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A Concept of Airspace Configuration and Operational Rules for UAS in Current Airspace

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Abstract — **Deployments and operations of civilian unmanned aircraft in urban environments have been seeing a significant rise, which increases the demand of urban unmanned air traffic and the need for airspace. Large-scale UAV operations in urban environments may pose risks to people on the ground and manned aircraft in the air. To safely and efficiently utilize the urban airspace, several concept of operations (ConOps) about urban airspace utilization are proposed and demonstrated in this paper. The proposed ConOps concentrates on airspace configuration and operational rules from three aspects. Firstly, AirMatrix airspace configuration is introduced and expanded with operational rules in the network. To balance the flight flexibility and airspace complexity, different resolution AirMartix is introduced. Moreover, AirMatrix corridor is proposed to connect reserved areas with safe and efficient traffic flows considering Communication, Navigation and Surveillance (CNS) performance. Secondly, Free-Flight Operation (FFO) and Trajectory-Based Operation (TBO) are illustrated and compared in terms of operational efficiency and airspace capacity based on simulation studies. Thirdly, under the AirMatrix framework, airspace risk assessment and contingency management are investigated to provide suggestions for urban airspace safety management and fail-safe system design.**

Keywords—UAS traffic management, concept of operation, airspace configuration, operational rules

I. Introduction

As the development on unmanned aircraft system (UAS), commercial applications are rapid and booming. The Federal Aviation Administration (FAA) has estimated that the number of registered drones has reached 1 million and over 80% of them are under recreational license [1]. The rapidly increasing number of drones is a great challenge to regulating bodies such as FAA and Civil Aviation Authority of Singapore (CAAS). Large-scale UAV operations in low altitude and complex airspace may compromise safety (e.g. midair collision) and efficiency (congestion and delay) of urban air transport. The need to manage and optimize UAS operations both safely and efficiently is crucial and urgent. To deal with these issues, numerous research have been conducted in areas like detect and avoid, path planning and mission scheduling, etc. However, problems of how to integrate UAS operation into current airspace and what kind of operational rules these operations should follow still left unsolved. ConOps of urban airspace configuration and operational rule for UAS operations are required to provide solutions for aforementioned problems.

Studies on concept of operation for UTM systems are the emerging areas. Pioneering works have been conducting to explore UTM ConOps [2,3] not only from whole framework, but detailed elements which consists of airspace management, operational rules, flight scenarios, etc. Urban Air Mobility (UAM), as a new branch, develops fast in recent years based on expected fast growth in passenger air-taxi and air-cargo transportations [4]. To enable this kind of operation in current airspace and air traffic management system, concept of operation has been proposed [5] in terms of airspace management, operational rules, traffic management regulations, essential infrastructures, etc.

The first UTM conceptual framework was proposed by NASA. After that, studies have been conducting to keep the evolution of UTM framework moving till a refined and comprehensive UTM ConOps was issued in 2018 [2]. The ConOps for airspace management was well presented and discussed in operational concept part with objectives to illustrate key conceptual and operational elements regarding UTM operations. With the evolution and development UTM system, the UTM ConOps v2.0 [3] has been released. One of the major updates of this version is taking more complex operation into account, including operations across both uncontrolled and controlled airspace.

The concept of U-space as European drone outlook studies was proposed [6], evolved [7], and released [8] by SESAR team focusing on airspace management and safety aspects to support UTM operations from user's point of view. The airspace rules and procedures for UTM operation have been well investigated and definitions for different airspace volume were proposed. Flight rules, risk assessment, conflict management, etc. were also discussed. Another key component of this ConOps is safety and social aspects. The ground risk, airport related risk and air risk have been analyzed, while social privacy and perception of drone operations in urban environments were also described. Contingency plans as the elements in this part were studied, and several new framework and procedures have been proposed for safety management. Further, ConOps of risk assessment [9,10] and risk cost map [11-13] for drone operations were studied considering operational risks and navigational deviations [14,15].

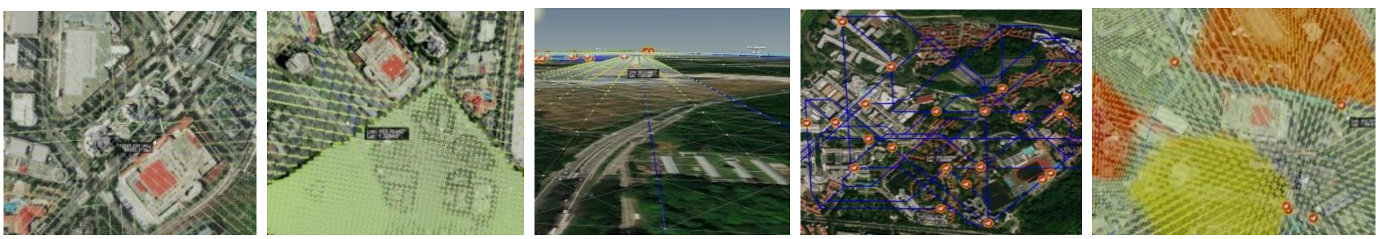
In another group of state-of-the-art research, researchers from Air Traffic Management Research Institute (ATRMI), Nanyang Technological University combined and produced a ConOps with a labyrinth of unilateral digital lanes to support

