Assessing the airspace availability for sUAV operations in urban environments: A topological approach using keep-in and keep-out geofence

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Abstract—The anticipated proliferation of small Unmanned Aerial Vehicles (sUAVs) in urban areas has garnered greater interest in capacity estimation of the low-altitude airspace. In the urban airspace, an airspace that is not only free but also usable needs to be considered as a first step to estimate its capacity. In this paper, we propose an airspace availability assessment framework that incorporates the underlying geospatial complexity as well as operational requirements. Specifically, we utilize two types of geofence - keep-out and keep-in. The keep-out geofence creates a boundary around a static object to keep sUAV out. The keep-in geofence defines a boundary for a vehicle to keep in. Three scenarios, keep-out, keep-in, and dual geofencing, were applied to the real 3-D environment of Seoul, South Korea. The results showed the unique capability to identify corridor segments as well as tradeoffs between the two types of geofence in a built-up environment. Both geofencing methods need to be considered in parallel in urban area, and the decision on the geofence parameters should be based on the geospatial complexity and flight purposes, rather than relying on fixed values. The proposed framework is not only capable of evaluating airspace availability in an adaptive and intelligent manner, but also has the potential to be applied to the urban airspace and route design.

Keywords—urban airspace design; airspace capacity; geofence; alpha shape method; UTM

I. INTRODUCTION

The anticipated proliferation of small Unmanned Aerial Vehicles (sUAVs) in urban areas has garnered greater interest in capacity estimation of the low-altitude airspace. Unlike the high-altitude controlled airspace with few obstacles, the low-altitude airspace needs to take into account the geospatial complexity derived from geometric variability of existing static objects such as buildings and terrains. Currently, several states have imposed sUAV operational restrictions based on proximity to population and man-made structures. Restrictions generally include minimum distance from people and from buildings or structures, depending on flight purpose and weight category. Where specified, the minimum keep-out distance ranges between 30 and 150 meters [1-5]. Such conservative and uniform flight restrictions can severely limit sUAV operations, especially in a densely built-up area. A more adaptive and intelligent approach is necessary to identify airspace that is not only free of obstacles but also usable within an acceptable level of risk [6-7].

When it comes to urban UAV operations in the low-altitude airspace, there are two notable recent studies to consider: Metropolis project [8-12] and Singapore’s Traffic Management of UAS (TM-UAS) program [13]. In the Metropolis project, four airspace designs were proposed and simulated in a virtual urban environment of Paris, France. The simplest design assumed no structure, whereas the most complex scenario was based on a pre-defined 4D tube structure. The operational requirement with a minimum cruising altitude of 300 ft AGL and 100 ft above the tallest building created airspace free of static obstacles. Such an assumption of obstacle-free airspace fails to examine the usability of lower airspace populated with abundant high-rises as well as medium to low-rise buildings. The TM-UAS program proposed a structured airspace design to incorporate not only ground structures such as buildings and trees but also the state’s stringent altitude restriction of 60 m AMSL. TM-UAS adopted a static waypoint concept, where waypoints are selected based on various geospatial elements, including Mass Rapid Transit (MRT) tracks, traffic and light poles, rooftops of buildings, and canals and drainage systems. Although both studies provided crucial insights in concretizing the operational concepts of urban UAV operations, systematic assessments of the airspace capacity based on various geospatial complexities must be researched in parallel.

In this paper, we assess the availability of the low-altitude urban airspace based on two types of geofence - keep-out and keep-in. Geofence, a widely accepted concept for ensuring safe
separation of UAVs, is categorized into two types based on its purpose - keep-out and keep-in. The more common keep-out geofence is used to define the boundaries that UAVs should not penetrate [14-15]. The necessary safety buffer to prevent physical collisions into buildings needs to incorporate factors such as wind disturbances [16], which is likely to differ when considering privacy protection [17]. The keep-in geofence is used to define a prescribed operation area that a sUAV should and be able to stay in [16,18,19].Recently, applying the concept of keep-in geofence as a way to manage trajectory separation has been proposed [16].

