Title: Method for Analysis of Drone Operations and Incursion Risk at Airports

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METHOD FOR ANALYSIS OF DRONE OPERATIONS AND INCURSION RISK AIRPORTS

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Abstract:

Advances in technology have enabled the deployment of low-cost drones for precision inspection and surveillance of industrial and agricultural infrastructure. This infrastructure is frequently situated in the proximity of airports that serve as transportation hubs and may have less expensive land (due to airport noise) appropriate for industry and agriculture. Airport operators would like to safely facilitate the use of drones by tenants and adjacent property owners in the airspace in the vicinity of the airport.

This paper describes a method for analysis of the Annual Drone Operations Exposure Hours (DOEH) and the Estimated Airport Drone Incursions (EADI) for an airport airspace. The DOEH and EADI are calculated based on the GIS analysis of the infrastructure in the vicinity of the airports, and estimates of frequency of drone operations, drone operations duration, and probability of incursion. A case study for 66 Virginia airports showed that drones deployed in the airspace within 5 n.m. of the airports would yield an estimated nineteen (19) Virginia airports would experience significant (i.e. more than 10) drone incursions per year. Implications of these results and limitations of the method and future work are discussed.

Key Words:

Drone Operations

Drone Incusrions

Annual Drone Operations Exposure Hours (DOEH)

Estimated Airport Drone Incursions (EADI)

1 INTRODUCTION

Advances in technology have enabled the fielding of small, inexpensive, easy-to-operate drones. These drones have resulted in significant economic benefits by performing tasks that could not previously be accomplished, or can now be accomplished with greater precision, lower cost, and less time. Examples include quarry surveying, railroad and powerline inspections, forest surveillance, crop surveillance, aerial photography, and package delivery.

The widespread use of these drones, including operations beyond visual line-of-sight (BVLOS), has created a potential collision risk for other users of the nation's airspace. This risk is especially high for those vehicles operating in low altitude airspace, such as manned aircraft for emergency medical services, aerial photography, search and rescue.

The collision risk is particularly acute in the proximity of airports where there is a high volume of low altitude arrival and departure traffic flow. These airports are generally located in the vicinity of industrial parks, adjacent to other transportation and energy distribution hubs, and waterways that are natural locations for drone operations (Figure 1).