This research is supported by the ATMRI UAS Programme, NTU, Singapore.

high-speed UAS operations [16]. Based on that, a modular UTM system has been proposed and the core modules of the framework are about urban airspace management, flight management and risk management [17]. Then, a preliminary ConOps was proposed for urban airspace management, which is the AirMatrix, a dynamic and scalable urban traffic management framework. In the framework [18, 19], UAS route planning is an important component for UAV operations planning. Proper flight management and airspace management can significantly reduce the risk of UAS mid-air collision and improve the total utilization of urban airspace, that is to say, more UAS operations can be carried out simultaneously within a specific airspace [20-22]. The dynamic AirMatrix traffic network and the risk-aware network have been proposed and discussed [11] to provide safer and more efficient airspace and traffic management.

Existing UTM frameworks and ConOps are more focusing on a big picture to describe the essential conceptual and operational elements and requirements regarding UTM operations, but less details were given for implementation purposes. What is more, existing ConOps considers airspace configuration and operational rules only from few points of view, there are still a lot of room for improvement. In this regard, our paper concentrates on the ConOps of UAS airspace configuration and operational rules, investigating the AirMatrix network (Fig. 1a) combined with different resolutions (Fig. 1b) and corridor (Fig.1c). Free-flight operation and trajectory-based operation (Fig. 1d) are studied and compared through simulation studies. Airspace risk-aware map (Fig. 1e) and risk assessment procedure are proposed. The ConOps of contingency management regarding airspace management also being studied and discussed in this work.

The rest of the paper is organized as follows. Section II presents the ConOps of AirMatrix and the UAV movement rules in the network. AirMatrix with different resolution and corridors are also introduced. Section III proposes the operational rules and compares the free-flight operation and trajectory-based operation in terms of efficiency and airspace complexity. Section IV investigates the risk-aware airspace ConOps and the risk assessment mothed, as well as the airspace contingency management. Section V summarizes this work.



a. AirMatrix b. Different resolutions c. AirMatrix corridor d. Trajectory-based operation e. Airspace risk-aware map

Fig. 1. Main components of airspace configuration and operational rules

II. AIRSPACE CONFIGURATIONS WITH AIRMATRIX

In this section, the AirMatrix ConOps is discussed with UAV movement rules in proposed airspace network. To balance the airspace complexity and operational flexibility, the ConOps of different resolution AirMatrix is proposed. Further, to connect the different resolution and segregated airspace areas, AirMatrix corridor is introduced with detailed illustrations.

A. *AirMatrix network*

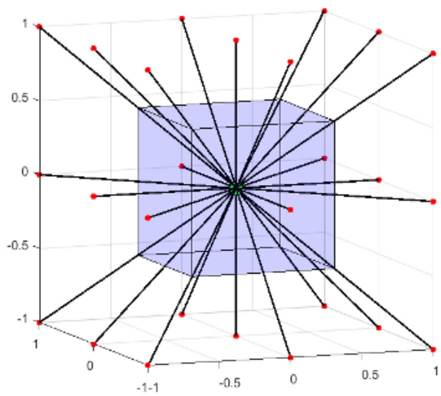
The basic AirMatrix describes an airspace structure (Fig. 2a), which provides discrete and standardized units to manage urban airspace, and the airspace is divided into uniform air blocks. This configuration allows quantitative analysis for a vast range of subjects. For example, the air blocks can encode information on command and control signal strength, population density underneath etc. Such information can be served as metrics for safe flight planning. Therefore, the setting and properties of the AirMatrix can be dynamically adjusted according to the change in environments.

To make the statement clearer, some terms used in the context of this paper are defined here.

- Movement freedom: number of possible waypoint AV can choose as next waypoint to fly.
- Flight flexibility: number of air block in a certain airspace.
- Traffic density: number of AV per unit airspace and per unit time.
- Crossing route points: more than four air routes intersect in same altitude.
- Airspace complexity: there are four contributors for airspace complexity in this paper. They are movement freedom, flight flexibility, traffic density and crossing route point. In a given airspace, with the increase of all these contributors, the airspace complexity will rise accordingly.

Aerial vehicles (AVs) operate in such an airspace structure will follow the operational rules. One rule is that how AVs move from one node to another. Unlike the free-flight operation, AirMatrix-based operation is one type of trajectory-based operations in which AVs will follow a set of waypoints with certain movement freedoms. In the proposed AirMatrix ConOps, AVs are enabled 26 movement freedoms from one node to another as shown in Fig. 2b.

a. Airspace structure



b. Movement freedoms of AV

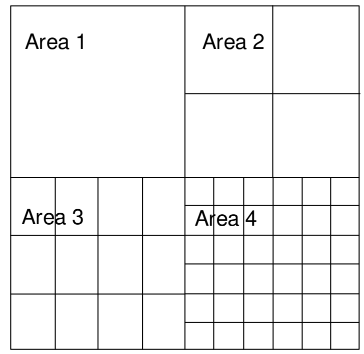
Fig. 2. AirMatrix airspace structure

B. *Different resolutions of AirMatrix*

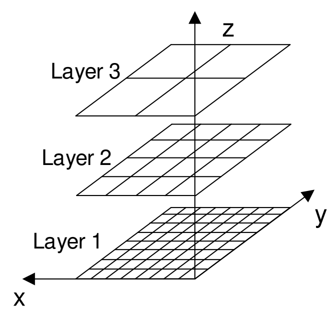
As aforementioned, the AirMatrix provides discrete and standard units of airspace, and which is useful for uniformized airspace management. However, in some situations, uniformized air blocks will not be able to keep the operations safe and effective. In this regard, the different resolution of AirMatrix is proposed to balance the airspace complexity and traffic density.

