Accommodating Low Altitude Autonomous UAS Flight Within the National Airspace System

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by

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DEDICATION

This is dedicated to my parents, Timothy E. and Martha A. Seitz, without whom, this would have not been possible.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
ADS-B	Automatic Dependent Surveillance-Broadcast (ADS-B)
CSD	Cockpit Situation Display
DME	Distance Measuring Equipment
DSLR	Digital Single Lens Reflex
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
GIS	Geographic Information System
GPS	Global Positioning System
LAANC	Low Altitude Authorization and Notification Capability
NAS	National Airspace System
RF	Radio Frequency
SFRA	Special Flight Rules Area
SUAS	Small Unmanned Aircraft System
TCAS	Traffic and Collison Avoidance Systems
UAS	Unmanned Aircraft System
UNICOM	Universal Communications (frequency)
TBVLOS	Tactical Beyond Visual Line-of-Sight
VOR	VHF Omnidirectional Range

ABSTRACT

ACCOMMODATING LOW ALTITUDE AUTONOMOUS UAS FLIGHT WITHIN THE NATIONAL AIRSPACE SYSTEM

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This thesis identifies trends in Unmanned Aircraft Systems (UAS) development and examines the status of UAS integration into the National Airspace System of the United States. The current states of Federal Aviation Administration technological initiatives, UAS operational guidelines and airspace regulations are described and explored. A review of academic literature, including scholarly journals and US federal legislation, examines trends in possible UAS applications, beneficial uses of employing UAS, potential risks associated with higher UAS ubiquity, and mitigation techniques to reduce risk. A low altitude aerial network is proposed in order to incorporate unmanned air traffic in a safe manner within the bounds of the selected study area of Fairfax County, Virginia. The results find that a majority of residential structures are capable of being accessed through this network and demonstrates that alternative methods of airspace conceptualization may lead to a reimagining of existing physical space for low altitude unmanned navigation.

CHAPTER ONE: INTRODUCTION

Unmanned Aircraft Systems, or UAS for short, have become a controversial subject within the civil aviation industry. As commercially available wireless technology, electro-optical imaging systems, and computer processing power have progressed, consumer UAS have progressed alongside. At one time, they were perceived as expensive toys for children and hobbyists, they are now powerful tools of research, data collection, and potentially danger. Where they were previously limited by short battery life, weak radio receivers, and poor camera equipment, systems may now be purchased commercially-off-the-shelf that rival the former data collection arsenals of Nation-States. Government and industry have struggled to assess and proscribe methods for accommodating their use, while private individuals have pushed the capabilities of their systems to their limits. As legislation continues to catch up, a wide gulf exists between what is currently legally permitted, and what potential worlds may come to be.

This work examines how existing government policies affect the current states of UAS Integration into the National Airspace System of The United States and proposes alternatives in Airspace development to encourage the separation of UAS from manned Aircraft. For the purposes of this research, integration is defined as the ability to operate drones within a well-defined navigational framework, pertaining to purposes such as drone delivery services, agriculture, and infrastructure maintenance. As it currently stands, UAS operations are severely limited in terms of their range, however not in terms of their capabilities. There are a number of compelling reasons why UAS integration may not only change the face of aviation within the United States, but also extend these changes to the wider culture and economy pending their full integration.

As of March 2020, The FAA has registered 1,563,263 small unmanned aircraft systems (sUAS) for civil aviation within the United States, with only 171,744 FAA Part 107 licensed pilots for sUAS (Federal Aviation Administration, 2020). Unregulated UAS usage has led to a degree of notoriety in terms of irresponsible operation with regard to operating in the proximity of manned aircraft, with incidents including a collision between a consumer-grade UAS and a US Army UH-60 Blackhawk flying in Staten Island, New York (Wallace, 2018). Carrying approximately 889,022,000 passengers in 2018, the United States already has the most congested civil airspace system in the world (World Bank, 2018). Integration of myriad unmanned low altitude flights into such a congested airspace system will be a challenging task. The regulatory landscape regarding UAS consists of a number of factors, such as congestion within the existing airspace system for manned craft, the physical limitations of UAS themselves, the physical limitations of UAS operators, private property rights, and low altitude airspace navigation. The process of UAS integration requires multiple steps; identifying economically viable uses for sUAS, identifying where sUAS may be operated without constraint, identifying where sUAS may be operated with mitigated constraint, and identifying methods to overcome the technical and physical limitations to manned operations of unmanned craft in order to ameliorate any constraints to flight beyond line-of-sight. Several regulations and initiatives have been proposed that attempt to address these issues such as the miniaturization of technologies such as Automatic Dependent Surveillance-Broadcast (ADS-B) to enhance anti-collision measures, the rollout of the Low Altitude Authorization and Notification Capability, and the development of a comprehensive manned Traffic Management for autonomous operations (Federal Aviation Administration, 2020).

THE NATIONAL AIRSPACE SYSTEM AND UNMANNED AIRCRAFT SYSTEMS

In order to understand how UAS integration may impact the National Airspace System, one must first examine the Airspace System itself. As the agency responsible for administering UAS policy and implementing the integration into the National Airspace System of the United States of America, The Federal Aviation Administration has developed a series of regulations governing UAS usage. Within the frameworks established under both FAR part 107 and section 336, UAS may be operated by private citizens within the United States. These licensure systems and their relationship with geographic airspace is explored in the following section.

Controlled Airspace Classes of the National Airspace System

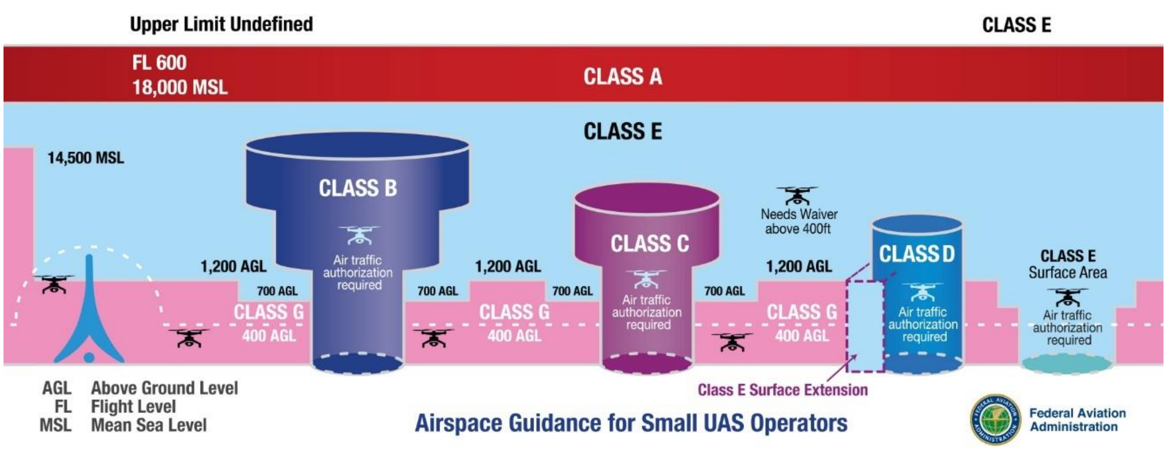


Figure 1: UAS Airspace Diagram (FAA, 2018)

Due to the unique nature of airspace as a 3-dimensional medium with regard to Geographic Information Systems, mapping and describing the structure of airspace presents unique challenges to typical topological cartography. Within the National Airspace System of the United States, airspace is divided into 6 separate classes, each with their own rules and regulations regarding their traversal. As the most hazardous phases of fixed-wing manned flight are take-off and landing, much of the way airspace is classified revolves around the location and traffic demands of airports located throughout the United States.

Class A Airspace

Class A Airspace exists above 18,000 feet and extends to 60,000 feet. This Airspace class is primarily used by commercial jet aircraft and military flights, inaccessible without clearance by General Aviation, including Fixed Wing aircraft. Flying under Visual Flight Rules is prohibited within Class A Airspace.