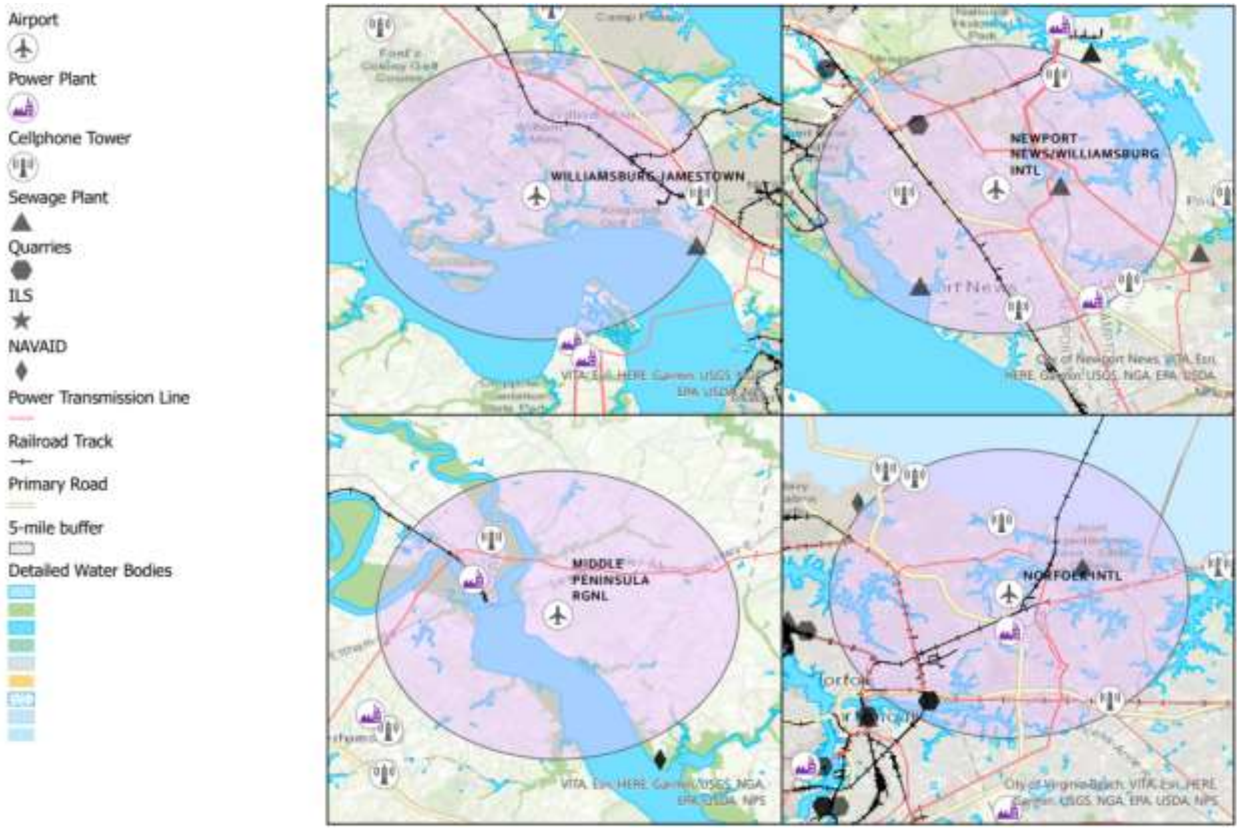

FIGURE 1: High collision risk between a small drone and high volume, low altitude traffic in to and out of airports. Airports tend to be located in proximity to facilities that benefit from drone deployment.

Federal regulations, such as U.S. 14 CFR Part 107 Small Unmanned Aircraft Systems, allow drone operations in all "uncontrolled" airspace below 400 feet above the ground (AGL). Drone operations in the vicinity of airports are in "controlled" airspace (i.e. Class B, C, D, and E) and are required to get permission from the Air Navigation Service Provider (ANSP) before flying in this airspace.

This paper describes a methodology for estimating the annual Drone Incursion Exposure Hours (DIEH) and the annual Estimated Drone Incursions (EDI). The DIEH and EDI are calculated based on the GIS analysis of the infrastructure in the vicinity of the airports, and estimates of frequency of drone operations, drone operations duration, and probability of incursion.

A case study for the airport airspace for 66 Virginia Airports showed Annual Drone Operations Exposure Hours (DOEH) averaged 23, 714 hours with a maximum of 50,742 (Shannon Airport – EZF). Annual Estimated Airport Drone Incursions (AEDI) for the 66 Virginia airports averaged 8.2 with a maximum of 36.9 incursions (Williamsburg-Jamestown Airport – JGG)

This paper is organized as follows: Section 2 provides an overview of drone operations and potential causes of incursions. Section 3 describes the method of analysis, Section 4 describes the results of the analysis for 66 Virginia airports. Section 5 discusses the implications of the analysis, as well as limitations and future work.

2 DRONE OPERATIONS AND INCURSIONS

Drones, also known as Small Unmanned Aerial Systems (sUAS), are outfitted with sensors for inspection and surveillance of infrastructure (e.g. railroad tracks, power generation stacks, quarries, agriculture, and nature (e.g. forests). Drone sensors provide very high-resolution images, that can be can be used to gain a high-quality perception of the condition of assets. The images can be processed automatically, and provide an opportunity for review multiple times. These images can also be archived and used for comparison over time. One of the advantages of using drones for these tasks is that the drones replace human (e.g. inspectors) presence in dangerous situations (e.g. climbing transmission line pylon or cell phone tower).

When Drones are connected to the internet, drones can be considered part of the Internet of Things (IoT) devices. They can share data with other IoT devices and systems and can provide real-time data as an input into ‘big data’ applications. This enables faster, more accurate enterprises, decision-making, and analysis in terms of service offerings and infrastructure improvements, as well as acting as an enabler for more effective asset-related decision making.

Drones can be configured as quad-copters or hexacopters, or as fixed-wing unmanned aircraft.

Drone Trajectories

Drone trajectories are derived from the command chain illustrated in Figure 2. A 4-D flight plan is defined by a sequence of waypoints (i.e. latitude/longitude). Each waypoint has an associated altitude and required time. To meet the required time at the waypoint, the leg between waypoints can be defined by a speed (i.e. distance between waypoints/required time between waypoints). The legs between waypoints can also be defined by the shape of the course (e.g. straight-line, curved, etc.). The definition of the flight plan is conducted by the Flight Planning function.