The size of air block significantly influences the airspace complexity and flight flexibility. For instance, with the decrease of air block size (Fig. 3a from Area 1 to Area 4), the flexibility of flight will increase. Because in trajectory-based operational environments, Area 4 provides more waypoints for AVs to operate in same area compared with Area 1, and the traffic density would increase accordingly from Area 1 to Area 4 if each air block serves the same number of operations. As the traffic density and flight flexibility both increase with the reduction of air block size, the airspace complexity will increase. With this relationship among air block size, flight flexibility, traffic density and airspace complexity, different airspace areas can be designed with different resolutions. For instance, in densely populated areas, to ensure the safety of operation, the AirMatrix can be designed with big size of air block to reduce flexibility and complexity of airspace. While in sparse areas with less population, more flexibility can be given to achieve better efficiency.

Regarding to three-dimensional airspace network design, the relationship among air block size and flight flexibility are illustrated as Fig. 3b. The air block size reduces from Layer 3, Layer 2 to Layer1. For high altitude layers, operations are more for high-speed, long distance air taxi or air cargo travels, since high altitude layers have less obstacles (e.g. buildings) to avoid. To this end, main trunk route should be allocated for high altitude layers to enable such kind of operations. While for very low altitude operations in urban environments (Layer 1), AVs need to avoid obstacle, taking off and landing frequently. In that case, more flight flexibility should be given, and the air block size should be small.



a. Different areas with different AirMatrix resolutions



b. Different AirMatrix resolutions in different flight altitudes

Fig. 3. Flexible resolutions of AirMatrix

A real-life example is given below. As depicted in Fig. 4, AirMatrix is formed by four different resolutions according to the respective population densities. For example, the parking area is less populated, while industry zone is the medium population density. Residential area is the high population density and stations (MRT, shopping mall, hospital) are very high density. If uniform resolution is applied in different population density areas, there will be unutilized nodes and links for parking and industry areas, wasting the airspace resources. However, there would be insufficient flexibilities (nodes and links in the network) for high-demand areas like downtown area with dense high-rise buildings need to avoid.

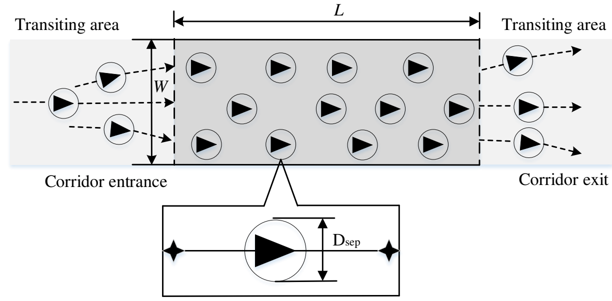
Fig. 4. Interconnection between different resolution areas

C. AirMatrix corridor

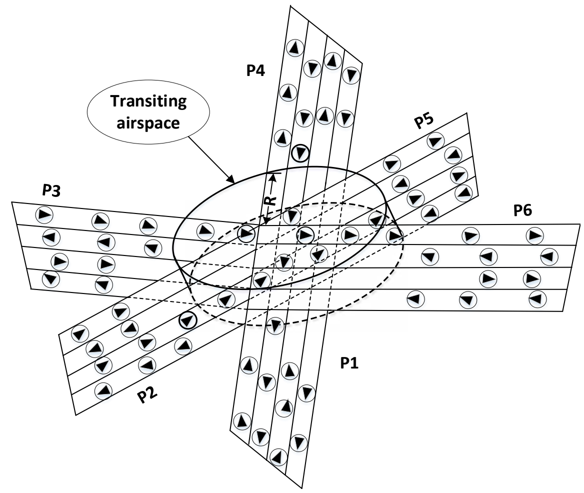
AirMatirx corridor serves as a bridge to connect separated areas with different resolutions and to provide high-speed traffic flow services, acted as highway. The corridor plays two roles in contributing to safe and efficient operations. One is to provide an air tunnel where high-speed traffic flows are supported. In a completely covered large area, high-speed operations between separated areas are highly required. For instance, in Singapore context, assuming AirMatrix is able to cover the whole country, operations between CBD, airport and residential areas can be intense. And these operations are always time sensitive. Enabling high-speed traffic will be beneficial for these operations. Another role the corridor plays is to connect separated and reserved areas, since not all areas are eligible to be covered by AirMatrix due to insufficient capacities in communication, navigation and surveillance (CNS) or constrains (e.g. prohibited, restricted and dangerous areas). Thus, the corridor can connect these separated areas and enable smooth flow of AV traffic.