Class B Airspace

Class B is established around major airports with high traffic demand, within 30 miles of each Class B Airport exists a 30 nautical mile radius known as the Mode-C Veil, wherein all operating aircraft must operate using a specific type of transponder that transmits altitude and location data to the local Air Traffic Control Authority. Class B Airspace begins at the surface and extends upward to 10,000 feet. Class B airspaces are often multitiered, expanding outward from the center as altitude increases, resembling a shape commonly known as the “upside-down wedding cake” (Figure 1). Explicit clearance from the controlling airspace authority is necessary to operate within Class B in order to safely separate the high amount of traffic.

Class C Airspace

Class C airspace is similar in restriction to Class B airports albeit with smaller radii and at airports that accommodate less traffic on average than most Class B airports accompanying a major metropolitan area or international airport. Class C is also a multi-tiered airspace, wherein the most proximate radius extends to 5 miles encompassing altitudes between the surface and 1200 feet, and a wider radius of 10 miles extending from 1200 feet to 4000 feet. Aircraft operating within this airspace must maintain radio contact with Air Traffic Control at all times, as well as prior to entering and exiting the airspace.

Class D Airspace

Class D surrounds even smaller towered airports, extending to a single variable radius from the runway center point, stretching from the surface to an altitude of 2500 feet. This type of airspace needs to be ascertained through the reading and understanding of FAA sectional charts, as each Class D airspace is unique to its accompanying airport.

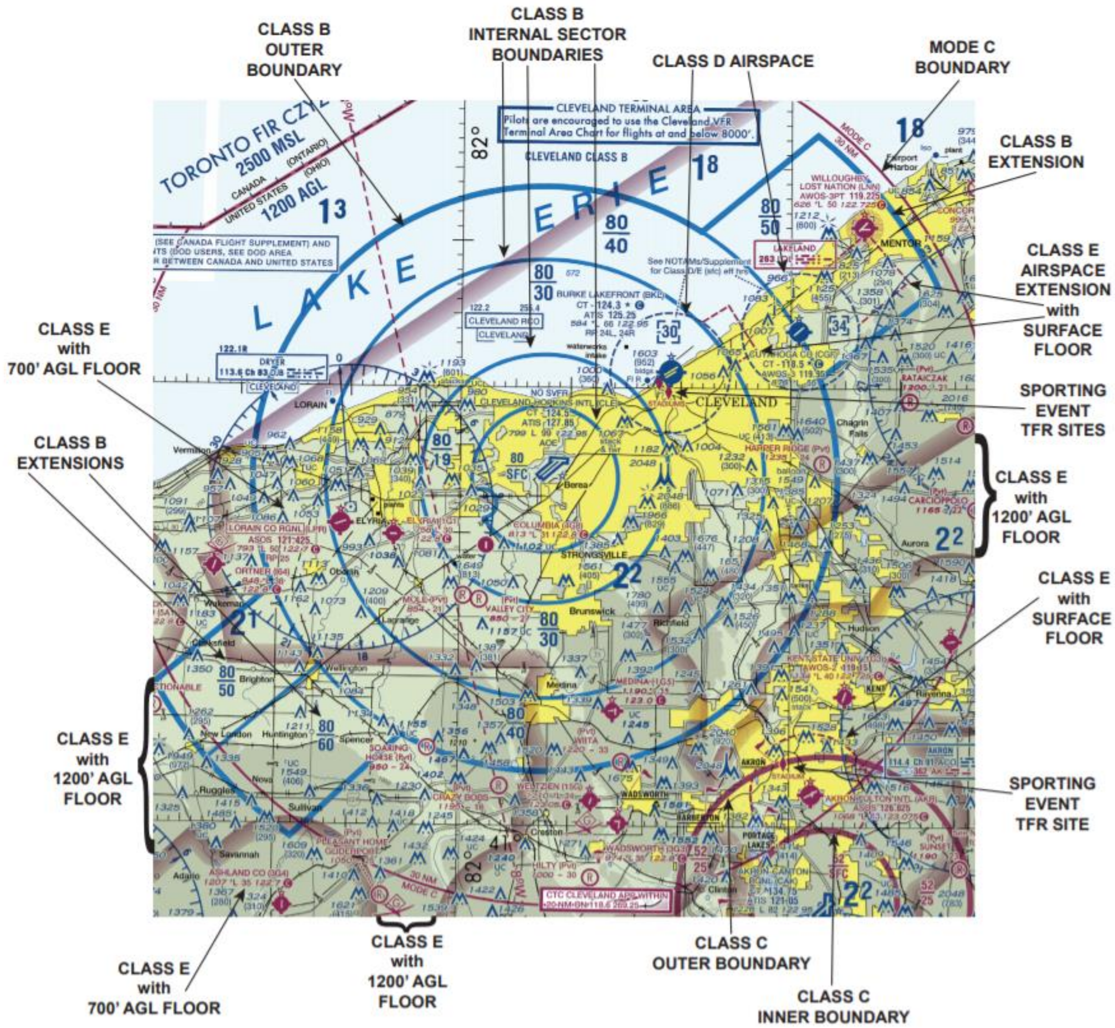
Class E Airspace

Class E airspace is a particularly sensitive and difficult to discern class of airspace surrounding airport approach and departure paths, as well as federal airways. Analysis and identification of these routes requires both FAA Terminal and Sectional Charts in order to determine the altitudes, angles, and slopes of these aeronautical pathways. As it currently stands, all federal airways exist above the legal UAS operating limit of 400 feet

AGL, so currently do not pose a limitation for UAS operations, although approach and departure routes often extend beyond the airspace veil of an airport and often accommodate low-flying aircraft. This particular subset of airspace encompassing low altitude flight is classified as Class E2 Airspace and must be discerned from the remainder of Class E airspace for UAS purposes (Morris, 2019).

Class G Airspace

Class G airspace consists of uncontrolled airspace wherein UAS may freely operate to an altitude of 400 feet AGL. Class G is airspace where UAS may operate with relative freedom, without the required need for obtaining authorization from a controlling airspace authority prior to flight. A large number of airports still exist within this airspace, so it is critical for UAS pilots to maintain separation from flights approaching and departing these airports.



Excerpt from Detroit Sectional Chart

Figure 2:Sample of an FAA Sectional Chart (FAA, 2021)

FAA UAS Licensure System

When examining issues of legal liability and the assurance of responsible use of Unmanned Aircraft Systems, once must inspect the standards with which Unmanned Aircraft Systems Pilots are licensed and held to account. Due to acts of legislation, both passed and proposed, Congress has pushed for the FAA to adapt and accommodate the ever-evolving challenges posed by UAS and their usage. Due to the high rate of change in the regulatory framework, the licensure and operating guidelines have shifted as late as 2019 with the enactment of the FAA Reauthorization Act of 2018. Previously, pilots operating within controlled airspace were to undergo a lengthy application process for filing a UAS flight plan, however this has been streamlined through the implementation of the Low Altitude Authorization and Notification Capability, an automated system for seeking UAS authorization that notifies the relevant controlling authority of an intended flight plan and offering near real-time authorization (Federal Aviation Administration, 2020). LAANC is currently available at 400 Air Traffic Facilities covering over 600 Airports.

Recreational Operation

Previously a tier of licensure created through the FAA Modernization and Reform Act of 2012, known as FAA FAR part 336, allowed recreational users to operate their UAS within Class G airspace within 400 feet of the surface. FAA Part 336 was commonly known as the ‘model airplane’ rule in that it governed the use of aircraft used by hobbyists, including model airplanes and helicopters, from which the early quadcopter UAS have been derived. This rule required that pilots must register their drone with the FAA, affix the registration number to their drone with a clear label, and operate their drone within visual line-of-sight at all times. Rule 336 only allowed UAS to be operated for hobbyist and private purposes only and precluded the use of UAS for commercial purposes. UAS operators flying under Part 336 were required to notify the Air Traffic Control authority when flying within 5 miles of an airport. In May 2019, Part 336 was repealed when the FAA Reauthorization Act was put into effect, limiting the use of recreational UAS within controlled Airspace to specific fixed sites (Federal Aviation Administration 2019). Alongside the repeal of Part 336 came a requirement for all recreational pilots to pass an aeronautical knowledge test and to provide proof of completion upon request (Federal Aviation Administration, 2019). Currently, guidelines are being developed to accommodate recreational pilots within the Low Altitude Authorization and Notification Capability system, however these are not currently available as of May 2020.