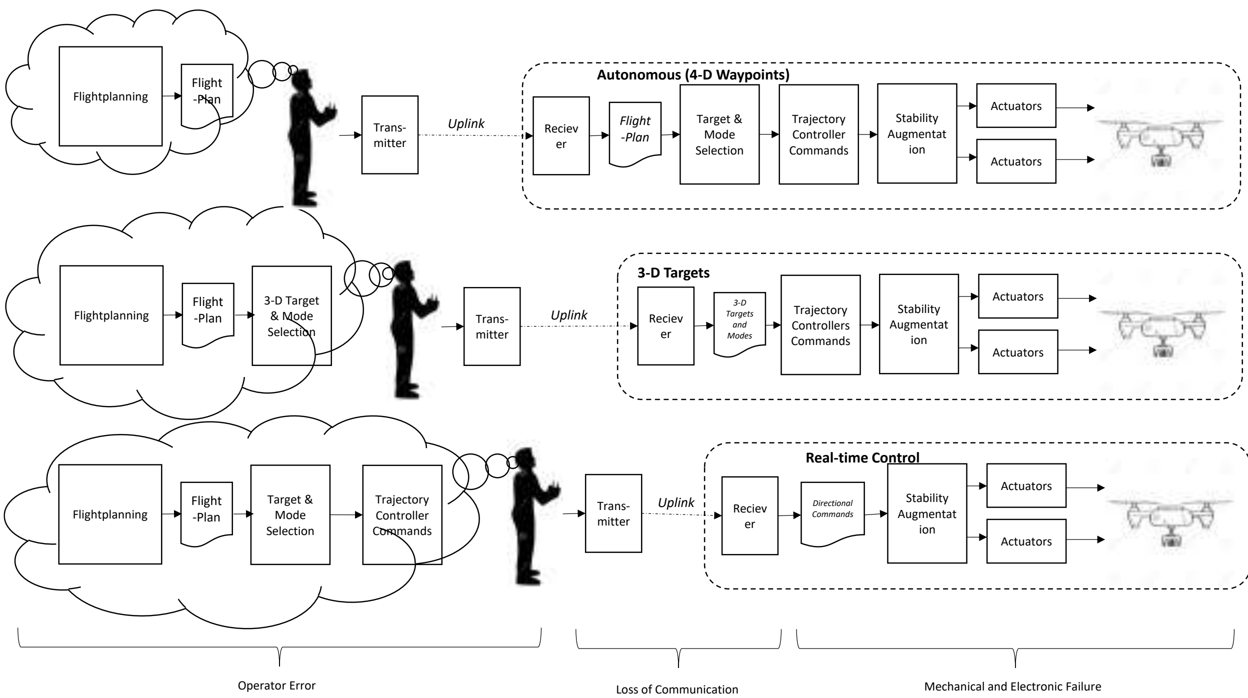

FIGURE 2: Command chain for vehicle trajectory control in three Flight Management Configurations: top – Autonomous, middle – Flightplanned, bottom – real-time control

Each leg in the flight plan is defined by a set of Targets (i.e. course, speed, altitude). As the vehicle sequences (i.e. passes over) each waypoint, the Targets change. The determination of the Targets at any given time is determined by the Guidance Function.

The commands to the vehicle attitude control and propulsion systems are determined by the relative “position” of the vehicle to the Targets. The determination of the Commands to achieve the Targets in a smooth manner within the performance constraints of the vehicle at any given time is determined by the Control Functions.

Depending on the type of vehicle (e.g. quad-copters or hexacopters, or as fixed-wing), the flight attitude and propulsion system commands are converted to specific commands to individual rotors. This function is known as Stability Augmentation.

Drone Flight Management Configurations

In any configuration, the drone can be operated autonomously, flight-planned, or real-time control (Figure 2). Autonomously operated drones are launched with a complete flight plan and return once the mission is completed. Autonomous drones generally have the flight plan loaded onto the airborne control system. The Planning, Guidance, Control, and Stability Augmentation are performed by the “avionics” on the vehicle. Human operator roles are limited to monitoring and intervention of the mission from a Ground Station connected to the drone via a (digital) communications link.

For Flight planned drones, the trajectory is determined by operators providing trajectory instructions by defining 4-D waypoints (i.e. latitude, longitude, altitude, and speed) via the communications link from the Ground Station. The Guidance, Control, and Stability Augmentation are performed by the avionics on the vehicle.

For real-time control drones, the trajectory is determined by the operator who issues attitude and propulsion commands to the vehicle via the communications link from the Ground Station. Only the Stability Augmentation is performed by the avionics on the vehicle.

Causes of Deviation from Allowable Airspace

The drone may deviate from the allowable airspace or desired trajectory by a failure in any link in the command chain. Operator error occurs when the operator issues an incorrect command. Loss of Communication occurs when the Receiver on the drone fails to receive the correct instructions/commands transmitted from the ground station controller. The drone may not follow the instructions/commands due to mechanical and/or electrical failures.

Geo-Fencing

Geofencing is a feature that uses a drone's GPS receivers to automatically enforce warnings or restrictions based on where the drone is flying (Liu, et. al. 2016). The system is typically integrated with a digital airspace chart that specifies no-fly zones and areas where there are active drone restrictions (Figure 3). The "avionics" on the drone will not command the drone to breach the geo-fence.

FIGURE 3: Geofence marks a perimeter beyond which the vehicle avionics will not command the vehicle trajectory.

3 METHOD FOR ASSESSMENT OF AIRPORT VULNERABILITY TO DRONE INCURSIONS

The vulnerability of airports to drone incursions is determined by:

(1) the type and count of infrastructure in the vicinity of the airport airspace (e.g. 5nm radius)

(2) the type of drone operations required to perform inspection and surveillance operations of each infrastructure

(3) the duration and frequency of the inspection and surveillance operations

(4) the probability of an incursion for each type of inspection and surveillance operation

The following 4 step process is used to calculate the Annual Drone Incursion Exposure Hours (DIEH) and the Annual Estimated Drone Incursions (EDI) for the airport airspace.