Each of AirMatrix corridor has at least two layers. The traffic flows in these layers are separated laterally or vertically and it is one-way traffic (e.g. the traffic is only allowed for left to right operations in the same layer, see Fig. 5a). In the corridor, AVs will practice safety separation considering CNS performance. There are also transiting areas for AVs to change flight altitude and enter or leave current corridor to smoothly join the next part. By doing so, the structure can mitigate risks from head-on collisions and will also improve the efficiency by separating the traffic.

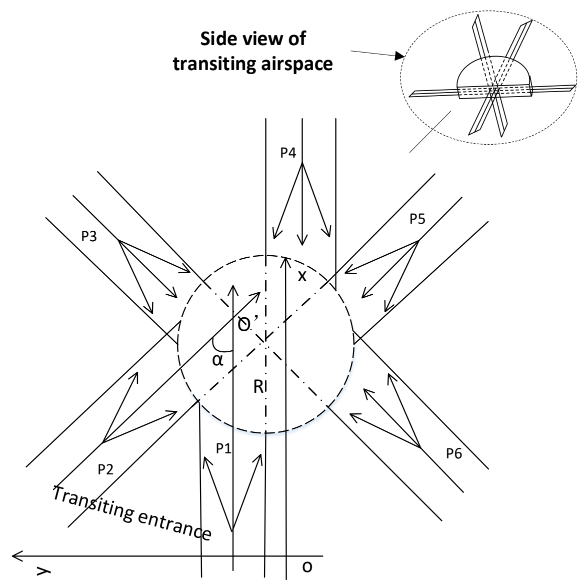
Fig. 5b shows the complex airspace with multiple crossing corridors and traffic flows. In each corridor, traffic is regulated in the corridor and cannot change the flight altitude. In transiting airspace, all traffics are allowed to change their flight altitudes. In Fig, 5c, the side view of the complex airspace and operational rules is presented. P1 to P6 presents the six corridors. Taken corridor P1 as an example, the climbing, descending and straight flight in transiting areas are represented as left-turn, right-turn and straight-flight in Cartesian coordinate system, which helps for the kinematic analysis of complex traffic flows in corridor airspace.



a. Traffic flow in AirMatrix corridor



b. Complex airspace with crossing corridors and traffic flows



c. Side view of complex corridor and traffic rules

Fig. 5. Concept of AirMatirx corridor and traffic flows

III. COMPARISON STUDIES OF FREE-FLIGHT OPERATION AND TRAJECTORY-BASED OPERATION

In this section, two operational ways (FFO and TBO) will be illustrated and analyzed in terms of safety and efficiency by simulation studies. FFO presents that for each operation, only origin and destination point will be given, and AVs do not need to follow the waypoint. While the TBO means that all operations need to operate based on waypoint, and the flight path is a set of waypoints in the network.

A. *Airspace complexity analysis*

As aforementioned, FFO has more movement freedom for AVs to operate. However, as we discussed in Section II, Part B, with the increase of flight flexibility, the airspace complexity will rise accordingly, given the traffic density is unchanged. While for the TBO, the operational efficiency will be sacrificed due to the movement freedom constraints that AVs only allow to operate based on waypoint. But, on the other hand, the TBO will help to reduce the airspace complexity by limiting the movement freedom of AVs.

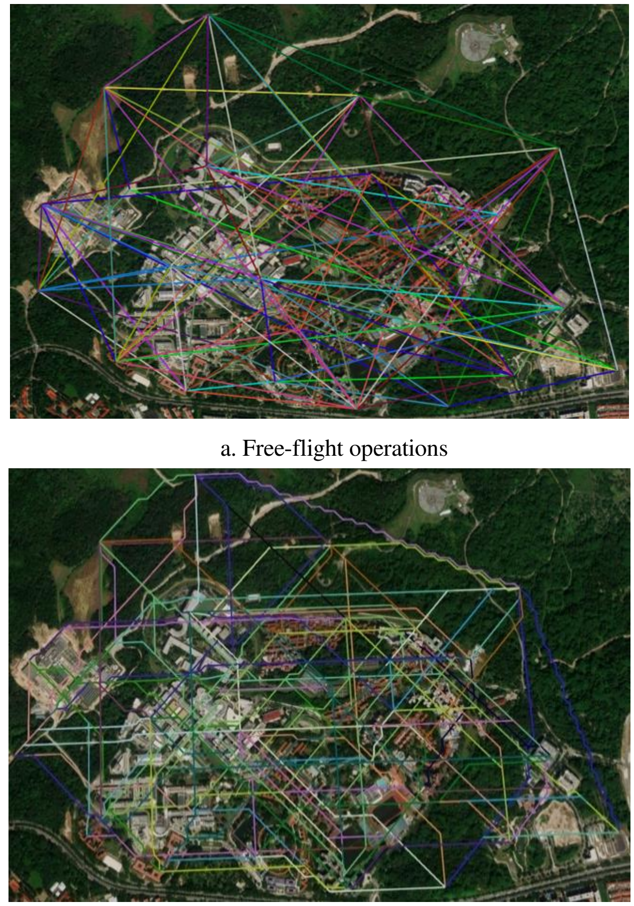
In order to find out the performance of FFO and TBO for large-scale UAV operations in urban environments, simulations are carried out in this part. The environments are selected as NTU campus, Singapore, with an area of 490 acres. 100 flights are randomly generated within this area flying below 200 ft. All flights are scheduled to take off in a ten-minutes time window.