Commercial Operation

Figure 3: Template of Part 107 Remote Pilot Certificate (Drone Pilot Ground School, 2020)

In response to legislative demand in the proposed Commercial UAS Act of 2015, the Federal Aviation Administration developed guidelines regarding the use of UAS for businesses and commercial interests. The result of these efforts, FAA FAR part 107, was published and put into effect in July 2016. This regulation also puts in place a framework for remote pilot licensure, requiring that a pilot receive a sufficient score on a written exam in an approved FAA testing center. This exam requires knowledge of safe UAS operating procedures, as well as the ability to read and understand FAA aeronautical charts in order to understand airspace classes as well as FAA cartographic symbology. In contrast to part 336, part 107 dictates the guidelines for operating UAS for commercial purposes. While designed to accommodate commercial uses, remote pilots may also fly recreationally under part 107. More permissive than its model airplane counterpart, part 107 established guidelines for the creation of UAS flight crews, which may include the remote pilot in command, a UAS operator, and a number of visual observers. Under these regulations, visual line-of-sight must be maintained, however may be extended using visual observers who must be in radio contact with the remote pilot in command and the UAS control operator (Federal Aviation Administration, 2016). Part of the material covered for part 107 licensure details the different types of airspace, and the ability to read an FAA sectional chart, this leads to a greater understanding of the National Airspace System by the average UAS user, while simultaneously allowing for remote pilots to contact air traffic control to request waivers using the correct terminology. Part 107 license holders are eligible to register their flight plans via LAANC for certain facilities, allowing for near instant flight plan authorization (Federal Aviation Administration, 2020).

Waiver System

Currently, a part 107 pilot may operate within controlled airspace if they submit a waiver to the responsible controlling entity for the airspace in question. When operating within controlled airspace, the UAS pilot must be in radio contact with the controlling regional tower and tuned into the UNICOM frequency in order to determine if there are any manned aircraft within the area. Operating within these regions requires justification and approval from the regional controller, who must sign off on the flight plan put forth by the Remote Pilot in Command. Once approved, the Remote Pilot in Command receives a document known as a Certificate of Authorization, shorthand COA, that allows them to operate within the airspace in question and mandates that they must strictly adhere to the coordinates and restrictions approved by the controller. Attached to the Certificate of Authorization is a mitigations form, used by the pilot to provide any form of potential mitigation that they may undertake to maximize safety and minimize risk. These mitigating actions may be altitude restrictions and equipment used by the remote aircraft crew to determine any air traffic in the area, such as radios tuned into the local UNICOM Frequency.

Range

Currently both forms of UAS licensure limit Remote pilots to flying their drones within the direct line-of-sight of their remote crew, however part 107 and rule 333 differ in their limitations in that the part 107 may have a member of their crew act as a Visual Observer. Through the addition of a Visual Observer, Remote Operators may extend their range beyond that of a singular person by allowing additional crew members to supplement the range of the UAS through their own line-of-sight, so long as they remain within constant radio contact with the Remote Pilot in Command. The Remote Pilot in command does not necessarily need to be the same individual controlling the aircraft, however whoever is controlling the UAS must be under the direct guidance of the remote pilot in command.

Objective

The spatial phenomenon under investigation will be the structure of the National Airspace System in relation to the physical and human geography that lay underneath the superimposed airspace classes. Several observations and inferences may be made from this cross-referencing, notably determining what potential uses of existing low altitude corridors may be leveraged to accommodate UAS flight. The National Airspace System of the United States has been developed over decades of aviation history, culminating in the most heavily traversed airspace in the world. Crafted through years of trial and error, aided by sequential waves of technological innovation, the National Airspace System is a result of constant adaptation. Generated through an exodus from literal physical ground markers for early airmail, rudimentary radio beacons, omnidirectional range-finding equipment, to modern GPS navigation, The National Airspace System features several generations of aviation innovations simultaneously. As the NAS has been able to accommodate the integration of such technological leaps and bounds, so too must it rise to the challenge of integrating unmanned Aircraft operations.

CHAPTER TWO: LITERATURE REVIEW

There are several factors that affect the status of UAS integration into the National Airspace System. Looking through a regulatory perspective, FAA Airspace Regulations place strict limitations on what UAS may and may not be used for. Through a user's perspective, one must look at where and how UAS may be leveraged in order to utilize them for their maximum potential. This Literature Review will first examine the potential benefits UAS integration may bring, and secondly will review the potential risks posed UAS to average citizens. Thirdly, a list of potential alternatives will be examined to determine how some of the risks associated with the aforementioned activities may be mitigated, in order to reap the most benefits from employing UAS, while preventing hazards to manned aviation, other UAS, and bystanders.

The impact of full UAS integration is staggeringly monumental in that UAS would act as a physical manifestation of the digital world, assuming corporeal form in the autonomous nature of swarming machines, with their navigation procedures dictated by decision making algorithms or perhaps even an omniscient artificial intelligence guiding their coalescing maneuvers. In a metaphor, they are akin to an electronic hive of bees, when handled correctly, able to be harvested for the honey of high-speed commerce, aerial imagery, and geographic information that may be utilized everywhere from agriculture to emergency services. If handled without the proper protections, they potentially bring the dystopian sting of terror, unwarranted surveillance, and an all-encompassing virtual panopticon. One may ask how these advantages and risks may be mitigated in order to reap the benefits, without reaping the whirlwind. The following section details a number of works that concern the possible advantages and disadvantages of UAS integration, the state of the current regulations, as well as detailing alternatives that seek to mitigate some of the challenges facing current integration efforts.

Potential Benefits of UAS Integration

Unmanned Aerial Systems may provide an easier means of conducting activities previously only capable through the piloting of manned aircraft. Due to their smaller size, lower cost, lower weight, and lack of a need for onboard crew safety systems required by manned aircraft, UAS may be used in scenarios that would previously have been impractical for manned aircraft. The smaller size of an unmanned system also allows for a greater flexibility in applications, not requiring the specialized facilities required of manned aircraft (i.e., Airports, Heliports) for launch and recovery purposes. There are a number of applications where the nature of UAS flight characteristics are particularly advantageous over traditional manned aircraft. These may be situations where operating a manned aircraft would be potentially hazardous to the flight crew, prove to be dangerous to individuals on the ground, or would be prohibitively expensive to accomplish when comparing the prices of UAS flight against those of collecting data using fixed wing aircraft for the same operation.

Comparison against other Data Collection Methods

UAS have the potential to gather high temporality, high spatial resolution geospatial data. There are distinct advantages to using UAS in geospatial research in that they are cheaper than fixed wing manned aerial imagery collection operations and have the potential to offer spatial resolutions as low as 1cm when outfitted with commercially available imaging equipment such as a DSLR. Flying at an altitude of 75m, wildlife researchers in 2010 were able to collect imagery with a spatial resolution of 1cm, accurate enough to ascertain the size and length of wildlife specimens they were observing (Watts, 2010). This is a much higher level of spatial resolution compared to commercially available satellite imagery data provided by Digital Globe's Worldview 3 platform, offering spatial resolutions of around 30cm (Grubesic et al., 2018).

Customization

Consumer drone firms have latched onto many of these ideas, marketing professional versions of their consumer products aimed at collecting data for commercial interests, providing sensors such as thermal and infrared, not available on base-level consumer products. Due to their lower operating costs and ease of use, there exists a high degree of specialization for UAS to suit its intended purpose with the outfitting of sensor packages and different thrust source configurations dependent upon the optimal maneuverability for the drone's intended use (Canis, 2015).

