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

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Any questions, comments, and feedbacks are more than welcome. Please contact us via jjw9171@kaist.ac.kr
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Background

- **Expected increase in the number of drones in activity**
  
<table>
<thead>
<tr>
<th></th>
<th>2017</th>
<th>2022</th>
</tr>
</thead>
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<tr>
<td><strong>Recreational</strong></td>
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<td>1.9M - 3.2M</td>
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<tr>
<td><strong>Commercial</strong></td>
<td>0.11M</td>
<td>0.45M - 0.72M</td>
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  **(Europe)**
  
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<th>2017</th>
<th>2025</th>
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<td>0.2M</td>
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</table>

- **Estimated impact measured in flight hours and distance**

Background

## Background

### NASA UTM\(^1\)

- Airspace operation and geofencing
- Route planning and re-routing
- Separation management
- Strategic de-confliction
- Contingency management
  ...

### SESAR U-space\(^2\)

- Airspace dynamic information
- Flight planning and approval
- Strategic de-confliction
- Capacity management
- Detect-and-avoid technology
- Flight monitoring
  ...

### S’pore uTM-UAS\(^3,4\)

- Fleet management
- Navigation solutions
- Sense-and-avoid technology
- Failure management
  ...

### K-UTM\(^5\) / J-UTM\(^6\)

- Airspace management and geofencing
- Risk-based traffic flow management
- Sense and avoid technology
  ...

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Background

- Urban airspace is very likely to be intruded by existing structures
- It is important to identify not just free but *usable/flyable* airspace

at 200 ft AGL
Related literatures

< Metropolis project >

- Static waypoints are selected based on various geospatial elements (building rooftop, road, canals, metro, etc) as well as its stringent altitude limit (60m AMSL)

< uTM-UAS project >

- Four airspace designs were proposed and evaluated in a virtual urban environment
- Capacity, safety, and efficiency measures
- Minimum cruising altitude of 300 ft AGL and 100 ft above the tallest building

(Schneider et al., 2014; Sunil et al., 2015; Hoekstra et al., 2016; Sunil et. al., 2016a; Sunil et al., 2016b)

(Low, Gan & Mao, 2016; Salleh and Low, 2017; Salleh et al., 2018).
Currently, regulatory bodies have imposed sUAV operational restrictions based on proximity to population and man-made structures.

- **Minimum keep-out distance ranging from 30 to 150 meters**

### State-wise operational requirement on the minimum distance from people and buildings

<table>
<thead>
<tr>
<th>State</th>
<th>Flight purpose</th>
<th>Weight category</th>
<th>Minimum distance from people</th>
<th>Minimum distance from a building or structure</th>
<th>Altitude limit</th>
<th>Reference</th>
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<td>30m</td>
<td>120m AGL</td>
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<td>Guidelines on Operations of Unmanned Aircraft Systems</td>
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<td>1kg up to 35kg</td>
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<td>150m</td>
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<td>30m</td>
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<td>AC UAS-1</td>
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<td>unspecified</td>
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<td>120m AGL</td>
<td>14 CFR Part 107</td>
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</table>
Related Literatures

- **Keep-out geofence**
  - used to define a protection boundary that a vehicle should not intrude
  - mainly focuses on protecting the static ground structures

- **Keep-in geofence**
  - a similar concept with the Containment Limit (CL) of jet aircraft, which is defined based on the Total System Error (TSE)
  - concerns the vehicle’s operational feasibility

[Atkins, 2014; Hayhurst et al., 2015; Dill et al., 2016]

[DLR, 2017]

[D’Souza et al., 2016; C. Johnson et al., 2017; M. Johnson et al., 2017]
Research Objective

- We apply two types of the geofencing method to identify *usable* airspace, as a first step to assess the urban airspace capacity.
- The main objective is to analyze urban airspace by incorporating vehicle operational requirements (keep-in) as well as providing an adequate level of protection for surrounding environments (keep-out).
Terminology and geofence specifications

- **Free airspace**: airspace that is free of static obstacle
- **Usable airspace**: airspace that is not only free of static obstacles but also not affected by geofencing

- **Keep-out geofence** is modeled as a buffer space around the objects, whereas **keep-in geofence** is used to contain a vehicle in a spherical ball and modeled using alpha-shape method.
Alpha shape method