Fig. 6a shows the trajectory pattern of FFO after simulation and Fig. 6b presents the TBO trajectory pattern. The FFO trajectory pattern is more complex than that of the TBO in terms of crossing route points, with a number of 38 for FFO pattern. While only two crossing route points for TBO pattern. That is because for FFO operations, all flights aim to fly straightly from origin to destination at better velocity and altitude, which may produce more congestions. For TBO, operations will be allocated in different altitude and route to avoid collisions and congestions. That may sacrifice some efficiency, for TBO may travels a longer distance due to non-straight path, but that will reduce potential collisions and congestions to improve the global safety and efficiency of operations.

B. *Airspace capacity analysis*

Airspace capacity is an important indicator for AV operations in urban airspace. Here we discuss simulation-based capacity evaluation way under TBO rule. For a certain size of three-dimensional airspace, with the increase of operations, the performance of safety and efficiency (target level of safety, total travel distance, etc.) will deteriorate due to the increasing congested traffic. When reaching the safety and efficiency thresholds, it can be assumed that the number of operations in the given time window is the capacity for the given airspace.

In this section, the simulation environments are the same as the aforementioned one. Number of operations increases from 20 to 100 with a step size of 20. Simulations are conducted and obtained trajectory patterns for each number of operations are presented as Fig. 7.



a. Free-flight operations

b. Trajectory-based operations

Fig. 6. Trajectory pattern of TBO is more organized than that of FFO

With the increasing number of operations in same airspace, the traffic pattern becomes more complex in terms of the number of crossing route point. To evaluate the performance of all operations, simulations are performed, and preliminary results are obtained as Table 1.

The performance of the indicators saw deteriorations. With the increase of operations, the number of crossing route point increases, and the average distance and time spent for each individual operation also saw notable increases.

The simulations conducted in this work are only for proof of concept, more rigorous assumptions, setting and simulations are required for further investigation of the capacity.

TABLE I. RESULTS OF DIFFERENT NUMBER OF OPERATIONS

Performance indicators	**Number of operations**				
	20	40	60	80	100
Crossing route point	1	5	8	15	29
Average distance (m)	1512	1535	1558	1621	1687
Average time spent (s)	142	148	160	175	199

