study case simulates a scenario where the ownship has a conflict with the intruder with higher priority. As plotted in Fig. 3, the conflicted flight states for ownship and intruder are $wpt_2(0s), \rightarrow wpt_3(17.95s) \rightarrow wpt_4(35.35s)$ and $wpt_2(0s) \rightarrow wpt_3(17.95s) \rightarrow wpt_9(32.95s)$. All arrival probabilities are set to 1.0 here. According to Eq. (1), the two UAM aircraft will have tactical conflict at wpt_2 and wpt_3 when $\Delta t = 30s$ and $\Delta p > 0.7$. We then employ the graph propagation scheme to solve this issue.

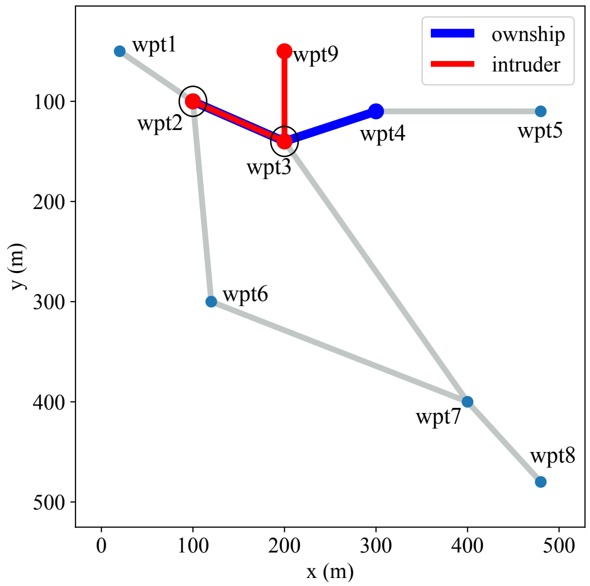

Fig. 3: Schduled Intruder with Higher Priority.

The generated subgraph views and corresponding global costs are demonstrated in TABEL II. We can compare two generated graph views about the speed change and local replanning. The final decision can be obtained by the lower-cost speed change view. Then the valid action is changing the speed from the original $6m/s$ to the maximum speed that the aircraft can provide. For different types of aircraft, the flight performance affects the final cost. We can find the difference from TABLE III that the cost can be minimized when the maneuverability of the aircraft is high because the aircraft can try to catch the expected schedule when it can fly as fast as possible.

C. Non-cooperative Intruder

In the flight scenario, not all aircraft are cooperative and regulated. When non-conformance aircraft intrude on the operational corridors, we set the intruder with a higher priority actively. In these kinds of scenarios, nominal flights should take short-term action to avoid collisions with harmful and non-cooperative small targets.

As depicted in Fig. 4, for the ownship with schedule $wpt_9(0s), \rightarrow wpt_3(15.0s) \rightarrow wpt_4(32.4s), wpt_5(62.4s)$, one non-cooperative aircraft is predicted to arrive at the vicinity of wpt_3 at $33.67s$ with 0.8 probability. To resolve the tactical conflict, the subgraph view analysis is listed in TABLE IV. We can find that in this scenario, the conflict will appear before crossing the wpt_3 for the ownship. It means that the ownship has no option to change the route, and it must delay and change the speed even if the global cost is not very high.

Finally, we can conclude from the pairwise conflict resolution scenarios that the graph propagation scheme is able to ensure flight separation. Effective actions can be generated to avoid potential conflicts and reduce global costs.

TABLE II: Global Costs from Different Views.

	Action	Time Delay (second)	Distance Increment (meter)	Collision Risk	Global Cost
View 1	Speed Change	19.37	0	0	19.37
View 2	Local Planning	119.7	718	0	241.03

TABLE III: Global Costs For Different Small Aircraft in Speed-change View.

	Time Delay (second)	Distance Increment (meter)	Collision Risk	Global Cost
DJI Matrice 600	18.03	0	0	18.03
DJI Matrice 100	16.94	0	0	16.94
DJI Matrice 200	16.73	0	0	16.73
DJI Mavic pro	18.03	0	0	18.03
Horsefly Gen 5.3	16.94	0	0	16.94
DJI AGRAS MG-1	19.22	0	0	19.22
DJI AGRAS T30	22.81	0	0	22.81
DJI AGRAS T16	22.81	0	0	22.81

TABLE IV: Global Costs for Resolving the Conflict with Non-cooperative aircraft.

	Action	Time Delay (second)	Distance Increment (meter)	Collision Risk	Global Cost
View 1	Speed Change	24.17	0	0	24.17
View 2	Local Planning	None	None	None	None

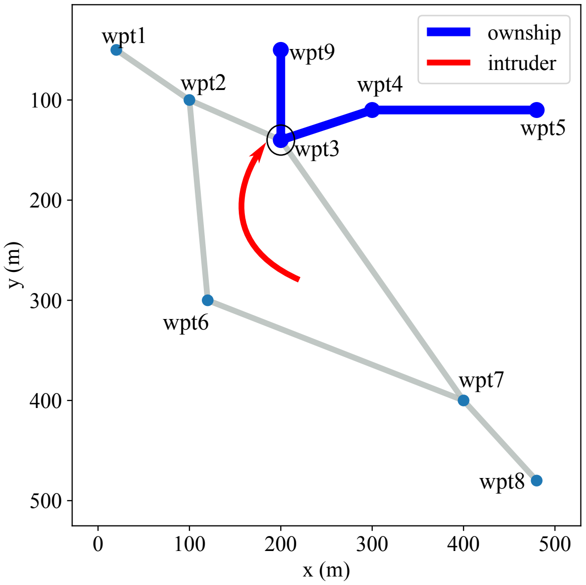

Fig. 4: Non-cooperative intruder.

V. CONCLUSIONS

In this paper, the tactical conflict management problem is modeled as the graph problem. The UAM corridors are formulated as the structural graph, in which the node features are constructed with aircraft schedules, and the edges are connected corridors. The conflict can be resolved by the proposed graph propagation scheme. It can generate multiple subgraphs from the global graph, and the graph propagation aggregates the information to check the reachability at the expected position. Candidate actions, e.g. speed adjustment and local re-routing, are determined by the global cost considering the delay, distance increment, and inducing collision risk. The validation cases demonstrate the effectiveness of resolving tactical conflicts with our approach.

This paper attempts to resolve the tactical conflict in a simple and straightforward way, however, the limitation is the pairwise-aircraft scenario. Although the multi-aircraft conflict can be solved by applying our approach iteratively, other uncertainties are expected to be involved to evaluate the resilience to complex scenarios in the future.

ACKNOWLEDGMENT

This research was partially supported by grants from the Funds of China Scholarship Council (202008420248).

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2023-06-26

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IEEE

Huang C, Petrunin I, Tsourdos A. (2023) Dynamic graph propagation for performance-based tactical conflict resolution in urban air mobility. In: 2023 International Conference on Unmanned Aircraft Systems (ICUAS), 6-9 June 2023, Warsaw, Poland

https://doi.org/10.1109/ICUAS57906.2023.10156320