- **Alpha shape method** is a computational geometric technique used to construct a shape of a finite point set using a spherical ball or $\alpha$-ball

- $\alpha$ defines the radius of the ball, hence the level of details of the shape

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**Methodology**

- Given a set of points $S$, suppose that $u$ is $\alpha$-ball of radius $r$, where $u$ is called empty if $u \cap S = \emptyset$.
- For any subset $T$ of $S$ with cardinality $p+1$ ($p=0,1,2,3$), $p$-simplex is geometrically interpreted as the convex hull of $T$ denoted as $\sigma_T$.
- $\sigma_T$ is called $\alpha$-exposed if there exists an empty open ball $u$ satisfying $\partial u \cap S = T$, where $\partial u$ is the surface of $u$.
- The set of $\alpha$-exposed $p$-simplices is referred as the *alpha shape* given filtration radius $r$.

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< Alpha shape of point set with $\alpha$-ball >

adopted from Sun et al., (2016)
Alpha shape method

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< Implementation of alpha shape with increasing radius in 2-D >

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Hypothetical case
Hypothetical case
Hypothetical case
Hypothetical case
3-D airspace availability assessment framework

- Define $\Gamma$ be the discretized 3-D lattice of the region of interest with a unit cube of size $\epsilon$.
  \[ \Gamma = \{ g_{lmn} : 1 \leq l \leq N_x, 1 \leq m \leq N_y, 1 \leq n \leq N_z \} \]

- Define three subsets of $\Gamma$ as follows:
  \[ \Gamma_o = \{ g_{lmn} \in \Gamma : g_{lmn} \text{ is occupied by static obstacles} \} \]
  \[ \Gamma_{out}^\delta = \{ g_{lmn} \in \Gamma : g_{lmn} \text{ is closed by keep-out geofence of size } \delta \} \]
  \[ \Gamma_{in}^r = \{ g_{lmn} \in \Gamma : g_{lmn} \text{ is closed by alpha shapes of radius } r \} \]

- When a grid is blocked by static obstacles, we call it occupied. Likewise, when a grid becomes unavailable due to geofence, we call it closed.

- The availability of cell $g_{lmn}$ defined as an indicator function
  \[ \text{cell}(g_{lmn}; \delta, r) = \begin{cases} 0, & g_{lmn} \in \Gamma_o \cup \Gamma_{out}^\delta \cup \Gamma_{in}^r \\ 1, & \text{otherwise} \end{cases} \]

- The usability of airspace at altitude $k$ is defined as
  \[ U(k; \delta, r) := \frac{\sum_{1 \leq l \leq N_x, 1 \leq m \leq N_y} \text{cell}(g_{lmn}; \delta, r)}{N_x \times N_y} \]
Results and discussions

**Study area:**
built-up area of size 3 km by 3 km in Gangnam, Seoul

**Cell in black:** static obstacles

**Cell in grey:** airspace closed by keep-out

**Cell in red:** airspace closed by alpha shape

**Altitude, \( k \) (0-150m):**
60 m AMSL

**Keep-out distance, \( \delta \):**
5 to 50 meters

**Keep-in radius, \( r \):**
5 to 50 meters

* Built-up area is defined as any group of structures such as houses, factories, service stations, grain elevators, apartment buildings, or other man-made structures that could interfere with UAV operations (Transport Canada, 2017b)
Results and discussions

- The topmost solid curves are the raw availability with no geofencing, or $U(k; 0,0)$
- Overall, the effect of geofencing was most restrictive in the lower altitude, roughly when $k \leq 40$
- $\delta$ of 10 or 20 meters closed the majority of free space when $k \leq 40$, indicating that the area is populated with static obstacles and that those are located in close proximity
- In the keep-in scenario, the lower airspace was less prone to the effect of geofencing
- Such a difference comes from the unique capability of alpha shape method to identify corridors that can safely accommodate flights with a certain keep-in requirement.

