Airspace Design and Trajectory Planning for Urban Air Mobility (UAM) Traffic Management System

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***Abstract*—Given the gaps between UAM flights and commercial flights and sUAV, neither ATM nor UTM is suitable for UAM flights. Thus, it is critical to develop an air traffic management system for UAM, which enables safe and efficient operations of high-density UAM operations. In the perspective of UAM traffic management system, the two most important aspects that determine the future operation are safety and efficiency. In order to safely organize the traffic and maximize the capacity of urban airspace and flight efficiency, a framework of airspace management for UAM is proposed. In the framework, a low-altitude airspace system (defining flyable space and flight levels) and trajectory deconfliction schemes to resolve the conflicts while minimizing the total flying cost are developed.**

Keywords: Urban Air Mobility; trajectory deconfliction; airspace design

I. INTRODUCTION

There is tremendously increasing interest in the industry and the public on the recent rapid development of Urban Air Mobility (UAM). Defined by NASA, UAM is a safe and efficient system for air passenger and cargo transportation within an urban area, inclusive of small package delivery and other urban Unmanned Aerial Systems (UAS) services, which supports a mix of onboard/ground-piloted and increasingly autonomous operations [1].

As opposed to ATM that air navigation service providers (ANSPs) provide the service for aircraft primarily by radio communications, while in the early stage of UAM operation there will be piloted aircraft using voice communications, the communication will rely more on data link to support the high-density operation as eVTOLs transition to autonomy. The trips in UAM is also much shorter than that of commercial aircraft with the typical range of 50 miles and less. The current ATM system in low-altitude urban areas is designed to serve helicopters and General Aviation aircraft that self-separate using see-and-avoid procedures, which is not suitable for UAM, as UAM flight for most of the time will fly in a high-density traffic environment in the low-altitude urban airspace.

In recent years, unmanned aircraft system (UAS) traffic management (UTM) has been developed to operate small UAS (sUAS) in the low-altitude airspace. A decentralized information network is proposed that communicates between sUAS and UAS service providers and ATM through flight information management system (FIMS) to support situation awareness and decision making. However this framework is not suitable for UAM. Firstly, early adoption of UAM would have piloted aircraft that using voice communication, which is not supported by UTM. Secondly, there is no central control entity that manages the whole sUAS traffic, which makes the framework challenging for an integrated traffic flow management plan for high-density UAM flights.

A traffic management system for UAM is necessary to address the unique needs of UAM flights. In order to safely organize the traffic and maximize the capacity of urban airspace and flight efficiency, the goal is to develop a framework of airspace management for UAM traffic management. In the framework, a low-altitude airspace system (defining flyable space, flight levels, and generating trajectories) and trajectory deconfliction schemes to resolve the conflicts while minimizing the total flying cost are needed.

II. LITERATURE REVIEW

The conflict detection and deconfliction methodologies are reviewed in this section. First, conflict detection methods are presented. Then trajectory deconfliction methods are reviewed in tactical and strategic manner respectively. For tactical trajectory deconfliction, the methods are distinguished in centralized and decentralized approaches. For strategic trajectory deconfliction, methods are discussed in flight level assignment, departure time adjustment, speed control, and the combination of aforementioned methods.

A. Conflict Detection Methods

One of the criteria to distinguish the conflict detection methods is by the projection methods of the future state of aircraft. How the future state is estimated determines the reliability of conflict detection. [2] identified three extrapolation methods, termed nominal, worst case, and probabilistic.

The conflict detection can be further classified as space-based, time-based detection, and space-time-based methods. Space-based methods use the distance between any two trajectory points at a time as the criteria to decide if they violate the minimum separation requirement in the horizontal or vertical plane. Space-based methods can be found in [3][4]. Time-based methods use the time interval between any two aircraft passing the intersection point as the criteria to decide if they violate the minimum time separation determined by the velocity and intersection angle of the two aircraft. Time-based methods can be found in [5][6]. Space-time-based methods discretize the space into grids by each time step [7].

B. Trajectory Deconfliction Methods

Extensive literature can be found for the flight trajectory conflict detection and resolution (CD&R) in the tactical/real-time phase both in commercial airplanes and UAS. In the tactical manner, methods can be generally classified as centralized and decentralized approach. Centralized methods are typically modeled as a constrained optimization problem trying to find the global optimum under the conflict-free constraints [8][9]. The mathematic model has been widely used to formulate the CD&R as an optimal control problem. Some literature developed an approximate model of aircraft dynamics using only linear constraints [10][11]. A nonlinear program (NLP) was used to addresse the flyability issue by the allowance of the use of dynamic aircraft models at any desired level of detail [12][13]. There are also other studies using MILP and NLP to solve the aircraft conflict problem with different maneuvers (heading, speed, and altitude), spaces (2D and 3D) and optimum objectives (flying time, energy consumption, and safety) [5][14]. A number of different approaches were used in the decentralized methods such as methods inspired by physical laws [15][16] and geometric optimization [17] [18].