Step 1) Identify Infrastructure that uses drones for inspection, surveillance, etc …

The following objects within a 5-n.m. radius of the airports were identified as exhibiting potential for drone use:

- Railroad Track Segments
- Power Transmission
- Water Bodies
- Power Generation Plants
- Cellphone Towers
- Sewage Plants
- Quarries
- Agriculture - Farmland
- Forests

- Navigation Equipment
- Highways
- Drone Transportation Corridors

Step 2) Identify Drone Activities in the Vicinity of the Airport based on the Presence of Infrastructure

Use a GIS system with available databases to identify the presence and magnitude of the selected Infrastructure within a 5nm radius of the airport.

The following objects within a 5 n.m. radius of the airports were identified as exhibiting potential for drone use (Table 1).

TABLE 1: Sources of Data, Unites and Activity Type for each Infrastructure

Infrastructure	**Units**	**Activity Type**	**Example Data-base**
Railroad Track	Segments	Inspection	Virginia Railroad by VGIN retrieved from https://www.arcgis.com/home/item.html?id=9e1e6aa9ee8041bb8a65b08bddcbeb1b
Power Transmission	Pylons	Inspection	Electric Power Transmission Lines by Esri U.S. Federal Datasets retrieved from https://hub.arcgis.com/datasets/fedmaps::u-s-electric-power-transmission-lines/about
Water Bodies	Square Miles	Surveillance, Transportation Corridor	USA Detailed Water Bodies by Esri retrieved from https://www.arcgis.com/home/item.html?id=84e780692f644e2d93cefc80ae1eba3a
Power Generation Plants	Count	Inspection	Power Plants retrieved from https://eia.gov/maps/layer_info-m.php
Cellphone Towers	Count	Inspection	Cellular Towers by FCC retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::cellular-towers/about
Sewage Plants	Count	Inspection	EPA FRS Facilities retrieved from https://www.epa.gov/frs/epa-frs-facilities-state-single-file-csv-download
Quarries	Count	Surveillance	EPA FRS Facilities retrieved from https://www.epa.gov/frs/epa-frs-facilities-state-single-file-csv-download
Agriculture - Farmland	Acres	Surveillance	US Department of Agriculture CropScape data retrieved from https://nassgeodata.gmu.edu/CropScape/

Forests	Acres	Surveillance	US Department of Agriculture CropScape data retrieved from https://nassgeodata.gmu.edu/CropScape/
Navigation Equipment	Count	Inspection	Pending NAVAID Component by FAA retrieved from https://adds-faa.opendata.arcgis.com/datasets/9e507e30922946ceb8d22c5be7ffb152_0/explore?location=10.312717%2C-1.658582%2C2.68 Instrument Landing System (ILS) retrieved from https://adds-faa.opendata.arcgis.com/datasets/9dcdee16e66b47d59c17f4dae53f6721_0/explore?location=40.887222%2C-116.485054%2C3.92
Highways	Segments	Inspection	US Primary Roads Database retrieved from https://catalog.data.gov/dataset/tiger-line-shapefile-2016-nation-u-s-primary-roads-national-shapefile

Step 3) Identify Frequency and Duration for Drone Activities in the Vicinity of the Airport

The Frequency of Drone Operations per year and the Duration of each Drone Operation are defined in Table 2.

TABLE 2: Frequency and Duration of Drone Operations

Infrastructure	Units	Activity	Frequency (Times per Year)	Activity Durations (Hours)
Railroad Track	Segments	Inspection	4	4
Power Transmission	Pylons	Inspection	4	10
Water Bodies	Square Miles	Surveillance, Transportation Corridor	50	10
Power Generation Plants	Count	Inspection	4	10
Cellphone Towers	Count	Inspection	4	6
Sewage Plants	Count	Inspection	50	4
Quarries	Count	Surveillance	50	4
Agriculture - Farm land	Acres	Surveillance	20	10
Forests	Acres	Surveillance	10	10
Navigation Equipment	Count	Inspection	4	4
Highways	Segments	Inspection	50	10
Drone Transportation Corridor	Segments	Transportation Corridor	50	10

Step 4) Calculate Annual Airport Drone Operation Exposure Hours (ADOEH) for Each Airport

Based on the presence of magnitude of the infrastructure within a 5 n.m. radius of the airport (Step 2) and the Frequency and Duration of Drone Activities for each Infrastructure-type (Step 3), calculate the Drone Exposure Duration (Hours per Year) for each airport.

Airport Drone Operations Exposure Hours (Airport j) = $\sum_{i\,=\,\text{Infrastructure Type}}$ Count (i,j) *Frequency (i) * Duration (i)

Step 5) Calculate Annual Airport Estimated Drone Incursions (AEDI) per Year for Each Airport

The Estimate of Drone Incursions per Year for each Airport is defined as a function of the count of the infrastructure, the frequency of drone operations, the duration of drone operations, and the Incursion probability as follows:

Estimated Airport Drone Incursions (Airport j) = $\sum_{i\,=\,\text{Infrastructure Type}}$ Count (i,j) *Frequency (i) * Duration (i) * Incursion Probability (i)

The Incursion Probability for each type of drone is defined in Table 3 below.

