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Accessibility Analysis of Unmanned Aerial Vehicles Near Airports with a Four-Dimensional Airspace Management Concept

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Abstract—The demand for UAS operations is increasing in recent years, as well as the traffic volume of civil aviation. The operations of both traffic modules are based on the utilization of airspace resources. Currently Unmanned Aircraft Systems (UAS) are not allowed to operate close to airports, where potential conflicts between UAS and manned aircraft may happen. This rule is constraining the application of UAS. Therefore, it is necessary to study the current airspace utilization pattern near airports, before the boundary determination of UAS operation to allow the UAS accessing airspace safely without conflicts. In this paper, a data-driven analysis on historical trajectories at Changi Airport in Singapore was carried out. Trajectory data have been clustered to recognize the utilization patterns of airspace. Discussions on the boundary of UAS operation were presented based on both current airspace utilization patterns and the estimated capacity. The airspace utilization was further modeled in an urban airspace management framework, and quantifiable area for potential UAS operation was analyzed. As this is the first research study to present the initial concept, more operational and other factors should be considered in the future study for the generation of potential boundary of UAS operations.

Index Terms—air traffic management, UAS Traffic Management, airspace management, clustering, traffic flow pattern

I. INTRODUCTION

Civil aviation plays a major role in driving sustainable economic and social development. The industry is growing rapidly. According to the latest ICAO's forecasts (by 2015 baseline), global passenger traffic will grow at 4.3 percent annually from 2015 to 2035 [1]. In the meantime, Unmanned Aerial Systems (UAS), as a new group of airspace users, is drawing more attention in recent years. Benefited from the new advances of related technologies like UAS control theories, computer vision, electrochemical techniques, advanced avionics systems, UAS is competent of more complicated missions. Therefore there is a growing interest in deploying UAS in parcel delivery, traffic monitoring and other industrial applications.

The air traffic management (ATM) system has been supporting safe and efficient flight operation for many years. It

is gradually developed as the air traffic demand grows. The ATM system is mainly designed for large horizontal take-off and landing (HTOL) aircraft, which has a very different aerodynamic performance from multi-rotors, a major branch of UAS. So, the ATM system cannot be directly applied to the traffic management of UAS. The demand for UAS operation increases so rapidly that the necessity of a well-organized UAS traffic management (UTM) system which ensures the safety, efficiency and equity of flights in the low-altitude airspace is immediate [2].

Manned aircraft involves more significant economic and social impacts, and clearly has a higher priority in airspace utilization. In order to prevent UAS from interrupting the operation of manned aircraft, UAS are not allowed to fly near airports, which is the place that the interactions between manned and unmanned aircraft most likely happens. In Singapore, for example, UAS are not allowed to access the airspace within 5 km from airport. As illustrated in Fig. 1, this kind of area is blue-shaded, covering a large ratio of Singapore airspace. Taking the other kinds of restricted areas into consideration, the airspace available to UAS is very limited, which is obviously limiting the development of UAS application. It is also worth to note that the 5 km range is a national standard in Singapore and the size of forbidden zone near airport differs between countries. For these reasons mentioned above, optimal design of the boundary for UAS operation near airports is needed, which should maximum the accessibility to UAS while maintaining a guaranteed level of safety for manned aircraft. A basis to the design is a clear understanding of how much airspace civil aviation utilizes.

There have been many studies on air traffic flow patterns in the literature, where clustering techniques are widely used. Frank Rehm [4] performed hierarchical clustering to analyze arrival traffic flow at Frankfurt Airport to support airport performance assessment. Marco Enriquez [5] analyzed air traffic flow and proposed two potential applications: identifying irregular air traffic pattern, and identifying the minimum number of PBN procedures required in the National Airspace

Fig. 1. Area limits map for UAV operation in Singapore airspace [3]