Deconfliction methods in strategic manner can be classified into several approaches based on the degree of freedom. Flight level assignment uses the spatial dimension to resolve conflicts [19][20]. Ground holding uses the temporal dimension to adjust the departure time to resolve conflicts. What's more, the speed can also be used to resolve conflicts [21]. The combination of different methods aforementioned can also be found the literature [3] [7].

In this study, a nominal conflict detection method is used according to the classification by [2]. While decentralized approach to resolve the conflicts tend to be less computationally expensive, it cannot guarantee the global optimum. A centralized trajectory deconfliction approach is used for this study that can compute the 4D conflict-free trajectories. When dealing with large scale and high density UAM operation, deconfliction methods like flight level assignment, departure time adjustment, and speed control are more feasible, because these methods typically don't need to consider the aircraft dynamics and including aircraft dynamics in the deconfliction model would increase the problem complexity and largely impact the computation time.

III. METHODOLOGY

The framework of urban airspace management is illustrated in Figure 1, which consists of three components: low-altitude airspace system, conflict detection, and trajectory planning. Each component will be discussed in the following part.

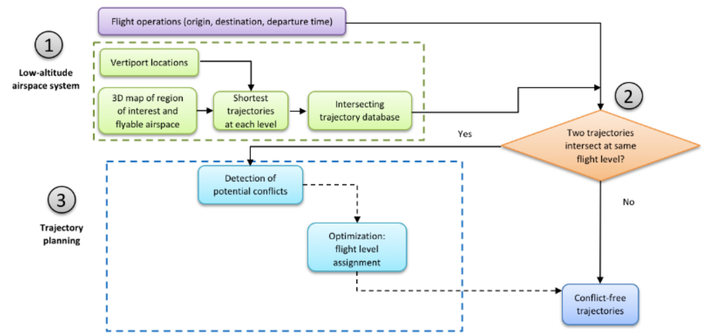


Figure 1. Framework of urban airspace management.

A. Low-altitude Airspace System

The goal of low-altitude airspace system is to achieve safety and energy efficiency through supporting direct flights and obstacles and restricted airspace avoidance. Four steps are developed to construct the system.

1) Construct a 3D GIS map of the region of interest with geographic and LIDAR data. A flyable airspace can be determined by the map and corresponding regulations.

2) Construct visibility graphs for each origin-destination pair at different flight levels (Figure 2).

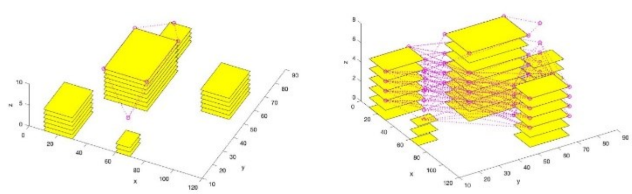


Figure 2. Visibility graphs at each flight level.

3) Given the visibility graphs generated at each flight level, the shortest path (trajectory) of any OD pair at each flight level can be obtained by applying a shortest path algorithm.

4) Pre-process and store geometrically intersecting points in the database.

The database is stored as follows:

$$\begin{array}{cc} h_1, & \begin{bmatrix} o_1 o_1 & \cdots & o_1 o_n \\ \vdots & \ddots & \vdots \\ o_n o_1 & \cdots & o_n o_n \end{bmatrix} \\ \vdots & \vdots \\ h_m, & \begin{bmatrix} o_1 o_1 & \cdots & o_1 o_n \\ \vdots & \ddots & \vdots \\ o_n o_1 & \cdots & o_n o_n \end{bmatrix} \end{array} \tag{1}$$

Each element in the matrix stores the intersection information of a trajectory that intersects with all other trajectories at a flight level. It stores the intersecting OD pair, the ordinance of the intersecting point, and the distance to the intersecting point from the origin shown in equation (2).