Recently, several studies explored and researched geofence with a focus on its applications in UAS Traffic Management (UTM). The focus of the recent studies is on calculating the size of geofence in relation to vehicle dynamics and detect-and-avoid performance characteristics. In NASA UTM TCL2 flight test, geofence was modeled as three boundary layers separated by a predefined distance [18]. The distance values were set conservatively to initiate alerts when a vehicle breaches the boundaries. The flight test result showed that 46% of the flights left the intended operation area and that lateral deviation reached farther than 100 ft in 33% of geofence violation cases. NASA’s Safeguard system also adopted three layers of geofence boundaries for both keep-in and keep-out geofencing - warning boundary, soft boundary, and hard boundary [14-15]. The computation of geofence size is based on velocity, vehicle dynamics parameters such as the mass, size of wings, and lift-to-drag ratio, and wind condition. D’Souza et al. (2016) adopted an aerodynamic approach to calculate the lateral and vertical boundary of geofence based on a vehicle dynamics model and self-stabilizing PID controller. A simulation study was conducted to calculate flight deviations incorporating wind disturbances near buildings. Assuming a 1-second control time for self-stabilization, the geofence size was reduced to 5 meters horizontally and vertically, which is much smaller than the 30-meter used in the earlier NASA UTM flight tests. More recently, C. Johnson et al. (2017) conducted a simulation study to investigate the detect-and-avoid behavior of UAVs in narrow air corridors between buildings. Assuming various sizes of buffer space, 10 ft, 15 ft, and 20 ft, around buildings and a well-clear volume assigned to each vehicle, the study measured the intrusion frequency to the buffer. It was found that large building buffers reduce the likelihood of collisions with buildings, but if the corridor is too narrow, the detect-and-avoid algorithm caused UAVs to fly into buildings to avoid traffic [20].

In this paper, we propose to apply two types of geofencing method to identify the airspace that is not only free of static obstacles but also usable for sUAV operations. The main objective is to analyze the urban airspace by incorporating the operational requirements of the vehicle (keep-in) and the protection of surrounding environment (keep-out) at the same time.

II. Methodology

A. Terminology and geofence specification

In this paper, we define several terms to represent the airspace availability. Free airspace is airspace that is free of static obstacles, which represents the raw availability. Free airspace is further classified into usable and not usable airspace. Airspace is not usable if it is affected by geofence and closed for operational use (see Fig. 2).

In this study, keep-out geofence is modeled as a uniform space around the surface of static obstacles. Keep-in geofence is defined as a spherical ball to contain a sUAV, and is modeled as α-ball in the alpha shape method. The idea of an alpha shape was first proposed by Edelsbrunner as an attempt to reconstruct the shape of a finite point set using spherical disks, or α-ball, where α controls the level of details of shapes [21]. Edelsbrunner’s eraser analogy intuitively explains the construction of an alpha shape, as illustrated in Fig. 1. Assume a 2-D space containing a set of points S. Suppose there is an eraser that can remove any circular area of radius α>0. If the eraser removes all the points not in S without touching any point in S, the resulting shape will consist of the set of arc-shaped boundaries that encloses S. The alpha shape of S is then obtained by replacing the arcs with straight lines. Note that the shapes derived from a point set vary upon the radius of the eraser or α-ball. The mathematical definition is based on the concept of α-ball and n-simplex [22]. Given a set of points S, suppose that u is an open ball or α-ball of radius α, where u is called empty if $u \cap S = \emptyset$. For any subset T of S with cardinality $n+1$ (n=0,1,2,3), n-simplex is geometrically interpreted as the convex hull of T denoted as $\sigma_T$. $\sigma_T$ is called α-exposed if there exists an empty open ball u satisfying $\partial u \cap S = T$, where $\partial u$ is the boundary of u. The set of α-exposed n-simplices is referred as the alpha shape given filtration radius α.

![Figure 1. (a) Alpha shape of a point set with α-ball (Sun et al., 2016); (b) Alpha shapes (in red) derived from a point set with increasing α](image)

B. Urban airspace availability assessment framework

In the first step, 3-D map data is discretized into a Cartesian grid. Discretization provides modeling and computational efficiency in processing the 3-D information without losing the shape information in the raw dataset. Let $\Gamma = \{g_{ijk}: 1 \leq i \leq N_x, 1 \leq j \leq N_y, 1 \leq k \leq N_z\}$ be the Cartesian grid with a size of $N_x \times N_y \times N_z$, which is the discretized 3-D lattice of the region of interest with a unit cube size of $\varepsilon$. Now, let us define three subsets of $\Gamma$ as follows: $\Gamma_0 = \{g_{ijk} \in \Gamma: g_{ijk} \text{ is occupied}$

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by static objects, \( \Gamma^\text{out}_{ijr} = \{ g_{ijk} \in \Gamma; g_{ijk} \text{ is closed by keep-out geofence of size } \delta \} \) and \( \Gamma^\text{in}_{ijr} = \{ g_{ijk} \in \Gamma; g_{ijk} \text{ is closed by alpha shapes of radius } r \} \). Given the occupancy of cell \( g_{ijk} \) defined as an indicator function \( \text{occ}(g_{ijk}; \delta, r) = \begin{cases} 1, & g_{ijk} \in \Gamma^\text{in} \cup \Gamma^\text{out} \cup \Gamma^\text{inr} \\ 0, & \text{otherwise} \end{cases} \), the usability of airspace at altitude \( k \) is defined as \( U(k; \delta, r) = \frac{\sum_{i,j,k} N_x N_y 1 - \text{occ}(g_{ijk}; \delta, r)}{N_x N_y} \). Lastly, we define loss ratio \( \rho(k; \delta, r) = 1 - \frac{U(k; \delta, r)}{U(k; 0, 0)} \) which is the amount of airspace closed by geofence with size \( \delta \) and \( r \) at altitude \( k \), divided by the amount of free airspace.