System (NAS). Stavros Sidiropoulos et al. [6] studied the air traffic flow patterns in Multi-Airport Systems (MAS) using spatial-temporal clustering, by with a focusing the inbound and outbound passages of air traffic on a pre-defined terminal airspace boundary. Their work was followed by a study on the optimization of terminal airspace operations in MAS [7]. Mayara Condé Rocha Murça et al. [8] also used clustering technique to study the traffic flow patterns in MAS, in order to enhance Air Traffic Flow Management (ATFM) in the terminal area by predicting the traffic demand and capacity in the following hours. For determining the boundary of airspace in which UAS can be allowed to operate, a document was published by EUROCONTROL. This document was developed based on JARUS Specific Operational Risk Assessment (SORA) tools, focused on the Concept of Operations (ConOps) of the UAS Traffic Management (UTM) system [9]. However, the report did not consider the range of airspace occupied by operations of manned aircrafts. Chung Hung John Wang used Monte-Carlo simulation to design Alert Zone boundaries near airports for non-cooperative UAS risk management [10], [11].

In this paper, it is assumed that UAS will be allowed to enter the airspace near airports as long as a required safety level can be guaranteed. The study aims at analyzing the potential boundary (possible useable airspace) of UAS operations. For this goal, a data-driven study was carried out to analyze the occupation of manned aircrafts near airports. The work reported in this paper provides the following contributions:

- The utilization pattern of airspace up to 10,000 feet above Singapore Changi Airport was recognized by using clustering technique;
- Potential boundary of useable areas for UAS operation near airport was defined;
- Capacity of each recognized pattern was estimated by analyzing the spatial distribution of the patterns;
- Airspace utilization in an urban airspace management framework was analyzed.

II. DATA PREPARATION

Trajectory data exported from Advanced Surface Movement Guidance and Control System (A-SMGCS) was employed in this study. A-SMGCS is a system providing routing, guidance and surveillance for the control of aircraft and vehicles in order to maintain the declared surface movement rate under all weather conditions within the aerodrome visibility operational level (AVOL), while maintaining the required level of safety [12]. A-SMGCS collects data coming from different surveillance systems including secondary surveillance radar, surface surveillance radar and ADS-B. Data fusion was performed by the system to provide high-accuracy tracking information. The exported data covers trajectories around Singapore Changi Airport in a duration of four months from 1st October 2017 to 31st January 2018. The trajectories of not only airliners but also ground vehicles and other objects were captured by A-SMGCS. The data contains detailed information of the flights, and the following information was used in this study:

- Date
- Time
- Callsign
- longitude and latitude (projected in Cartesian coordinates and denoted by X & Y)
- Flight level
- Departure and arrival airports

Currently, UAS is only allowed to fly no more than 200 feet Above Ground Level (AGL), which is far from enough to promote UAS operations. It does not make sense limiting this study to this altitude constraint. The capability of drones allows them to operate at 10,000 feet or higher, let alone larger UAS that will appear in the future. Accordingly, flight movements lower than 10,000 feet MSL were considered in this study. Flights whose departure or arrival airport in Singapore were extracted from the dataset. The trajectories of non-airliners were also filtered out. By grouping tracking records with same Callsign on the same date, trajectory of a flight can be formed. As Changi Airport is an international hub, there are many stopover flights. Normally a stopover flight has only one callsign for both flight legs arriving at and departing from Changi Airport, there will then be only one trajectory formed, which will be an error trajectory in the next steps. To solve this problem, data of departure and arrival flights over the four-month period were separated into two datasets, in which the total number of trajectories is 60,646 and 60,787 for arrival flights and departure flights, respectively.

III. TRAFFIC FLOW PATTERN RECOGNITION

Trajectory clustering was carried out as a preliminary study, to gain an intuition of typical airspace utilization patterns. In this study, density-based spatial clustering of applications with noise (DBSCAN) [13] was chosen because of two reasons: (1) the algorithm can decide the number of clusters automatically, and (2) outliers can be identified. It's characteristics meet the requirement of trajectory clustering, because: (1) the number of typical air traffic flow patterns is unknown, and (2) flights

performing abnormal maneuverings can be extracted from clusters as outliers. Successful applicaiton of DBSCAN in air transport research can be found in the literature [8] [14] [15]. Algorithm 1 shows the pseudocode of DBSCAN.