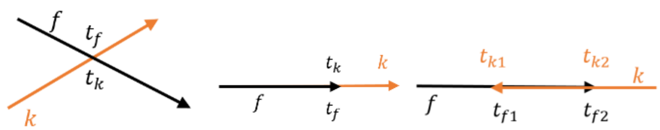
$$\left\{\begin{matrix} (o_i o_j) \\ \left\{\begin{matrix}(1, x_{i1}, y_{i1}), \dots, (2, x_{j1}, y_{j1}, x_{k1}, y_{k1}), \\ \dots, (3, x_{m1}, y_{m1}, x_{n1}, y_{n1}), \dots \end{matrix}\right\} \\ \{(d_{i1}, d_{i2}), \dots, (d_{j1}, d_{j2}), \dots, (d_{m1}, d_{n1}, d_{m2}, d_{n2})\} \end{matrix}\right\} \quad (2)$$

B. Conflict Detection

The conflict is a situation occurring when two or more aircraft violate the minimum separation. The time-based conflict detection method is used. Given aircraft speeds, intersection angle, minimal horizontal separation, and linearly extrapolated trajectories, the temporal separation between aircraft is given as:

$$S_{ij} = \frac{D^s}{v_i v_j |sin(\theta_{ij})|} \sqrt{v_i^2 + v_j^2 - 2 v_i v_j cos(\theta_{ij})} \quad (3)$$

In the designed flight network, aircraft can fly between any origin and destination pairs on any available flight levels, which resulting in three types of intersections: : (1) pure intersection; (2) collinear with the same direction; (3) collinear with opposite direction.



(1) Pure intersection (2) Collinear with same direction (3) Collinear with opposite direction

Figure 3. Types of intersection

The conflict detection can be conducted by checking the crossing times at the intersecting points for each type of intersections. For type (1) and (2), the conflict detection equation is shown in equation (4) and for type (3) it shown in equation (5):

$$|t_f - t_k| \geq S_{fk} \quad (4)$$

$$t_{f1} \geq t_{k1} + S_{fk} \ \ or \ \ t_{f2} + S_{fk} \leq t_{k2} \quad (5)$$

C. Trajectory Planning

Three trajectory deconfliction schemes are proposed: (1) flight level assignment, (2) flight level assignment and ground holding, and (3) flight level assignment, ground holding, and speed control.

1) Flight level assignment

For the flight level assignment scheme, the conflict resolution method is assigning two aircraft to different levels if there is a conflict. The mathematical model is formulated as follows:

$\phi_h^f = 1$: if flight f takes flight level h; otherwise, $\phi_h^f = 0$.
C_f^h: flying cost of flight f taking flight level h.
I_h^f: set of flights that conflict with flight f on level h .
P_h^{fk}: set of intersecting points between flight f and flight k on level h.
t_{fp_i}: crossing time of flight f passing intersecting point p_i, when is a pure intersection.
$t_{fp_{i1}}$: crossing time of flight f passing the first intersecting point p_{i1}, when is collinear.
$t_{fp_{i2}}$: crossing time of flight f passing the second intersecting point p_{i2}, when is collinear.
$y_{fkhp_i} \epsilon \{0,1\}$: $y_{fkp_i} = 1$, if the intersecting point p_i of flight f and k is intersection type (3) and satisfy the first constraint of equation (4); $y_{fkhp_i} = 0$. If p_i is intersection point type (3) and satisfy the second constraint of equation (5).

$$Min \sum_{f \in F} \sum_{h \in L^f} C_f^h \phi_h^f \quad (6)$$

Constraints:

1. Each aircraft assigned one and only altitude level:

$$\sum_{h \in L^f} \phi_h^f = 1, \quad \forall f \in F \quad (7)$$

2. Conflicts avoidance:

(1) For pure intersection and collinear with same directions:

$$|t_{fp_i} - t_{kp_i}| \geq S_{fk} + M(\phi_h^f + \phi_h^k - 2) \quad (8)$$

$$\forall f \epsilon F,\ k \epsilon I_h^f,\ p_i \epsilon P_h^{fk},\ h \in L^f \cap L^k$$

(2) For collinear with opposite direction:

$$y_{fkhp_i}(t_{fp_{i1}} - t_{kp_{i1}} - S_{fk}) \geq M(\phi_h^f + \phi_h^k - 2) \quad (9)$$

$$(1 - y_{fkhp_i})(t_{fp_{i2}} - t_{kp_{i2}} - S_{fk}) \leq M(2 - \phi_h^f - \phi_h^k) \quad (10)$$

$$y_{fkhp_i} \epsilon \{0,1\},\ p_{i1} \epsilon P_h^{fk},\ p_{i2} \epsilon P_h^{fk}$$

2) Flight level assignment and ground holding

Another degree of freedom, temporal measure, is considered in conflict resolution. New notations need to be introduced for ground holding. Let $\delta_f \epsilon \Delta_f$ be a departure time shift attributed to flight f. Discretize the of the shift range into time slots, given the slot interval of δ_s and $\Delta_f = \{0, \delta_s, \dots, (N_f - 1)\delta_s, N_f \delta_s\}$. The formulation is similar to the first scheme only except the objective function needs to add a term of cost of departure delay and the departure time shift δ_f needs to add to the constraints.