Applications of UAS

The advent of UAS ubiquity will revolutionize the ways in which academics and laymen alike think about and access geospatial data. Where web-hosted imagery has established the popularity and effectiveness of remotely sensed aerial and satellite imagery, crowd-sourced UAS collected data may prove to provide an incredibly high degree of temporality for the sake of spatiotemporal analysis. The utilization of UAS lowers the overall costs of doing geospatial research, through increased market competition leading to lower prices of not just aerial platforms, but of sensors and data recording systems as well. UAS flight has the potential to increase popular familiarity with Geographic Information Systems as amateur UAS pilots seeks to use the data collected through their flights beyond merely observation, entertainment, and enjoyment of the flight experience itself, while in turn aiding professional geographers through the provision of a data collection platform that was previously unavailable for smaller scale projects.

Agriculture

Remotely sensed aerial and satellite imagery have been leveraged in crop analysis for several years now. In turn, Inroads have been made with regard to the deployment of UAS within the realm of precision agriculture for similar uses. Using UAS mounted multispectral sensors, water levels, insect damage, and soil composition may be quickly ascertained and inexpensively deployed compared to traditional fixed wing cropland aerial analysis conducted by the USDA. Such systems would allow for a high temporal resolution and lower cost of operation over time in comparison to such traditional methods and would allow for new economic opportunities for industry to provide a range of data driven services for farmers (Zhang et al., 2012). Using high temporal and spatial resolution data it would allow farmers to spot-treat issues before they spread, leading to lower use of fertilizer, pesticides, water, and general waste of resources while using conventional farming methods, thus reducing the environmental impact of agricultural operations (Hayhurst et al., 2016).

Infrastructure Assessment

There are already a number of instances where utility companies and railways have implemented the use of UAS for inspection of their hard assets over long distances (Canis, 2015). Commercially ready UAS have been successfully tested as a means of collecting point cloud data for High voltage transmission lines (Jozkow, 2015). Substituting human workers on scaffolding and climbing equipment with UAS for inspections could lower risk for utility employees (Canis, 2015). Using onboard multispectral sensors to augment optical video data, a wide array of phenomenon may be observed over a utility network that would otherwise take a substantial amount of time for ground-based line crew to detect or would prove to be hazardous for manned fixed or rotary-wing aircraft to collect. UAS mounted with thermal sensors and aerosol detectors have successfully been utilized in the assessment of leaks in pipes, tanks, and pipelines (Eninger, 2015).

Urban Planning and Management

UAS alter the vantage point of the social researcher. When conducting surveys and analysis of urban areas, many are only assessed from public roads and city streets, far removed from the interiors of city blocks where crime, disrepair, and signs physical disorder may go unnoticed. Semi-public spaces such as courtyards, stairwells, backyards, and alleyways are pulled into view when observed from above (Choi-Fitzpatrick, 2014). With high spatial resolutions, UAS are able to capture imagery of signs of physical disorder such as used syringes and litter, while their flight characteristics remove them from street level, allowing for observations of residents from afar. This allows for observations to be made of how residents interact with their environment, while allowing researchers to surreptitiously assess conditions within a neighborhood away from danger (Grubesic et al., 2018).

Law Enforcement

Integrating drones into the arsenals of public safety officials presents all new capabilities previously unavailable to first responders. Within law enforcement, Unmanned Aircraft Systems can provide a bird’s-eye view of a situation, allowing for a greater degree of situational awareness with regard to the location of an officer, as well as providing a second method of video recording in addition to that of an officer carried body cam. Optical and GPS location data may be logged and recorded in order to reconstruct a scene where an incident may have taken place. UAS may be used to provide situational awareness in high-risk situations (Canis, 2016). Counter to the use of UAS flights by law enforcement officials themselves, is the operation of UAS by civil liberties groups to ensure accountability by representatives of the state (i.e., law enforcement officers) during events of civil disorder (Choi-Fitzpatrick,2014).

Firefighting

Firefighting may benefit from the advent of Unmanned Aircraft Systems in numerous ways, allowing first responders to determine if people are trapped within an area of a structure immediately inaccessible to firefighters. Due to the expendable nature of UAS, drones may go places where human beings may not, searching floors where stairwells may have collapsed or in inaccessible ravines or canyons that would otherwise take hours to search on foot, saving precious search and rescue time. Thermal and Lidar data may be collected to ascertain structural conditions of a flaming building, providing an accurate 3-dimensional map of a structure allowing for well-informed tactical decision making in incident response (Persie, Oostdijk, Sijl, & Edgardh, 2012). UAS have the potential to monitor forests for fire development, and aid in directing proper responses while providing a valuable communication relay and imaging resource (Yfantis, 2017).

Medical Assistance and Response

The unique flight capabilities of UAS have been leveraged in medical emergencies and public health scenarios, sometimes carrying equipment such as Automatic External Defibrillator (AED) Devices (Schootman et al., 2016). In addition to medical emergencies, UAS have also been used in test scenarios to ensure safety compliance when ensuring personnel wear proper Personal Protective Equipment (PPE) (Eninger, 2015). In addition to delivering lifesaving medical equipment, UAS have the potential to be leveraged in lifeguarding duties at popular swimming destinations, possibly deploying self-inflating buoys to aid individuals struggling to swim (Claesson, 2018). In light of the COVID-19 Pandemic of 2020, UAS have been used for aiding public health officials in both Spain and China, relaying messages for public health awareness, as well as for delivering critical parcels of food and medicine (Yaacoub, Noura, Salman, & Chehab, 2020).

Natural and Man-made Disaster Response

Perhaps one of the most important aspects of UAS for emergency and disaster response is their ability to travel where humans cannot, in ways humans cannot, in comparison to traditional rotary or fixed wing aircraft. In response to the Fukushima Daiichi Nuclear

Disaster of 2011 in Japan, Autonomous Unmanned Aircraft Systems have proven effective at taking readings in areas affected by radiological contamination, able to cover large amounts of territory and the ability to collect data for mapping incident response and cleanup operations by the Japan Atomic Energy Agency (JAEA) (Torii & Sanada, 2015). In a separate instance following this release of radiological material, UAS were utilized in analyzing topsoil, with the ability to linger longer in a contaminated area than a manned aircraft, without putting the flight crew immediately in harm's way. In another study in the wake of the same incident, UAS were leveraged to determine contamination at Yamakiya Junior High school in Fukushima Prefecture Japan (Martin et al., 2016).

Risks of UAS Ubiquity

The push for inclusion of Unmanned Systems into the National Airspace System has many positive merits, but full integration also potentially possesses many unforeseen negative aspects. Despite the best efforts of regulatory agencies and institutions, there is the potential to cause harm by malicious non-state actors, the cost-threshold for access to unmanned systems being much lower than conventional aircraft, as well as the degree of anonymity provided by the ability to operate remotely. High profile incidents involving consumer drones include the use of commercial UAS in the attempted assassination of Venezuelan politician Nicolás Maduro (BBC, 2018) as well as in combat by the Islamic State (BBC, 2017). The speed and maneuverability of these systems will pose new and difficult challenges to security forces as they attempt to counter malevolent usage of UAS against potential civilian and government targets. The nature of UAS flight bypasses traditional terrestrial means of securing and area, such as walls, gates, and sentries

(Yakabe, 2015). Solutions currently being developed to counter these threats include research into Radio Frequency (RF) and Laser Anti-Aircraft Systems, in addition to conventional means including gunnery and expensive anti-aircraft munitions (Herrera, Dechant, & Green, 2017). There have already been a number of incidences of UAS being implemented in planned attacks, thankfully thwarted by the FBI, most notably in the Semlali and Ferdaus cases, wherein the maneuverability of commercial UAS was to be exploited in delivering explosives to a target (Yakabe, 2015). Even barriers surrounding the most critical of National Security assets are susceptible to penetration, highlighted by an incident in 2016 where a National Geospatial-Intelligence Agency employee lost control of the UAS they were operating, ditching their aircraft on the White House Lawn (Shear & Schmidt, 2015). One alleged approach used by the government of the Russian Federation has been the potential spoofing of GPS signals in order to provide inaccurate locations, triggering built-in auto-land mechanisms or throwing off aerial navigation, thwarting consumer drones that may be attempting to surveil Russian military assets or VIPs (NBC, 2019).