Algorithm 1: DBSCAN Algorithm

Input:

Dataset - D ,
distance - ϵ ,
minimum number of points to create dense region - $minPts$

Output:

Cluster assignment for each trajectory

```

1 for each point  $P$  in dataset  $D$  do
2   if  $P$  is visited then
3     Continue to next  $P$ 
4   else
5     mark  $P$  as visited
6      $nbrPts \leftarrow$  points in  $\epsilon$ -neighborhood of  $P$ 
      (distance function)
7     if  $sizeof(nbrPts) < minPts$  then
8       mark  $P$  as NOISE
9     else
10       $C \leftarrow NewCluster$ 
11      Call Expand Cluster Function( $P$ ,  $nbrPts$ ,  $C$ ,
         $minPts$ )

```

A. Data Pre-Processing

Multi-step data cleaning was carried out carefully for the requirement of the input of DBSCAN algorithm and also for a better performance of clustering. This includes:

- By balancing the capability of UAS in the market and the possibility of interaction between UAS and manned aircraft, tracking data below 10,000 feet Mean Sea Level (MSL) was extracted. Then the data belonging to non-aircraft objects, like vehicles, was filtered out.
- Tracking data of departures flight and arrival flights were separated, making it easier in the next step. Original data, in which each row refers to one aircraft position report, was merged into trajectories. The total number of trajectories is 60,646 for arrival flights, and 60,787 for departure flights.
- In DBSCAN algorithm, the distance between two trajectories needs to be computed. In this study, Euclidean Distance (ED) was used for its short computation time. In order to compute ED, trajectories need to be vectors with the same dimension. Therefore, trajectories were standardized by re-sampling. According to previous experiences, the trajectory information will not lose significantly during the re-sampling if the time interval is less than 30 seconds. considering each trajectory below 10,000 feet will not last more than 25 minutes, equal time sampling was performed to each trajectory to result in a vector of 50 tracking points.

B. Clustering Result

Changi Airport, whose layout is shown in Fig. 2, has three independent parallel runways: 02L/20R, 02C/20C, and 02R/20L. Note that runway 02R/20L is a part of Changi Airbase (East) and is used only by Singapore Air Force. The runway layout of Changi Airport is shown in Fig. 2. The clustering of departure and arrival flights were performed separately. Six clusters, referring to airspace utilization patterns, were identified for each of departure traffic flows and arrival traffic flows. Table I shows the description of each cluster.

Fig. 2. Runway layout at Changi Airport [16]

TABLE I
CLUSTERING RESULT

Clusters (Patterns)		Runway Used	Description
Dep.	1	02L and 02C	Separate to two main branches of traffic flow heading to east and southeast
	2	02L and 02C	Traffic flow heading to northwest
	3	20R and 20C	Traffic flow with a counterclockwise maneuvering and heading to northwest
	4	20R and 20C	Traffic flow towards southeast ($\sim 120^\circ$) and then turn towards south
	5	20R and 20C	Traffic flow towards southeast ($\sim 150^\circ$)
	6	20R and 20C	Traffic flow towards east
Arr.	1	02L and 02C	Arriving from north or northeast
	2	02L and 02C	Arriving from west
	3	02L and 02C	Arriving from east
	4	20R and 20C	Arriving from east/east south or west and almost or have already intercept the final approach
	5	20R and 20C	Arriving from north
	6	02L and 02C	Arriving from south

Fig. 3 illustrates the clustering result of departure flights. Fig. 3a shows the trajectories in each pattern in two-dimensional projection, while Fig. 3b shows the ratio of each pattern. Pattern Dep1, Dep2 and Dep3, the three main departure patterns, share a total of 80% of departure flights. Dep1 and Dep2 (refer to runway direction 02) together contribute to 68% of departure flights, which implies that runway direction 02 is used for nearly two thirds over the four months. Dep2 and Dep3, the two patterns heading to northwest, contribute 58%

of the traffic. Note that Changi Airport is close to the equator. The northern hemisphere of the earth has more air traffic compared with the southern hemisphere. This potentially leads to more flights towards north-like. However, it should be noted that only the trajectories below 10,000 feet were covered in this study, which means that the destinations of the north-going flights do not necessarily be in the north. These flights may turn in other directions on a higher altitude.