TABLE 3: Drone Incursion Probability for each Type of Drone Operations based on a worst-cased High Altitude/BVLOS of 0.001 (i.e. 0.1%) probability

Infrastructure	Altitude	Line of Sight	Incursion Probability per Hour of Operation
Railroad Track	Low	BVLOS	1E-06
Power Transmission	High	BVLOS	0.001
Water Bodies	High	BVLOS	0.001
Power Generation Plants	Low	LOS	0.0001
Cellphone Towers	Low	LOS	1E-07
Sewage Plants	Low	LOS	1E-07
Quarries	Low	LOS	1E-07
Agriculture - Farm land	Low	BVLOS	1E-06
Forests	High	BVLOS	0.001
Navigation Equipment	Low	LOS	1E-07

Highways	High	BVLOS	0.001
Drone Transportation Corridor	Highs	BVLOS	0.001

Incursion probability statistics are difficult to come by. Empirical data on the UAS sightings in the vicinity of airports is available from voluntary UAS sighting reporting data-bases. However, the total number of operations is not available. This prohibits derivation of the probabilities. Agent-based simulation models (e.g. Fricke et.al. 2021) provide a range of probabilities between 10^{-2} and 10^{-58}. For the purpose of this paper, the Incursion Probability is estimated based on a baseline of 0.001 (i.e. 0.1%) of the probability of blunder for the geo-fenced drone airspace for drone operations Beyond Visual Line of Sight (BVLOS) operating at the highest allowable altitude (i.e. 400 ft Above Ground Level or higher if within 400ft of Structure). This is a worst-case scenario. For lower altitude and Line of Sight (LOS) operations, the drone incursion drops by a magnitude of 0.01 (Table 4). Note, these value may be adjusted with improved empirical or simulated data.

TABLE 4: Multiplier for Probability of Drone Incursion based on a baseline of for Line-of-Sight and Altitude.

	Altitude	
	Low (10 ft)	**High (e.g. 400 ft)**
Line of Sight	0.0001	0.01
Beyond Visual Line of Sight	0.001	1

5 CASE STUDY: VIRGINIA AIRPORT (66)

Sixty-six airports in Virginia were evaluated. Washington National (DCA) and Dulles International Airport (IAD) were not included in this analysis. The infrastructure counts were derived from the GIS data described above. Examples of the infrastructure within 5nm of four Virginia airports are shown in Figure 1.

The DEH and EDI were calculated as described above.

Annual Airport Drone Operations Exposure Hours (ADOEH)

The maximum annual Drone Operations Exposure Hours (ADOEH) were estimated at 50,743 hours at Shannon Airport (EZF). Shannon has significant Rail Road Segments (420) within 5nm of the airport as well as Power Transmission Lines (10), Water Bodies Segments (22), Cellphone Towers (3), Sewage Plant (3), Quarries (1), Agriculture - Farmland, Forests, Navigation Equipment (1), and Highways (1).

The minimum annual ADOEH was estimated at 183 hours at Lee County Airport (0VG). Within 5nm of the airport, Lee County has only Rail Road Segments (3), Agriculture - Farmland, Forests.

The annual ADOEH has a median and mean at approximately 23, 800 hours. These airports had combinations of all the infrastructures.

The annual ADOEH statistics are provided in Table 5. The distribution of Annual Drone Operations Exposure Hours exhibits two modes (Figure 4). Twenty (20) airports have less than 15,000 hours. Twenty-one (21) airports have more than 35,000 hours.

TABLE 5: Statistics for Estimates of Airport Drone Operations Exposure Hours (DOEH) at 66 Virginia Airports

Annual Airport Drone Operations Exposure Hours (ADOEH)	
MIN	**183**
MEDIAN	**23,981**
AVG	**23,714**
MAX	**50,742**