Lack of Effective Enforcement Mechanisms

As airspace regulations were initially designed to ensure the proper operation of fixed wing passenger aircraft, regulations have not been drafted to accommodate the lower fight levels utilized by consumer and commercial UAS(s). Important issues of personal sovereignty come into play regarding property rights and control of airspace in the immediate area above one’s abode. New standards with regard to legal liability for damages need to be determined regarding incidents occurring between landowners and

UAS operators. Homeowners may claim an invasion of privacy due to the presence of drones above their property. Due to the lack off an effective immediate enforcement mechanism at the federal level, aside from revocation of operating licensure, there is not a legal authority tasked with deterring UAS being used with criminal intent from being apprehended in the act. This responsibility has often fallen to state and local law enforcement officials (Yakabe, 2015). A number of States and cities have passed ordinances regarding the use of UAS within their city limits in order to prevent harassment of their citizens from the ill-use of UAS. Deterring and defeating malevolent use of UAS will continue to be a major challenge to law enforcement and National Security officials, potentially requiring entire new suites of electronic weaponry to detect and defeat wayward UAS. Potential methods of defeating UAS include kinetic means, including ballistic and energy-based weaponry, employing physical barriers, as well as electronic methods of signal interference (i.e., jamming) and attempting to wrest control of an inbound from a wayward operator (Herrera,2017).

Aerial Collision

One of the primary concerns with regard to full integration of UAS into the National Airspace system is the potential hazard that may be caused by UAS to manned passenger aircraft. The current regulations in place reflect this desire by preventing Drones from traversing the same classes of navigable airspace as manned aircraft and precluding UAS from being used around major airports lessens the chance of aerial collision, however this does not necessarily deter bad actors. A number of incidents involving UAS and helicopters operating at low altitude have been recorded, both in Hawaii and South

Carolina, with one incident considered a complete hull loss (Wallace, 2018). Between 2015 and 2018, 8 separate mid-air collisions involving a sUAS and a manned aircraft have taken place within the United States (Wallace, 2018, p.5).

Surveillance by state

As drones begin to undertake delivery tasks within residential areas, concerns regarding civil liberties and privacy will arise. The constant presence of high-definition cameras within the air raises concerns regarding the sovereignty of one's airspace over occupied land. In stark contrast to the potential malicious use of drones by non-state actors, through use by government entities, there exists the potential for the development of an unprecedented electronic panopticon never seen outside of works of dystopian fiction. The shift in perspective from a street-level view to an aerial one opens many areas that were once semi-private to potential surveillance by public officials (Grubesic et al., 2018). In an optimistic light, the presence of millions of aerial image sensors could potentially be leveraged to quickly respond to incidents for crisis assessment and emergency response purposes. An opposing viewpoint, however, may argue that the use of such a wide array of sensors may be abused by government or corporate entities to monitor a population that does not consent to ubiquitous video surveillance. UAS are currently employed in Mexico City supporting what has been described as "the world's most ambitious urban security program" wherein military-grade Command, Control, Communications, Computers, Intelligence, Surveillance, Target Acquisition, and Reconnaissance (C4ISTAR) systems have been adapted for civilian monitoring and control, branded as Command, Control, Communications, Computing, Intelligence, Integration and Investigation (C4I4) (Mushkin, 2016). This point lends itself to a discussion regarding the personal sovereignty of United States Citizens with regard to airspace directly above their domiciles, currently restricted to the easement directly around their dwelling structure. Current federal legislation, passed and proposed, does not address the use of drones above private property, either by private or public entities, however several states have passed laws requiring search warrants for the use of UAS by law enforcement and public safety officials (Yakabe, 2015). For purposes of surveillance by the state, legal precedent has been set in the case of *Kyllo v. United States*, establishing that sensor technologies such as thermal and infrared may not be used in surveillance, and such surveillance must be undertaken with the unaided eye (Ison, Terwilliger, & Vincenzi, 2014). New guidelines and definitions of personal property and airspace will be argued upon and redefined as issues arise through the development of legislation, as well as court cases that will inevitably occur as individuals push the boundaries of UAS usage, as well as their technological limits.

For National Security purposes, mass collections from a UAS panopticon would provide unprecedented real-time surveillance capabilities. Large privacy concerns surround the hosting and storage of such vast swaths of sensor data. In the hands of private corporations, targeted marketing could be aimed directly at consumers based upon optical data from passing drones. Privacy groups may demand a short temporal window for the storage and handling of collected data, while intelligence agencies may seek to preserve and utilize such data in investigations and counter-intelligence actions using facial recognition technology (Choi-Fitzpatrick, 2015). Questions regarding who controls such data, the allowance of private data collection, and the purposes for which UAS capabilities may be used by and among the general public need to be answered by the legislative branch as well as executive regulatory bodies, namely the Federal Aviation Administration.

Surveillance by other persons

Beyond the inherent worries of surveillance by the government in a criminal investigation or of a corporation leveraging courier UAS data to surveil potential customers for marketing data, is the risk of coming under surveillance by other private individuals. As FAA policy does not clearly delineate where private property and public airspace begin, enforcement of UAS policy has fallen to state and local officials, and often to sworn law enforcement officers to take care of issues regarding nuisance UAS. Regarding violations of the law, UAS are handled as extensions of the operator. In the State of California, legal precedents to California Penal Code 647(i) regards unwanted surveillance by UAS to be equivalent to that of the individual operating the UAS and is prosecutable (Choi-Fitzpatrick, 2015). Operators apprehended for the ill-use of UAS may be charged criminally with local and state laws for reckless endangerment (Yakabe, 2015).

Airspace Sovereignty

Major questions need to be addressed with regard to how Low Altitude airspace may be used over private property. As it currently stands, controlled airspace within the Nation Airspace System does not start until above 500 feet AGL, however civilian UAS are limited to altitudes under 400 AGL. Constitutionally, the fourth Amendment protects individuals from unlawful search and seizure by government officials, however, does not necessarily provide protections from aerial surveillance. *United States v. Causby* from 1946, wherein a farmer's livestock were affected by the operations of low-flying aircraft from a nearby airfield, sets precedent for the ownership of the immediate reaches of airspace surrounding one's inhabited property potentially protecting the homeowner from overflying UAS surveillance (Atkins, 2014). In contrast to *Causby,* in the legal case of *Florida v. Riley,* a police helicopter operating at 400 feet above a residence was utilized in detecting marijuana in a private greenhouse, and did not constitute an unlawful search (Ison, Terwilliger, & Vincenzi, 2014).

Alternatives and Mitigations

Long Range Flight and Transportation Network

How would commercial UAS be navigated beyond a pilot's line-of-sight? The current regulations prohibit such maneuvering, however full integration into the NAS would not include anything less. Services such as high-speed delivery would require such a capability, or they would not be any more economically viable than a delivery driver. Long distance travel requiring line-of-sight would entail a pilot traveling in a ground-based vehicle, which may be sufficient for utility work and data collection but would not unlock the full potential for UAS to deliver goods. How could a UAS traverse these longer distances safely and efficiently? How could Drone operators maintain a sense and avoid capability while undertaking these operations? The solutions to these questions are not merely engineering challenges, but geographic challenges, requiring an analysis of the geographic layout of the National Airspace System, legal limitations of private airspace sovereignty, and issues regarding spatial navigation in order to mitigate any risks with UAS flight that may impact manned aviation, other unmanned craft, and individuals on the ground.

Technical Challenges

Perhaps the largest technical hurdle to full UAS integration is the lack of a comprehensive traffic control mechanism for unmanned traffic. Both the FAA and NASA have dedicated resources and tasked researchers to develop a system for Unmanned Traffic Management (UTM) that will handle low-flying civilian drones (Canis, 2016). As the number of UAS flights is projected to outstripped manned aviation flights in the coming future, such a system would need to operate autonomously in order to reduce the potential for human operator error, while allowing a higher threshold of unmanned aircraft to operate within the same airspace. Using a multitude of means for positional reckoning, an autonomous control system would be able to synthesize vast quantities of information coming from different sources (GPS, radio beacons and cellular networks) much more quickly than human beings would be able to process, while also calculating for communications latency across the network (Grose, 2016). Currently technologies such as Automatic Dependent Surveillance–Broadcast (ADS-B) are being miniaturized from their use in commercial airliners to be used for low altitude UAS to increase their operational safety (Canis, 2015). The implementation of such systems would allow UAS to step beyond the current constraints imposed by the FAA regarding line-of-sight operation, while simultaneously providing a framework for sensing and avoiding potential aerial collisions between flights, both manned and unmanned. This key component lays the cornerstone upon which effective full UAS integration will be built in the United States.