The patterns of arriving traffic flow are illustrated in Fig. 4. Pattern Arr1 and Arr4 are the main arrival patterns, sharing a total of 84% of the arrivals. The runway direction 02 was also used for nearly two thirds over the four months by arrival flights, which can be found by comparing the ratio of Arr1 and Arr4. It is worth mentioning that both Arr4 and Arr5 are coming from north while for Arr4 the trajectories below 10,000 feet are much shorter than those of Arr5, which reflects that Arr4 has a higher descending rate. This might be the result of Continuous Descending Operation (CDO) procedure.

By combining the departure and arrival traffic flow patterns referring to the same runway direction, a snapshot providing a total situation awareness of the airspace utilization by manned aircraft can be acquired. Fig. 5a and Fig. 5b illustrate the airspace utilization referring to runway direction 02 and 20 respectively, in which potential zones for UAS operation are green-slashed. Despite the ignorance of vertical profile of the manned traffic, i.e. areas that have been used manned aircraft are considered non-accessing regardless of their altitude, there is still a large area that can potentially be used by UAS. Let alone the space underneath manned aircraft whose altitude is relatively high. The boundary provided in this paper is based on an empirical study and careful design considering protection zones of flight procedures should be carried out before used in the real world.

IV. TEMPORAL DISTRIBUTION ANALYSIS

The temporal distribution of departure and arrival patterns has been carried out by computing the number of flights falling into a pattern in every hour. Fig. 6 illustrates the temporal distribution of patterns in a week. A large number of flights can be seen in Patterns Dep1, Dep2 and Arr1, implying that runway direction 02 was used in most of the operational hours in the week, while a change of runway direction can clearly be recognized in the latter half of the week between two vertical lines. Seven peaking trends can also be found in Fig. 6, referring to the peaking hours during each day.

Based on the temporal distribution, the capacity of each pattern can be estimated. In this study, capacity is defined as the 95th percentile of the hourly flight counts during the hours that the corresponding runway direction is activated. Table II shows the values of the capacities of departure and arrival patterns. Without loss of generality, a week in January 2018 was chosen in the visualization of traffic pattern capacity. Runway direction 02 was used for the whole week. Accordingly, only six traffic patterns in this week were considered. The operational situation of the week is illustrated in Fig. 7, where the horizontal red lines refer to the capacity of the

Fig. 3. Clustering results of departure flights

corresponding pattern. All of the six patterns are showing a periodic behavior, whereas there is no zero value throughout the week, indicating the airport operates throughout the day.

TABLE II
CAPACITY OF EACH CLUSTER

Cluster	1	2	3	4	5	6
Dep	13	22	21	5	6	3
Arr	28	3	3	28	5	2

V. AIRSPACE UTILIZATION ANALYSIS IN AIRMATRIX FRAMEWORK

A. AirMatrix Concept

AirMatrix concept was developed for urban airspace management [17]–[19]. The idea of AirMatrix is to use a three-dimensional array of cubes to model the airspace, as shown

Fig. 4. Clustering results of arrival flights

Fig. 5. Potential boundaries for UAS operation

in Fig. 8. When an aircraft operates in the airspace, it occupies one or several cubes, depending on its size as well as navigation performance in terms of the probability and range of deviation from its pre-defined path. The system-wide state of occupation is varying as the aircraft moves. And the statues of each cube in AirMatrix varies accordingly. Therefore, airspace situation awareness can be achieved by this time-varying occupation modeling, therefore AirMatrix provides four-dimensional airspace management capability to support UAS operation in urban environment.