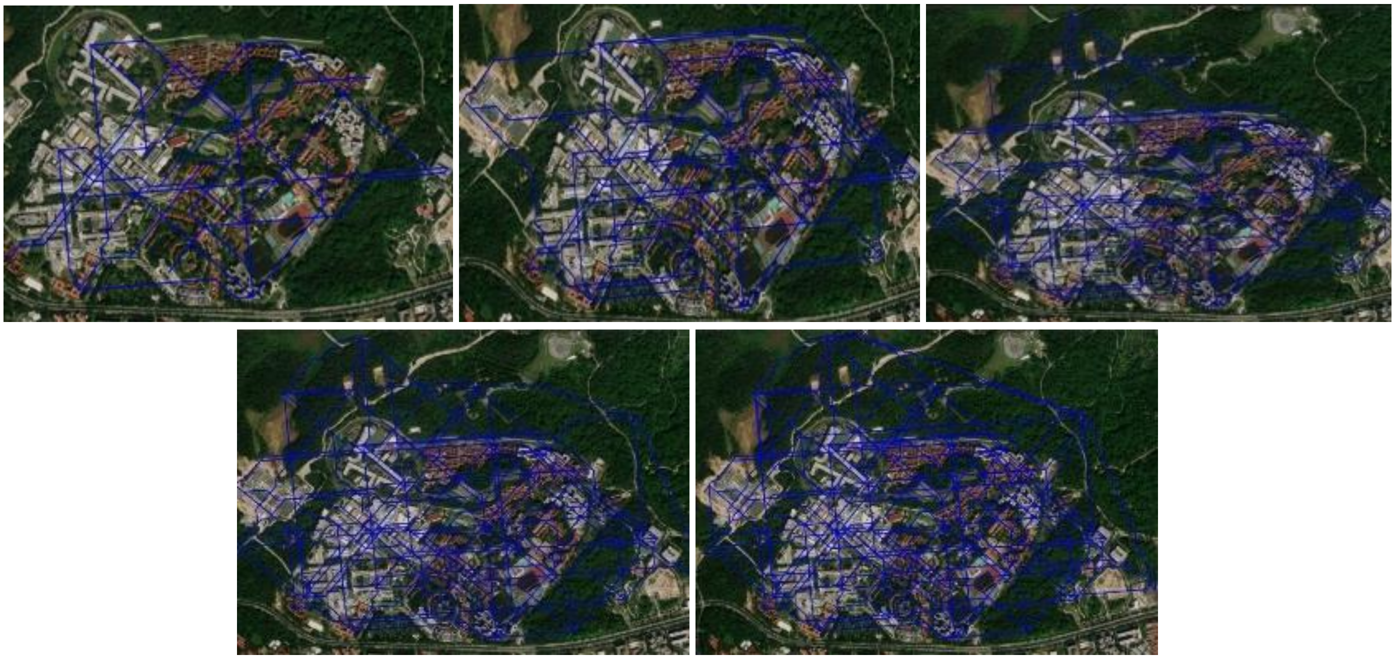


Fig. 7. Trajectory pattern for different number of drone operations in same airspace (the number of operations from top left figure to the bottom right are: 20,40,60,80 and 100 respectively)

IV. Basic framework for risk assessment and contingency management

Risk assessment and contingency management are key players in role of aviation safety. Strategic risk assessment and risk-based path planning can significantly prevent safety issues from being happening. Airspace contingency management, as precautionary plans and procedures, can mitigate the influence caused by unexpected accidents. In this section, airspace risk assessment will be discussed, and contingency management procedures will be proposed.

A. *Airspace risk assessment*

This section will describe the risk cost map. Ground risks (UAV hits pedestrians and vehicles on the ground) and air risk (UAV hits manned aircraft) will be discussed. The modelling for each of these risks will be analyzed and incorporated in risk cost map.

The airspace risk cost map is illustrated as Fig. 8. The map is formed in AirMatrix. Each link has a risk cost value computed according to the risk severity within the specified area. The color of the air block represents the risk cost value, in which different colors stand for different levels of risk severity. The path shown in Fig. 8 is the one avoiding the high-risk cost area (red color). It is obvious to see that the path is not the shortest-distance one, but its risk cost is much lower than the one entered the high-risk area.

The key point of this part is to illustrate the risk cost map and to propose risk assessment views. Ground risk and air risk are considered in the risk assessment process.

1) Ground people risk. As it is possible that UAV might be loss of control or power when flying and falling UAVs may be possible to hurt ground pedestrians. The risk cost of UAV hitting pedestrians is modelled as follows: There are three steps a crash incident will cause damage to pedestrians: (a) malfunction of UAV; (b) the falling UAV impacting pedestrians on ground; and (c) the fatality damage caused to the pedestrian.

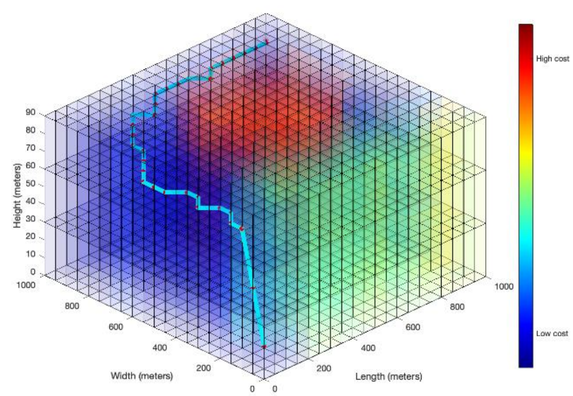


Fig. 8. Illustration of risk cost map and risk-based path planning

2) Ground vehicle risk. There are also three factors when UAV causes an incident on road traffic: (a) UAV crashes above the road traffic; (b) UAV hits the vehicle on the ground; (c) crashed UAV causes a traffic accident and subsequently injuries people. Like the ground pedestrian model, the expected fatality of UAV impacting a ground vehicle can be defined as the number of vehicle accident per hour caused by falling UAVs.

3) Air risk presents the collision risk between UAV and manned aircraft. The safety issues of collision between manned aircraft and UAV are crucial to the UTM-ATM integration. To this end, the present work also considers airports as risk areas where the risk should be accounted for. The incidence of collision between manned aircraft and UAV can be defined as the number of collisions per flight hour of UAV.

B. Contingency management

Airspace Management (ASM) is commonly used in Air Traffic Control (ATC) to ensure aviation safety. By allocating airspace to aircraft based on availability and demand, flight paths can be deconflicted and safe separation between aircraft can be guaranteed. Drawing inspiration from ATC [23], ASM has been used in various UTM architectures to ensure UAV's safety including contingency plans [24-25]. UAV Airspace Management (U-ASM) system allows for dynamic allocation of airspace to the UA operators and UTM service providers, thus enabling advanced functionalities such as geo-fencing of high-risk areas and deconfliction of UAV flight paths.

The main enabler of U-ASM is the communication channel between various agents, namely the UA Operator, the UAS Service Supplier (USS), the ATM as well as other non-ATM/UTM agents. Combining with the state-of-the-art sensors on the UAV and other field equipment, this communication channel will allow for real-time communication and time-critical information acquisition. The framework of UTM contingency management is shown in Fig. 9.