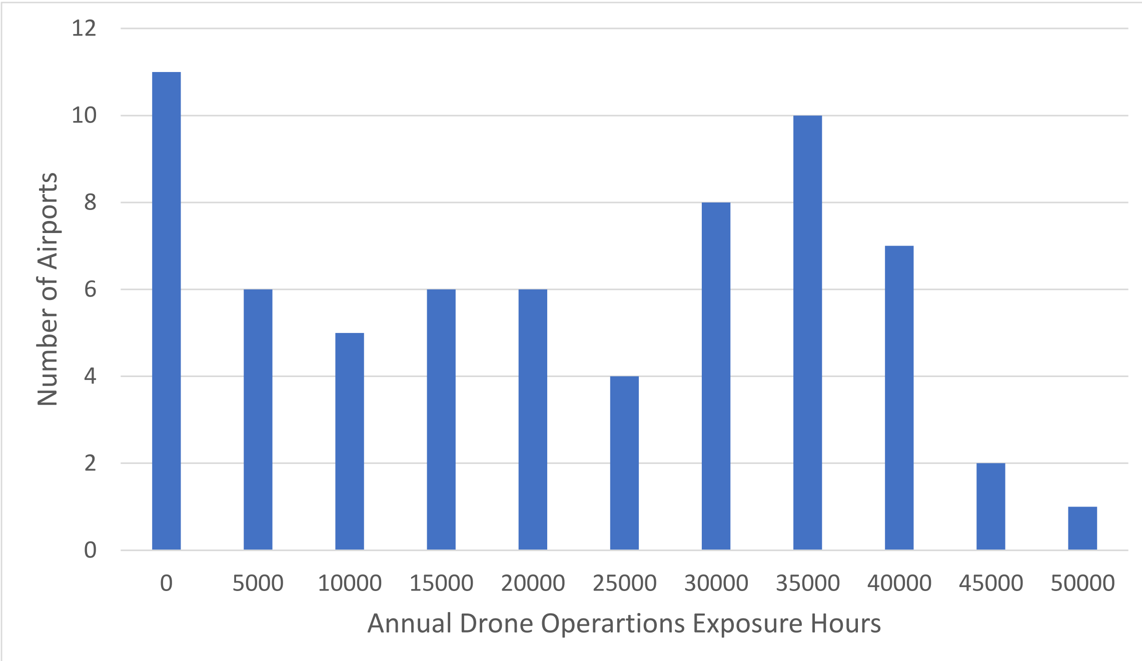

FIGURE 4: Histogram of Annual Drone Operations Exposure Hours (DOEH) at 66 Virginia Airports. Twenty-one airports have more than 35,000 exposure hours.

Airport Estimated Drone Incursions (AEDI)

The maximum annual AEDI was estimated at 36 at Williamsburg-Jamestown Airport (JGG). JGG has significant Rail Road Segments (36) within 5nm of the airport as well as Power Transmission Lines (8), Water Bodies Segments (72), Sewage Plant (1), Quarries (1), Agriculture - Farmland, Forests, and Highways (1). These infrastructures are dependent on High Altitude with BVLOS drone operations.

The minimum annual AEDI was estimated at 0.1 at Lee County Airport (0VG). Within 5nm of the airport Lee County has only Rail Road Segments (3), and, Forests. The low count ensures a low incursion rate.

The annual AEDI has a median at 6.9 and mean at 8.2 These airports had combinations of all the infrastructures with a range of high/low altitude and LOS/BVLOS operations.

The annual AEDI statistics are provided in Table 6. The distribution of Estimated Drone Incursions per Year is exponential (Figure 5).

TABLE 6: Statistics for Estimates of Airport Estimated Drone Incursions (AEDI) at 66 Virginia Airports

Annual Estimated Airport Drone Incursions (AEDI)	
MIN	0.1
MEDIAN	6.9
AVG	8.2
MAX	36.9

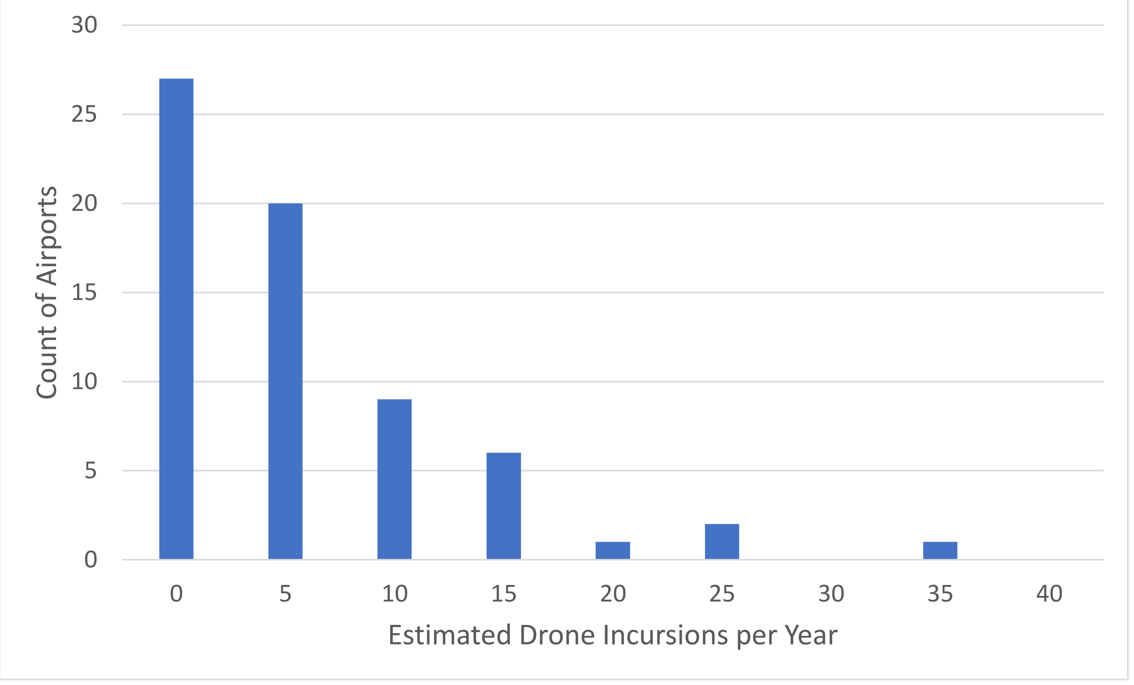

FIGURE 5: Histogram of Annual Airport Estimated Drone Incursions (AEDI) at 66 Virginia Airports. Nineteen airports are estimated to have more than 10 incursions per year.