$U(k; \delta, r)$: Airspace usability
$k$: altitude (m)
$\delta$: keep-out parameter (m)
$r$: keep-in parameter (m)

- $U(40; 20,0) = 6.8\%$ and $U(40; 0,20) = 20.7\%$
- $U(70; 20,0) = 45.2\%$ and $U(70; 0,20) = 68.3\%$
- 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
Results and discussions

\[ U(k; \delta, r) : \text{Airspace usability} \]
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< Airspace usability curves of keep-out only and keep-in only scenarios >

< 2D snapshots of individual effect of keep-out and keep-in geofence of size 20 at altitude 70 m>
Dual effect of keep-out and keep-in geofence

\[ U(k; \delta, r) \]: Airspace usability
\( k \): altitude (m)
\( \delta \): keep-out parameter (m)
\( r \): keep-in parameter (m)

\( U(40; 10, 10) \)
\( U(70; 10, 10) \)

< 2D snapshots of the dual effect of keep-out and keep-in geofence of size 10 at altitude 70 m>
Dual effect of keep-out and keep-in geofence

(a) 40 ≤ k ≤ 120

(b) k = 40

(c) k = 70

(d) k = 100

- **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.
- Even though $U(70; 15, 8) = U(70; 5, 33) = 50\%$, reducing $\delta$ from 15 to 5 meters increases the amount of usable airspace by 17% given $r=8$. On the other hand, increasing $r$ from 8 to 33 meters reduces the amount of usable airspace by 8% given $\delta=15$.
- Although larger $\delta$ might seem like a simple solution for enhanced safety, our results show that it comes at a cost of greatly reducing a usable airspace that can safely accommodate vehicles of various containment limits.
Conclusions

- Airspace assessment framework effectively identifies usable airspace even in a highly built-up environment.
- Our approach captures the inherent benefits of the individual geofencing method as well as their tradeoffs.
- It also has the potentials to identify departure/arrival locations and design ascent/descent routes.
- Framework is applicable to any geospatial dataset given various geofence parameters.
Further studies

- The proposed framework provides a crucial dataset to study geospatial continuity in 3-D.
- Identifying the continuity of open segments will be necessary for structured urban airspace design and path planning.
- We apply various topological analysis techniques, including topological data analysis (Carlsson, 2009) to model such continuity of usable airspace.
Topological clustering

**Mapper algorithm**

1. Choose distance metric: Euclidean
2. Filter function to map data to a single value: horizontal and vertical projection
3. The ranges of each filter application are divided into overlapping segments or intervals using two parameters cover and overlap. Cover (resolution) controls how many intervals each filter range will be divided into
4. Compute the Cartesian product of the range intervals and assign the original data points to the resulting regions based on the filter values.
5. Perform clustering in the original space for each region. Each cluster represents a node. The nodes are connected by an unweighted edge if any clusters have points in common.
6. By joining clusters in feature space, a topological network is derived in the form of a graph.

**Topological equivalence**

**Nerve of a covering**

**Mapper algorithm**
Sample illustration

Further studies
Sample illustration
Network representation of airspace

- Airspace can be turned into discrete shape combination
- Simplified representation of airspace can be derived in a network form

Segmentation of usable airspace, $A(k=60, \delta=10, r=5)$

Network representation of airspace

$A(k; \delta, r)$: Usable airspace at altitude $k$ given geofence parameters

$k$: altitude (m); $\delta$: keep-out parameter (m); $r$: keep-in parameter (m)
Network representation of airspace

- Filtrations at multiple resolution settings
- Clusters may change with scale, but connectivity is preserved

**resolution = 10**

\[ A(k; \delta, r) = (60, 10, 10) \]

**resolution = 20**

\[ A(k; \delta, r) = (60, 10, 10) \]

\( A(k; \delta, r) \): Usable airspace at altitude \( k \) given geofence parameters

- \( k \): altitude (m)
- \( \delta \): keep-out parameter (m)
- \( r \): keep-in parameter (m)
Network representation of airspace

- Network shape also changes with geofence parameters (keep-out and keep-in)

\[ A(k; \delta, r) = (70, 10, 10) \]

\[ A(k; \delta, r) = (70, 30, 10) \]

\[ A(k; \delta, r) \]: Usable airspace at altitude k given geofence parameters
\[ k \]: altitude (m); \[ \delta \]: keep-out parameter (m); \[ r \]: keep-in parameter (m)
Betweenness Centrality

Further studies
2.5D/3D view

\[ A(k; \delta, r) = (k; 10, 10) \]

\[ A(k; \delta, r) = (k; 30, 10) \]
References


References


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