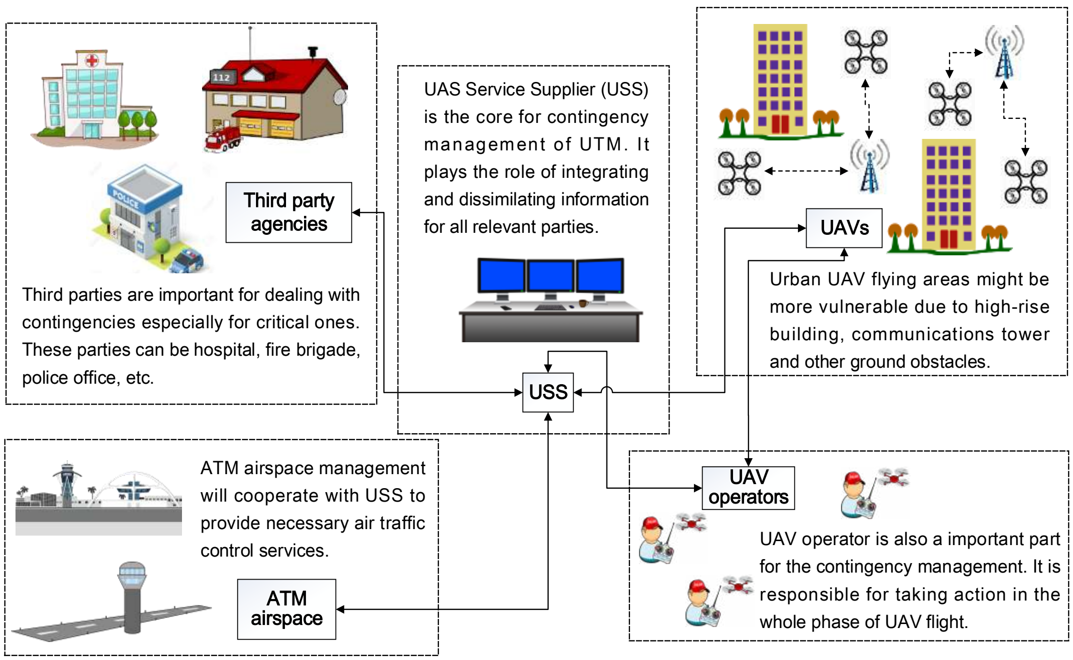


Fig. 9. Framework of UTM contingency management

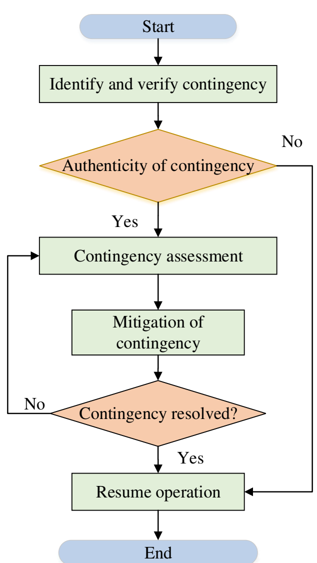


Fig. 10. Flowchart of airspace contingency management

The main idea of contingency U-ASM is to quarantine a contingency by applying informed and time-critical adjustment to available airspace. This is possible by taking advantage of the inter-agent communication in the UTM framework, specifically between USS, UA Operators, the UAVs and third parties, as well as the availability of real-time data. It can be implemented by enhancing the capabilities of a pre-existing USS which provides airspace management or flight path control. In this work, the contingency management is being performed by an USS. The overall workflow for U-ASM contingency is shown in Fig. 10.

1) Contingency Identification

During runtime, the UAV is expected to broadcast its intended flight path and status to both the USS and the UA Operators. The UA operator is expected to monitor their UAV and provide status updates to the USS. The USS will be tasked to monitor the flight path for the UAV and communicate with the UA Operators to detect operation anomalies. The USS may also communicate with other external agents such as weather service to monitor other external factors which may lead to contingency.

A contingency is assumed to occurred when one or more of the following has occurred:

- The UAV has deviated from its intended path;
- The UA Operator or UAV has reported an operational anomaly;
- There is no feedback from the UA Operator or UAV;
- The UAV approaches a restricted airspace;
- There is disturbance (disturbance refers to presence of disruptive elements in the airspace, included but not limited to bad weather, unknown obstacles, and rogue agents), informed through the UA Operator, UAV or any third party agent.

2) *Contingency Assessment*

Once a contingency is identified, it will be assessed to determine its risk and type. To provide a general procedure for contingency management, the contingency is evaluated based on their severity and affected airspace.

Severity is defined as the damage caused for people and/or properties, and the potential harm due to the contingency will be examined based on the severity caused. Affected airspace is not just the UAV's current airspace, but also includes the airspace that may be traversed by the UAV during the entire duration of the contingency. This evaluation metric will determine which external party to establish communication with during the contingency.

3) *Contingency Mitigation*

Once a contingency is assessed, a mitigation step is being carried out to resolve or to reduce the potential harm of the contingency. The suggested mitigation requirements for the respective risks and their common characteristics are listed as follows:

a) Low Risk Mitigation

- Only requires sending basic warning and notification to the affected UA agents;
- Human intervention is not required;
- Does not require immediate reallocation of airspace.

b) Medium Risk Mitigation

- Only requires communication between USS, UA Operators and UAV;
- Human intervention is preferred;
- May require immediate reallocation of airspace.

c) High Risk Mitigation

- Require communication and cooperation with third-parties, non UTM-agents or authorities;
- Require human intervention;
- Require communicating with UA agents in the vicinity;
- Require reallocation of airspace.