3) Flight level assignment, ground holding, and speed control.

In this trajectory deconfliction scheme, we further include another degree of freedom, speed, to resolve the highly complexed trajectory conflicts under high-density operation when the first two schemes are unable to find optimal solutions. The scheme successively solve the conflicts. First use flight level assignment and ground holding to deconflict the trajectories. If there are some remaining conflicts, speed control will be used to solve the rest of the conflicts. The speed control model is shown as follows:

P_f: remaining conflicting points of flight f.
v_f^{min}, v_f^{max}: minimal and maximal velocity of flight f.
t_{fi}: the time flight f takes to travel from $(i-1)^{th}$ waypoint to the i^{th} waypoint. The crossing time of flight f passing

remaining conflicting point $p_{fi} \epsilon P_f$ can be expressed as: $C_{fp_{fi}} = \sum_{i=1}^{i_{p_{fi}}} t_{fi}$.

Given route segment distance d_{fi}, the speed constraint can be expressed in relation to distance and travel time: $\frac{d_{fi}}{v_f^{max}} \leq t_{fi} \leq \frac{d_{fi}}{v_f^{min}}$.

The speed control model is formulated as follows:

$$Min \sum_{f \in F} \sum_{p_{fi} \epsilon P_f} c_f^d |C_{fp_{fi}} - C_{fp_{fi}}'| \quad (11)$$

$$|\sum_{i=1}^{i_{p_{fi}}} t_{fi} - \sum_{i=1}^{i_{p_{ki}}} t_{ki}| \geq S_{fk} \quad (12)$$

$$\frac{d_{fi}}{v_f^{max}} \leq t_{fi} \leq \frac{d_{fi}}{v_f^{min}} \quad (13)$$

$$\frac{d_{ki}}{v_k^{max}} \leq t_{ki} \leq \frac{d_{ki}}{v_k^{min}} \quad (14)$$

$$\frac{d_{f,i+1}}{v_f^{max}} \leq t_{f,i+1} \leq \frac{d_{f,i+1}}{v_f^{min}} \quad (15)$$

$$\frac{d_{k,i+1}}{v_k^{max}} \leq t_{k,i+1} \leq \frac{d_{k,i+1}}{v_k^{min}} \quad (16)$$

IV. PRELIMINARY RESULTS

The urban airspace management framework developed in section 4.3 was used for a case study of Tampa Bay area. The trajectory deconfliction scheme resolve conflicts only through flight level assignment. The 3D information in Tampa Bay area was extracted form LIDAR data. In the case study there were total 30 vertiports (Figure 4) and every 5 minutes there is a takeoff from each of the vertiport to a randomly assigned destination vertiport. The simulation parameters are shown in Table 1. The true airspeed of cruise was set as 130 knots with rate of climb and rate of descent both 1000 ftm. The minimal temporal separation was set as 55 seconds, which corresponding to the 0.3 nautical mile distance separation. The case was run for 45 minutes.

The optimization problem was solved to optimality with no conflicts between trajectories. Each flight was assigned a 4D trajectory.

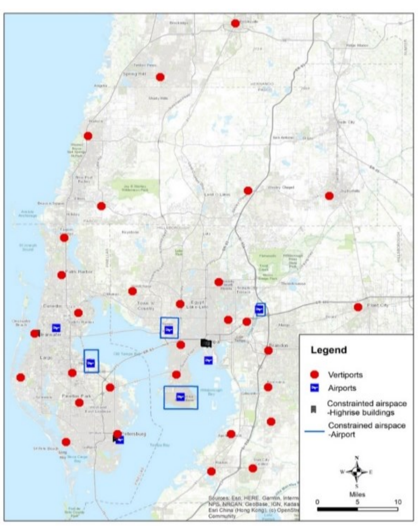


Figure 4. Vertiports locations planned and restricted airspaces in Tampa Bay

TABLE 1. CASE STUDY PARAMETERS

True airspeed for cruise	130 knots
Rate of Climb/Rate of Descent	1000 ftm
Number of vertiports	31
Departure schedule	One takeoff every 5 minutes at each vertiport
Minimum temporal separation	55 seconds (0.3NM)
Number of flight levels	10 (100 ft. vertical separation from 0 ft. to 1000 ft.)
Simulation time	45 minutes

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