Sense and Avoid.

Despite legislative advances in licensure, numerous challenges exist in bringing Unmanned Aircraft Systems to their full potential. The requirement for sense and avoid capabilities presents a major technical challenge for long range UAS operation, as onboard cameras do not provide a satisfactory level of capability. The implementation of onboard Traffic and Collison Avoidance Systems (TCAS) could potentially flag UAS to other aircraft operating within the same airspace sector, however their implementation on UAS has been excluded by the FAA (Fern, Kenny, Shively, & Johnson, 2012). The weight limit of 55 lbs. and relatively small size of Unmanned Aircraft Systems covered by part 107 limits the types of sensors that may be onboard in order to provide operators with greater levels of information than may be available through the onboard camera in overcoming this technical hurdle. A potential technical solution would be the inclusion of a controller station-based Cockpit Situation Display (CSD) which may increase situational awareness for UAS pilots through depicting their UAS's relative position to other aircraft for flight separation purposes (Fern, Kenny, Shively, & Johnson, 2012). As mandated through FAA regulations drones are required to integrate a sense and avoid capability for navigation within the National Airspace System. Cameras onboard commercially available UAS do not currently meet the threshold for a sense and avoid technology.

Low Altitude Traffic Management

Identifying where and how different flight rules apply to UAS is necessary to avoid navigational misunderstandings within a congested airspace system. Unmanned Aircraft Systems currently rely on a remote human operator to serve as a pilot, linked to the UAS via a radio connection. As airspace becomes more congested, the physical limitations of a human pilot may come into play regarding sense and avoid capabilities onboard an unmanned aircraft system (Grose, 2016). Long-range travel by unmanned aircraft systems will be hampered by the line-of-sight requirement and would require increasingly complex communication methods in order to link large numbers of visual observers with remote pilots in command. Automation may provide a solution to this problem (Atkins, 2014). Automated Traffic Management Systems that would leverage TCAS data may be implemented to control the flow of UAS air traffic over long distances within drone flight corridors, wherein remote pilots would be required to render control of their UAS over to an artificial intelligence system that would be able to manage a UAS's flight path, recharging patterns, and trajectory in order to avoid collisions and ensure and optimal time management using linear programming methods (Narayan et al., 2012).

Due to the limitations of human pilots, Unmanned Traffic Management would seek to limit human error in flight planning and operation. Leveraging sensor data from all active drones would provide an incredibly detailed account of the airspace network, allowing optimal situational awareness to air traffic controllers as well as automated air traffic control systems (Federal Aviation Administration, 2020). The implementation of unmanned Traffic Control would allow for Unmanned Aircraft Systems to reach beyond their current range limitations and capabilities, removing human error from the immediate operational aspect of UAS flight. The Sensor data from such a vast array of drones could prove incredibly valuable, and potent when leveraged by differing entities. As air traffic management includes a higher degree of automation, the potential for "Management by Exception" may arise, wherein Human remote pilots may step in and take control of a UAS facing an in-flight emergency or risk. Such responses taken by the Remote Pilot in Command may be recorded in order to optimize the automated handling behavior of a wayward UAS should a similar scenario arise (Narayan et al., 2012). This traffic management program would require a high degree of API and Hardware standardization from drone manufacturers to ensure compliance with automated traffic management inputs as well as the ability to broadcast information to the traffic management system regarding course, bearing, and battery data to ensure collision avoidance as well as optimal route planning. The capabilities of dedicated air traffic management servers will far outpace the capabilities of human analysts to route and track vast numbers of flights within a relatively small air corridor.

Common communication backbone

The development of automated pathways for drone navigation is reliant upon a standardized method of communication between centralized control and the myriad of drones traversing the airspace system. All systems within this network would require matching interfaces to ensure that all directions and controls sent from the main control would be correctly interpreted by the individual UAS System. The development of such a system would require an immense amount of cooperation by both industry and government to ensure that all parties involved with automated UAS navigation would be able to interpret and carry out instructions. The symphonic movement would need to be encrypted and protected in order to prevent malicious actors. Projects being undertaken by the Defense Advanced Research Projects Agency have generated a theoretical communication and control network for unmanned traffic while preventing rogue actors from hacking such systems (Grose, 2016).

Low Altitude Airspace Network

Tangential to the technical challenge of developing a traffic control mechanism, is the geospatial challenge of finding airspace where UAS may operate with minimal interference with manned air traffic as well as bystanders on the ground. The potential development of a proverbial "Class U" airspace would seek to identify particular land use areas that would allow for safe UAS operation within a geofenced area, leashing a launched UAS within the geographic area put forth in a set flight plan. In order to develop such an airspace class, the physical terrain and property underlying a segment of class G airspace would need to be evaluated for its use as "Class U" airspace (Atkins, 2014).

Drone transit corridors and designated transit airspace will become a necessity in order to minimize the perception of a persistent electro-optical panopticon. One particular method of minimizing intrusion within residential areas is the provision of airspace congruent with utility rights-of-way. In this method, terrestrial infrastructure is already occupying a large amount of space that minimizes much of the utility within the areas directly above.

Several viable UAS pathways may already be available through the leveraging of existing utility infrastructure due to the potential to use UAS for collecting data of Electrical transmission lines and Natural Gas pipelines (Logan, Bland, & Murray, 2011). These Rights of Way as drone corridors lend themselves to consumer drone usage through the sharing of a similar purpose: the effective and efficient distribution of resources to the population across geographic space. Many of these spaces are free of residences and put into easement in some cases to allow for ease of access with regard to utility maintenance (Fairfax County, 2020). A potentially derived usage from the nature of these rights of way, is that they may be used for consumer service distribution with minimal further physical development, thus with minimal interruption to nearby residents, presumably already comfortable with the existing rights of way. Ideal drone corridors would consist of spaces that connect much of the population, where their flight would cause minimal interruption in day-to-day life.

An effective transportation network for low-level drone flight has yet to be established in contrast with the well-developed airway system currently used by fixed wing passenger aircraft. Consumer drone deliveries would pose a unique challenge to low-level traffic control through sheer volume alone. Development of drone airways could pose a potential political challenge, as a combination of potentially hazardous and subjectively unpleasant conditions including noise pollution, air traffic congestion, visual eyesore, as well as the potential for suffering UAS crash damage may lead populations to push back against the development of a UAS corridor through their neighborhoods. Areas previously thought to be private, such as property enclosed by fencing, rooftops, and backyards may be unwantedly observed by passing UAS, redefining personal concepts of privacy on one's own property (Choi-Fitzpatrick, 2016).

A number of domestic utility firms have already turned to UAS as a means of monitoring and collecting data on their networks. Piggybacking on this desire, a mutually beneficial agreement could perhaps be made between drone operators and utility providers wherein UAS pilots may use established utility corridors for transit, in turn providing a benefit to the utility owner by sharing any data collected by UAS traversing their airspace. Commercially ready UAS have been successfully tested as a means of collecting point cloud data for high voltage transmission lines (Jozkow). Substituting human workers on scaffolding and climbing equipment with UAS for inspections could lower risk for utility employees (Canis, 2016). During their collection process, Jozkow et. al. discovered that the quality of their data improved with increased sidelap and endlap of their study area. Perhaps due to their requirement of large areas of open space for their construction and maintenance, as well as their connectivity to the power grid, these lines have the potential to be leveraged for the development of high volume UAS corridors.