4) *Contingency Reassessment*

After mitigation is carried out, the situation will be reassessed. If the contingency is resolved, operations will return to normal. Otherwise, the contingency will be re-assessed to determine suitable mitigation methods.

5) *Illustrations of Contingency Management*

The procedures of contingency management is illustrated and carried out by the USS. A detailed explanation of contingency management procedures is illustrated in Fig. 11 using an example of a UAV engine failure.

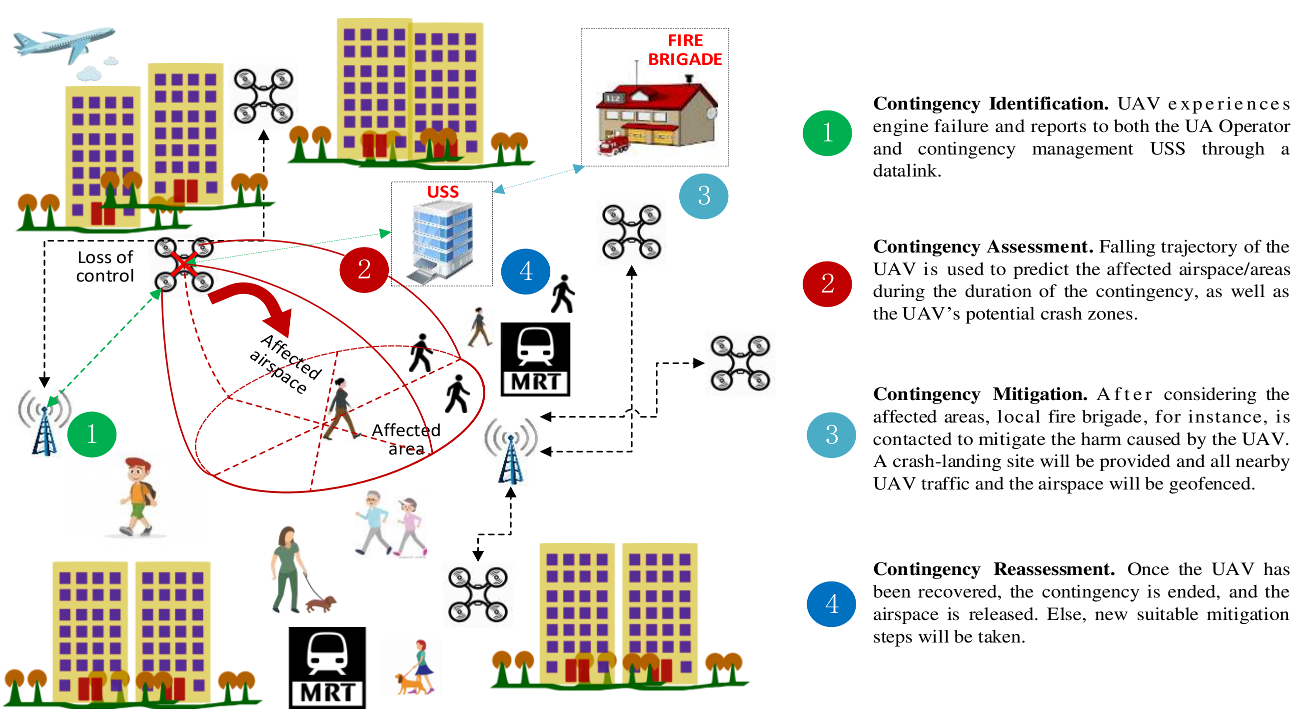


Fig. 11. Illustration of contingency management procedures using engine failure example

V. CONCLUSION REMARKS

This paper proposes the ConOps of airspace configuration and operational rule for UAS operation in urban environments. Main conclusions are summarized as follows:

(1) ConOps of AirMatrix is introduced and expanded with operational rules in the airspace network. The different resolution of AirMatrix is proposed to better facilitate the airspace utilization by balancing the flight flexibility, traffic density and airspace complexity in different areas in terms of population density and CNS performance. The AirMatrix corridor is introduced to enable high-speed traffic flow across cities and connect reserved areas with different network resolutions.

(2) Free-flight operation and trajectory-based operation are discussed and compared in terms of airspace complexity and capacity. Results show that TBO traffic pattern is less complex than that of FFO in terms of crossing route points. As to capacity analysis, for TBO with the increase of operations, performance of the indicators used in this paper deteriorates. It is suggested that more indicators (e.g. target level of safety) can be carefully modeled to evaluate the airspace capacity threshold. That can be the future works to investigate.

(3) The airspace risk cost map and risk-based path planning are proposed for strategic risk mitigation of UAS operations in urban airspace under AirMatrix framework. The contingency management procedures and use case are presented to provide suggestions for risk-aware system and fail-safe system design.

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