B. AirMatrix structure building

In order to understand the airspace utilization by manned aircraft under AirMatrix framework, cube array was built in the airspace near Changi Airport. Considering the regulation of 5 km range from the airport and the geometrical size of Changi Airport itself, AirMatrix was built in a square area with

15 km length and 15 km width, i.e. ± 7.5 km in both X and Y direction (referring to longitude and altitude respectively) from the midpoint of runway 02L/20R. In order to save the cost of computation, an upper limit was set to reduce the total number of AirMatrix cubes. Fig. 9 shows the density distribution of tracking points on different altitudes, in which the tracking point within the area of interest is shown in blue and outside is shown in orange. Two clusters can be seen from the tracking point in the area of interest, a majority of which appear below 2,000 feet and most of the others have an altitude of 6,000 feet or higher. And most of the tracking points outside the area appear higher than 2,000 feet. In this study, 2,000 feet was chosen as the upper limit of AirMatrix, therefore most of the manned air traffic in the area of interest

Fig. 6. Temporal distribution of clusters in a week

Fig. 7. Operational situation in one week when runway direction 02 is used

on an altitude that has a high probability of interacting with UAS can be captured. The width and length of each cube is 100 meters, and the height is 200 feet (60m). Thus the dimension of AirMatrix in X, Y and Z (referring to height) direction is 150, 150 and 10, respectively. Time dimension is also required to capture the variation of system state over time. In this study we chose the trajectory data of October 31st, 2017 to analyze the airspace utilization, because runway direction 02 was used throughout the day. So that there's no need to take care of the change in runway direction. After comprehensive consideration of typical aircraft speed and the size of AirMatrix cube, the step length of time was set to 10 seconds, then the dimension of time in one day is 8640. The total AirMatrix structure for analyzing airspace utilization near Changi Airport is illustrated by Fig. 10.

Four-dimensional array $M \in \mathbb{R}^{150 \times 150 \times 10 \times 8640}$ was used to present airspace utilization in AirMatrix. For given X, Y, Z and t values, take $X = 1, Y = 1, Z = 1, t = 1$ as an example, if the AirMatrix cube referring to $X = 1, Y = 1, Z = 1$ was occupied by an aircraft during 00:00:00 to 00:00:10 on October 31st 2017, then the corresponding value in M will be set to 1.

Fig. 8. AirMatrix structure in typical Singapore town area

Fig. 9. Density distribution of tracking points in different altitudes

Fig. 10. AirMatrix for analyzing airspace utilization near Changi Airport

Fig. 11. Two-dimensional airspace occupation in AirMatrix

C. Results and Discussions

1) *Two-Dimensional Analysis*: Despite the assumption that UAS will be allowed to access the airspace within 5 km range from airport, enlarging the range of accessibility will be carried out gradually. In the first phase, vertical overlapping between UAS and manned aircraft may not be allowed. A two dimensional illustration of the utilized airspace near Changi Airport is shown in Fig. 11, in which the white parts denote the regions that have been used by manned aircraft and the green ones refer to those not used. It can be seen that under the altitude of 2,000 feet, there's no significant deviation in the trajectories of manned aircraft. The lower part of the figure refers to the arrival flights, whose trajectories, benefited from the guidance of the ILS system, are highly concentrated. Meanwhile the upper part of the figure refers to the departure flights, in which the deviation is higher than the arrivals. The overall airspace utilization rate is relatively low from this point of view. The 2,000 feet altitude upper-limit is a key factor influencing the utilization rate. By varying the limit, the relationship between altitude limit and rate of airspace utilization can be shown in Fig. 12. The rate can be as low as 2.54% under current regulation in Singapore, in which UAS can fly no higher than 200 feet AGL.

2) *Three-Dimensional Analysis*: Three-dimensional analysis was carried out for a better understanding of airspace utilization. Considering the UAS will not be allowed to operate above manned aircraft, the cubes higher than the cube occupied by manned aircraft are also labeled as "utilized". The

Fig. 12. Altitude limit vs. airspace utilization rate by manned aircraft

result is illustrated by Fig. 13, in which the airspace of interest is shown as the large blue cube and the red cubes refer to the cubes that have been utilized within the week. The lower-left part in this figure shows the occupation of arrival flights, and the upper-right part shows the occupation of departure flights. The descending rate of arrival flights is lower than the climbing rate of departure flights, thus the departure flights have left a large room beneath their trajectories where UAS could possibly utilize, while there's little space left on the arrival side. On the other hand, the arrival flights distribute in a smaller area compared with the departure flights, thus the movement of manned aircraft are comparatively predictable and UAS operation near this region is safer benefited from this predictability.