As public thoroughfares are already cleared for the traversal of automobiles, they could prove to be well-suited for UAS overflight as well. As UAS are not immediately hampered by ground traffic, they may supplant traditional delivery methods, lowering congestion (Choi, Choi, Briceno, & Mavris, 2019). UAS traversing spaces such as public roads, bridges, and highways could perform a two-fold task of carrying our commerce, while collecting data on the condition of the underlying infrastructure. In addition to providing data regarding physical road networks, they could also provide highly temporally relevant traffic information for commuters and emergency services alike (Logan, Bland, & Murray, 2011). In exchange for permission to fly across public thoroughfares, state governments could perhaps collect the information gathered by drones in order to supplement maintenance and inspection efforts for critical transportation infrastructure, including aging bridges and overpasses. This echoes a strategy presented and discussed by Qin et al. (2018) and Rice et al. (2016, 2018), who adopt a crowdsourcing approach with a benefit of public infrastructure and accessibility inspection. This same permission-for-access relationship may also be beneficial in inspecting similar ground-based rail infrastructure.

Ground based routing

When addressing the need for the utmost spatial accuracy, existing systems are in place that may aid in the positional reckoning of unmanned craft. Legacy systems and navigational beacons previously used by manned aircraft could be leveraged in the low altitude UAS transportation network of the future. Currently these systems allow for pilots of manned aircraft to reckon their position through the transmission of radio waves from a known established geographical location. Ground-based Distance Measuring Equipment (DME) may be upgraded for “passive” distance measuring in order to accommodate battery-powered UAS that may be too weak for onboard “Active” DME systems (Lo et al., 2014). Using these established radio beacons in conjunction with GPS could allow for a hybridized navigational system that would allow a higher-level accuracy when assessing where a UAS may be when beyond line-of-sight in the future.

UAS are currently being used for measuring signal strengths of VHF Omnidirectional Ranges (VOR) in Germany (Schrader et al., 2019).

Recommendations for Future Research

The possibilities that may be unleashed by the full integration of Unmanned Aircraft Systems, not only into the National Airspace System, but society as a whole, are myriad in number. For these possibilities to come to fruition, this duty rests upon the ability of geographers working with geospatial data within geographic information systems to integrate, process, analyze, and utilize the input data of an Unmanned Aircraft System, no matter the application. Through the storing and utilization of this remotely sensed data within a geographic information system, geospatial analysis may be conducted in order to determine the best method of response to a disaster or incident, allowing for the efficient use of time and resources. Unmanned Aircraft Systems, hand in hand with Geographic Information Systems able to process and handle their input data, will only continue to grow in importance as decision makers seek to increase the quality and temporality of their latest data in order to make the most informed choice.

Due to the limitations of human pilots, automated systems would seek to limit human error in flight planning and operation. Leveraging sensor data from all active drones would provide an incredibly detailed account of the airspace network, allowing optimal situational awareness to air traffic controllers as well as automated air traffic control systems. The implementation of unmanned Traffic Control would allow for Unmanned Aircraft Systems to reach beyond their current range limitations and capabilities, removing human error from the immediate operational aspect of UAS flight. The Sensor data from such a vast array of drones could prove incredibly valuable, and potent when leveraged by differing entities. For National Security purposes, mass collections from a UAS panopticon would provide unprecedented real-time surveillance capabilities. Information agencies would be able to aggregate collected data in order to provide a constant survey capability for DHS, USGS, and NASA. The United States Postal Service could regulate the use of low-level airspace for consumer drone deliveries. Large privacy concerns surround the hosting and storage of such a vast swatch of sensor data. In the hands of private corporations, targeted marketing could be aimed directly at consumers based upon optical data from passing drones. Privacy groups may demand a short temporal window for the storage and handling of collected data, while intelligence agencies may seek to preserve and utilize such data in investigations and counter-intelligence actions, the collection of this data achieved through the persistent presence of 'eyes in the sky'. Questions regarding who controls such data, the allowance of private data collection, and the purposes for which UAS capabilities may be used by and among the general public need to be answered by the legislative branch as well as executive regulatory bodies, namely the Federal Aviation Administration.

There are multiple roads that may be traveled down with regard to how UAS may integrate into the lives of the average American citizen, with the differing solutions offering wildly different potential futures dependent upon the methodology and manner in which UAS are utilized, and for what purpose. Along the axis regarding the manner of

UAS utilization, there exists a spectrum lying somewhere between a Libertarian hyper-privatization of 3D space and a potential totalitarian dystopia wherein all developed areas are under constant video surveillance. Along the axis of UAS ubiquity, there lies a difference between forbidding UAS for an abundance of purposes without explicit regulatory permission, and that of a highly permissive system wherein access to airspace is seen as a right or privilege, allowing a wide range of UAS potential to be explored. Who controls the low-level airspace and how it may be used will be a constant battle in the coming years through the courts as well as the legislative bodies of government? Perhaps even more contentious is who controls the flow of UAS collected data, and the rules regarding consent of data collection and particularly serious 4th amendment ramifications with regard to data collected by UAS being used in criminal investigations.

CHAPTER THREE: METHODOLOGY

When examining the potential for UAS integration, one must first examine the limitations put in place by the current system. Identifying areas where UAS may freely operate, areas where UAS face partial restriction (i.e., requiring authorization) and areas where UAS flight is absolutely forbidden. Due to the recent trend of urbanization within the United States wherein a larger share of the population now lives in urban areas as opposed to rural areas, a rough estimate of the population living within the lateral boundaries of controlled airspace will need to be assessed. The identification of low altitude airspace that takes private property concerns and underlying terrain into consideration will aid in the development of an unmanned airspace system that seeks to minimize disruption to both manned air traffic as well as bystanders on the ground.