III. CASE STUDY ANALYSIS

A case study of a real 3-D urban area was conducted in the 3 km by 3 km area of the Gangnam district in Seoul, South Korea. The 9 km² area is the busiest and most built-up area in metropolitan Seoul. Airspace below 150 m AMSL was discretized into a 600×600×30 Cartesian grid. Fig. 3 shows (a) the aerial map and (b) the height distribution of ground structures. The majority of the highest buildings are located along the major road sections with 6 to 8 lanes, which created several long and wide corridors in (b).

![Illustration of free, usable and not usable](image)

**Figure 2. Illustration of free, usable and not usable**

A. Single application of geofence

In this section, we present and discuss the individual effect of keep-out and keep-in geofence on \( U(k; \delta, r) \). Fig. 4 shows the results of the ‘keep-out only’ scenario with \( \delta=20 \) and ‘keep-in only’ scenario with \( r=20 \), at altitudes \( k=40 \) and 70. At \( k=40 \), the majority of the area is occupied with static objects, colored in black on the map, and each geofencing scenario produced \( U(40; 20, 0) = 6.8\% \) and \( U(40; 0, 20) = 20.7\% \), respectively.

Such a large difference originated from the long and wide corridor segments, as one can observe by inspecting \( U(40; 20, 0) \) and \( U(40; 0, 20) \) figures in juxtaposition. The alpha shape method identified a set of corridor segments that can accommodate vehicles with minimum separation of 20 m or less in this lower altitude area. When \( k=70 \), the overall availability improves significantly in either scenario, yielding \( U(70; 20, 0) = 45.2\% \) and \( U(70; 0, 20) = 68.3\% \). However, the keep-out scenario generated open spaces that are spread out in silos, while the keep-in scenario preserved several corridors connecting the open segments. The results show the benefit of using alpha shape method in a highly built-up environment.

![2D snapshots of single application of keep-out and keep-in geofence of size 20 at altitude 40 and 70 meters](image)

**Figure 4. 2D snapshots of single application of keep-out and keep-in geofence of size 20 at altitude 40 and 70 meters**

In Fig. 5, the curves of \( U(k; \delta, r) \) are shown with respect to altitude. The topmost solid curves are the raw availability with no geofencing. Overall, the effect of geofencing was most restrictive in the lower altitude, roughly when \( k \leq 40 \), and the airspace gain followed the rate of increase of the raw availability afterwards. In the keep-out scenario, even the smallest \( \delta \) of 10 or 20 meters closed the majority of free space when \( k \leq 40 \), despite a robust gain in the raw availability. Such an observation not only indicates that the area is populated with abundant buildings and other static objects, but also implies that those objects are located in close proximity.

![Airspace availability curves of keep-out only and keep-in only scenarios](image)

**Figure 5. Airspace availability curves of keep-out only and keep-in only scenarios**
In the keep-in scenario, the lower airspace was less prone to the effect of geofencing as severe as the keep-out scenario, particularly when r was sufficiently small.

**B. Dual application of geofence**

In Fig. 6, the dual effect of δ and r on $U(k; \delta, r)$ is shown in a 3-D contour plot for $0 \leq \delta \leq 50$ and $40 \leq k \leq 120$. In the contour plot, all combinations of $\delta$ and r on the same contour result in the same airspace usability. As anticipated, altitude is the main determinant of overall usability. For instance, $k=40$ yields $U(k; \delta, r)$ of 40% or less in most parameter combinations, whereas $k=70$ and 100 result in $U(k; \delta, r)$ larger than 30% and 70%, respectively. Reduction in the usable airspace is much greater in the lower altitude, while the effect of geofence becomes minimal at the altitude of 100 m or higher. Another interpretation of such an observation is that the area is nearly free of obstacles above 100 m.

![Figure 6. 3-D contour plot of airspace availability from the dual application of keep-out and keep-in geofence](image)

**IV. CONCLUSION AND FUTURE STUDY**

In this study, we proposed an airspace availability assessment framework that effectively identifies usable airspace in a highly built-up urban environment. By incorporating both keep-out and keep-in geofence, our approach not only captures the inherent benefits of the individual geofencing method but also measures the tradeoff between them. A case study of a Gangnam district in Seoul, South Korea provided further insights into the nature of geofencing outcomes in a real 3-D environment. The keep-out geofence mainly focuses on protecting the existing man-made structures, while the keep-in geofence concerns the vehicle operational feasibility. The tradeoffs between two geofencing methods need to be studied, and decisions on the minimum requirements need to be tailor-made to the nature of the area of interest and flight purposes. Our approach also has the potential to produce useful information to design waypoints and routes in the built-up area.

**REFERENCES**