3) *Analysis in Time Dimension*: In order to simplify the visualization of the time variation of cube utilization, a binary transformation was used to reduce the dimension of the array. The occupation of 10 vertical cubes was represented as a vector $V \in \mathbb{R}^{10}$, where $V = [v_1, v_2, \dots, v_{10}]$, $v_i \in \{0, 1\}$, $i = 1, 2, \dots, 10$. Then decimal transfer was performed to map V into an integer $s \in [0, 1023]$ without information loss. Thus the dimension of the array was reduced and the array became $M' \in \mathbb{R}^{150 \times 150 \times 8640}$. By plotting the time series for a given X and Y index pair, the characteristic of a horizontal block with varying time can be visualized as shown in Fig. 14, in which a block with low, medium or high workload is shown in Figs. 14a, 14b, and 14c, respectively. The busiest cubes are mostly located near the runway, which UAS should not operate close to. The least busy cubes as shown in Fig. 14a can also be accessed by UAS as long as the effective management strategy can be achieved to ensure that the UAS could leave before the manned aircraft comes.

VI. CONCLUSION

In order to estimate the boundary of UAS operation near airdromes, a data-driven study has been presented in this paper. By adopting DBSCAN algorithm to cluster the trajectories below 10,000 feet around Singapore Changi Airport, 12 traffic flow clusters have been recognized in representing airspace

Fig. 13. Three-dimensional airspace occupation in AirMatrix

utilization patterns of airliners. Potential zones for UAS operations can then be obtained. Capacity of each pattern has also been analyzed by studying the temporal distribution of traffic patterns. Furthermore, the airspace utilization of manned aircraft was modeled in AirMatrix, a four-dimensional airspace management framework. Analysis was made in different dimensions, and discussions were made regarding the characteristics of airspace utilization. The result in this study will benefit the UTM-ATM integration and promote the development of intelligent airspace management methods.

Considering the airspace utilization of each pattern, CDO procedure can significantly shorten the trajectories within the airspace below 10,000 feet. Furthermore, the airspace occupied by manned aircraft can be minimized and more UAS operations will be allowed. CDO procedure also leads to lower fuel consumption, noise, and emissions. The current obstacle of adopting CDO procedures in a larger scale is that CDO procedure will decrease the capacity of sectors involved. Because the main factor influencing sectors' operational capacities is air traffic controllers' workload. As most of the flights are descending, additional workload is required from air traffic controllers to take care of the vertical separations among the flights, compared with the scenario where all the flights are leveled. Therefore, the number of flights that controller can simultaneously take care of will be reduced. Researchers have been working on auxiliary tools that help controllers with the separation maintenance. The achievement of these efforts will also benefit UAS operation by releasing more space in the low-altitude airspace.

Outliers of clustering is not considered in Section III-B. However, some of the outlier trajectories appear in the green-slashed zones shown in Fig. 5. By assuming that the capacity of the recognized patterns is sufficient to include the outlier flights, it is possible to manage the airspace resource if the UAS are allowed to access the airspace. There are also

several holding patterns in these zones according to the AIP Singapore. The Minimum Holding Altitude (MHA) of them are at least 6,000 feet. An upper limit for UAS operations can be designed to prevent vertical conflicts. This requires further analysis where vertical navigation performance of both UAS and manned aircraft should be taken into consideration.

The analysis in this study was based on the tracking data of airliners. The operations of other airspace users, e.g. military aircrafts, general aviation traffic and VFR flights, were not considered. To better manage the airspace near airdromes, besides recognizing the boundary between manned and unmanned air traffic, an integrated framework for various airspace users is required.

The empirical study is based on the traffic data at Changi Airport. However, COVID-19 violently breaks the continuously growing trend. In April 2020, Changi Airport recorded 25,200 passenger movements, crashing 99.5% from the year ago. The airport is suffering from the impact of the pandemic, so is the air traffic industry of the whole world. The darkest hour is that before the dawn. Another thriving growth is expected in the air traffic industry, in which UAS traffic will be a major component in the near future.

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(a) Cube with low utilization rate

(b) Cube with medium utilization rate

(c) Cube with high utilization rate

Fig. 14. Cube utilization pattern in time dimension

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