Drone Operations Exposure Hours (DOEH) vs. Airport Estimated Drone Incursions (AEDI)

The relationship between DOEH and AEDI is complex (Figure 6). Airports with high exposure rates on the right-hand side of the chart can exhibit both high and low incursion rates depending on the types of drone operations. Twenty-nine of the Virginia airports have both low DOEH *and* low AEDI. Twenty of the Virginia airports have both high DOEH *and* high AEDI.

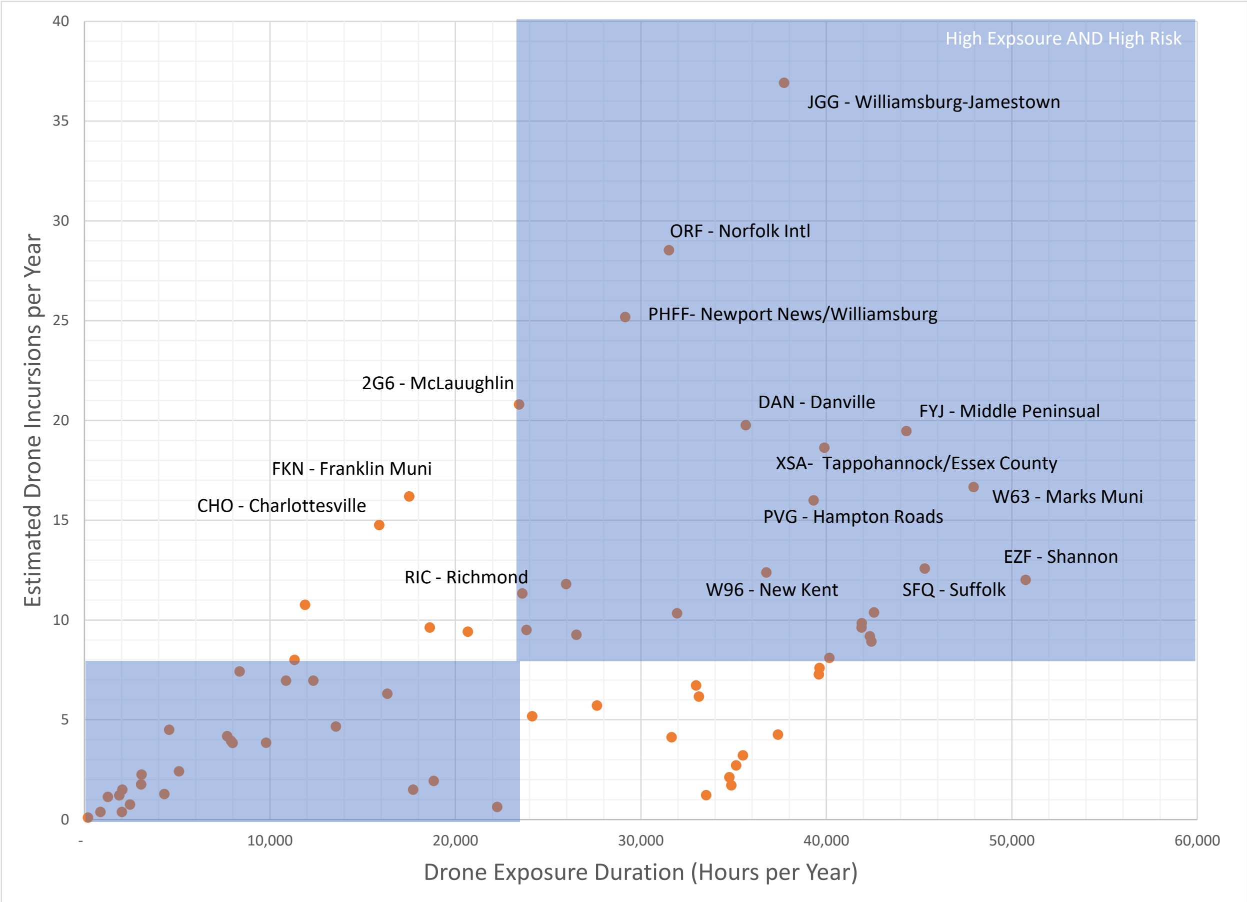

FIGURE 6: Airport Drone Operations Exposure Hours (DOEH) (x-axis) vs Airport Estimated Drone Incursions (AEDI) (y-axis).

CONCLUSIONS

The analysis of Virginia airports confirms the high density of industrial and agricultural infrastructure within a 5-n.m. proximity of airports. A detailed analysis of the potential application of drones for inspection and surveillance of these activities of industrial and agricultural infrastructure identifies a *maximum* Annual Drone Operations Exposure Hours (ADOEH) of 50,746 hours per year (Shannon – EZF).

The maximum annual Airport Estimated Drone Incursions (AEDI) of 36 (Williamsburg-Jamestown Airport (JGG)) The average ADOEH across all 66 Virginia airports is 24,000 hours per year with an associated AEDI of 8.2.

Twenty-nine of the Virginia airports have both low ADOEH *and* Low AEDI. Twenty of the Virginia airports have both high ADOEH *and* high AEDI.

Limitations and Future Work

The results of the analysis are dependent on two types of information: GIS data and Incursions probabilities. The GIS data is considered up-to-date and accurate. The Incursion probability baseline (0.001) and adjustments for altitude and LOS are estimates and require further validation.

Airport Airspace Drone Incursion Protection Systems (A^2DIPS)

Recently, the Federal Aviation Administration (FAA) published a final rule for a "Remote ID" (RID) to be broadcast from UAS aircraft ("drones"). The RID signal can be received by any party with an appropriate receiver on the ground or in the air. The RID signal will identify the identity and provide the location of the drone.

The RID provides an enabling technology to provide the airspace in the proximity of airports used for airport arrivals and departures with a drone incursion protection system (A2DIPS). This will enable safe, widespread, legal use of drones to support aerial surveillance, photography, inspection, etc tasks while ensuring airport traffic safety.

Concept-of-Operations:

The A2DIPS command-and-control portal will provide Airport Operations Managers, Air Traffic Control, aircraft operators, and law enforcement, situation awareness of drone operations in the vicinity of the airport with sufficient time and position accuracy to take the necessary mitigation actions to avoid a drone incursion into the airport airspace. Mitigation actions include tracing and contacting the drone operator (Figure 8).

The A^2DIPS is composed of a set of RID sensors and a Command Center software application.

The set of RID receivers are strategically situated in the vicinity of the airport creating a multi-layered surveillance perimeter. The RID receivers are connected to a Command Center located in the Air Traffic Control Tower, Airport Operations Management office, FBO, and/or local law enforcement.

The Command Center software application would provide a 3-D visualization of the airspace along with the location of RID drones as well as other air traffic broadcasting their positions via transponders.

The Command Center software application will also provide caution warnings and alerts. The warnings and alerts will be made on proximity sensing criteria and also on AI-derived assessment of RID drone flight tracks operating legally in the vicinity of the airport.

The Command Center software application will also monitor for spoofing activity and provide spoofing alerts.

The Command Center software application will also log RID flight activity in a database and provide visualization of drone operations trends and anomalous behaviors. Machine Learning technology to detect patterns in the data that may indicate emerging threats via anomaly detection. The system will provide safety reports as appropriate to the FAA for use in safety improvement programs.

The RID sensor system will not interfere with existing air traffic control radar and other surveillance, navigation, and communication systems.

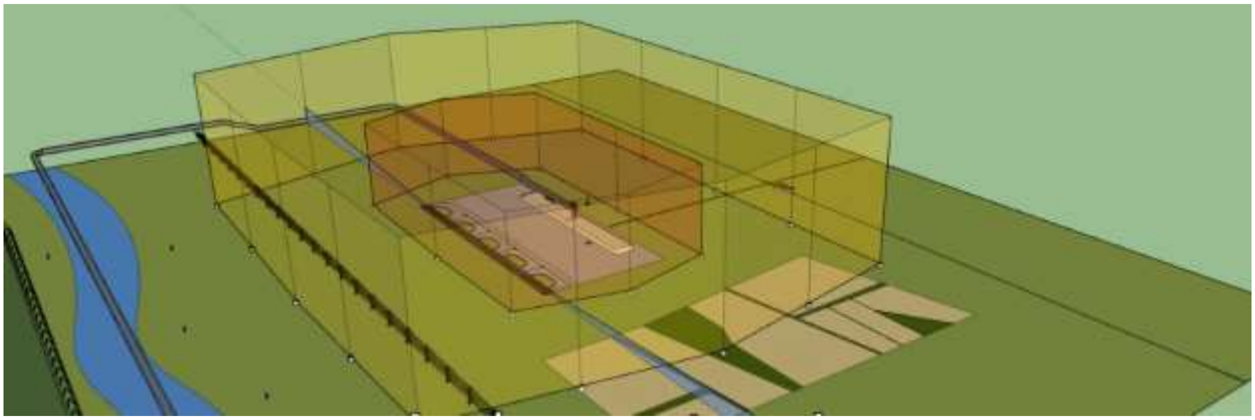
FIGURE 8: Conceptual Model of A2DIPS

The A^{2}DIPS can also be used to protect other critical infrastructures, such as heliports, critical infrastructure (e.g. Nuclear Power Station at Lake Anne), outdoor stadiums during well-attended events, and other sensitive assets.

The A^{2}DIPS can also be used to provide Ground-based Detect & Avoid services for drones operating in the vicinity of the airport.

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