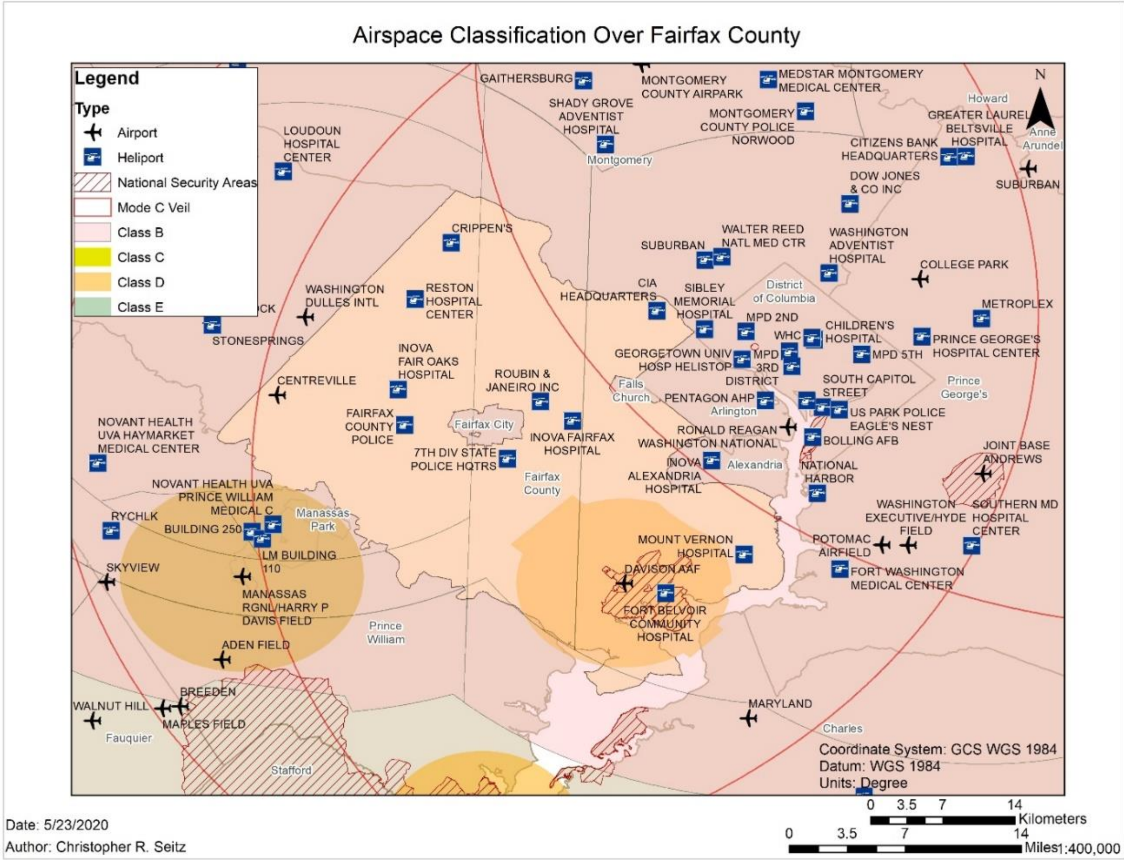


Figure 4: Airspace Classification over Fairfax County

Fairfax County Study Area

In order to examine the efficacy of a hypothetical low altitude UAS network, the study area of Fairfax County has been selected. Located within the Washington DC Metropolitan Area, Fairfax County is the most populous within the State of Virginia, with over 1 million residents and consisting of a mix between rural, suburban, and urban areas (Census, 2019). For the purposes of this study, data from the Fairfax City administrative region was disregarded, due to disparities in data types and attribution. With close proximity to the National Capitol, Fairfax resides within a complicated neighborhood in terms of airspace featuring numerous National Security areas, as well as International, National, and Regional Airports. As it currently stands, the Washington DC area has its own unique airspace classification known as the Washington Special Flight Rules Area (SFRA) wherein 2 radii extend from Ronald Reagan National Airport (DCA). Within 15 miles of DCA, specific authorization is required to operate a UAS, while within 30 miles, UAS may operate while adhering to standard UAS operating procedures. In the hypothetical advent of an automated flight authorization mechanism and ubiquitous UAS for all manner of economic and public safety activities, how might UAS navigate such a complicated airspace?

When examining how the regulatory framework governing UAS would affect the development of traffic networks and protocols, the primary regulation affecting UAS traversal of the study area is FAA FAR Part 107. Under the version of FAA Part 107 as released in 2016, UAS are limited to operating during daylight hours, within 400 feet AGL, within the line-of-sight of the UAS operational team, while also precluded from operating over people as well as over moving vehicles. If the flight operation is to take place within a controlled airspace class, such as the large Class B areas encompassing Fairfax County, a waiver is required from the FAA leveraging the LAANC system. The requirements under this initial version of FAA Part 107 would preclude county-wide operations, not only as a result of the line-of-sight requirement but would also preclude large swaths of underlying geography from navigation, as it would entail the traversal of spaces occupied by persons or moving vehicles.

As a result of changes to the FAA regulations regarding operations over people and moving vehicles, as well as the development of an initial waiver system for Tactical Beyond Visual Line-of-Sight (TBVLOS) operations for first responders with a valid part 91 General Aviation license, there have been regulatory headways into developing procedures and protocols for expanding beyond the limitations set forth when FAA FAR Part 107 was first released in 2016. In addition to these changes, the FAA has also released guidance in March 2021 stipulating protocols for remote identification and identity broadcasting of drones and remote-control stations, to provide greater geospatial situational awareness regarding UAS and their operations in congested airspace. The modified FAA regulations introduced in 2021 would allow for the ability of a Category 4 UAS equipped with remote identification equipment and an FAA Part 21 Airworthiness certificate to take full advantage of a low altitude airspace network, provided that a feasible sense and avoid mechanism could provide a mitigation for the line-of-sight requirement.

Taking these regulatory developments as indicators of a wider trend towards full integration while developing a low altitude airspace network within Fairfax County, a number of suppositions have been made with regard to the legal constraints that govern typical UAS flight under FAR Part 107, and how they would be affected by autonomous flight control. Under such an autonomous system, the control of the aircraft would be deferred to a centralized control system, able to manage high traffic flow as well as supplement its decision-making process leveraging remote identification data broadcast from the participating UAS themselves, as well as Traffic Collision Avoidance System (TCAS) data broadcast from manned air traffic which would take navigational priority over any unmanned aircraft. This ability for situational awareness would mitigate some of the issues regarding current onboard equipment in meeting the sense and avoid requirement for aerial collisions, as well as enhance the waiver granting process, as control over an autonomous system would be granted to the air traffic authority granting the waivers in the first place.

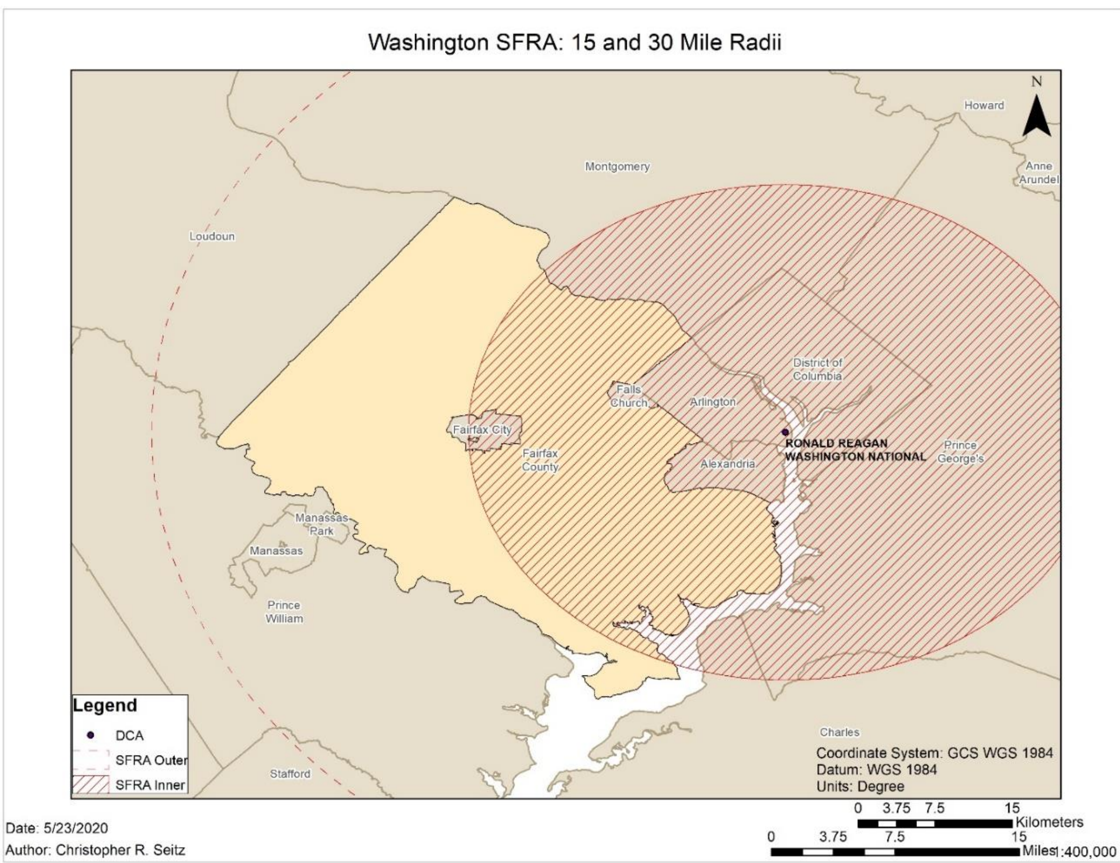


Figure 5: Washington SFRA 15- and 30-Mile Radii

Data Sources

The data used within this study is publicly available through a variety of public authorities both local and federal. Fairfax County provides a large amount of infrastructural data online including major utility lines, ingress and egress easements, public rights of way, parcels, as well as structural data of buildings within the county through their Open Geospatial Data Program. Through the Homeland Infrastructure Foundation Level Data Program operated by the Department of Homeland security, a large amount GIS data is provided including railroads, natural gas pipelines, and aboveground electrical transmission lines used in this particular study. The Federal Aviation Administration provides a wide array of UAS-specific data tailored to provide UAS pilots with the latest information designed to ensure safe operation including UAS specific National Security restrictions. This data was compiled and processed within a Geographic Information System in order to run spatial intersections between the proposed low altitude airspace sectors and the underlying terrain.

Network Generation

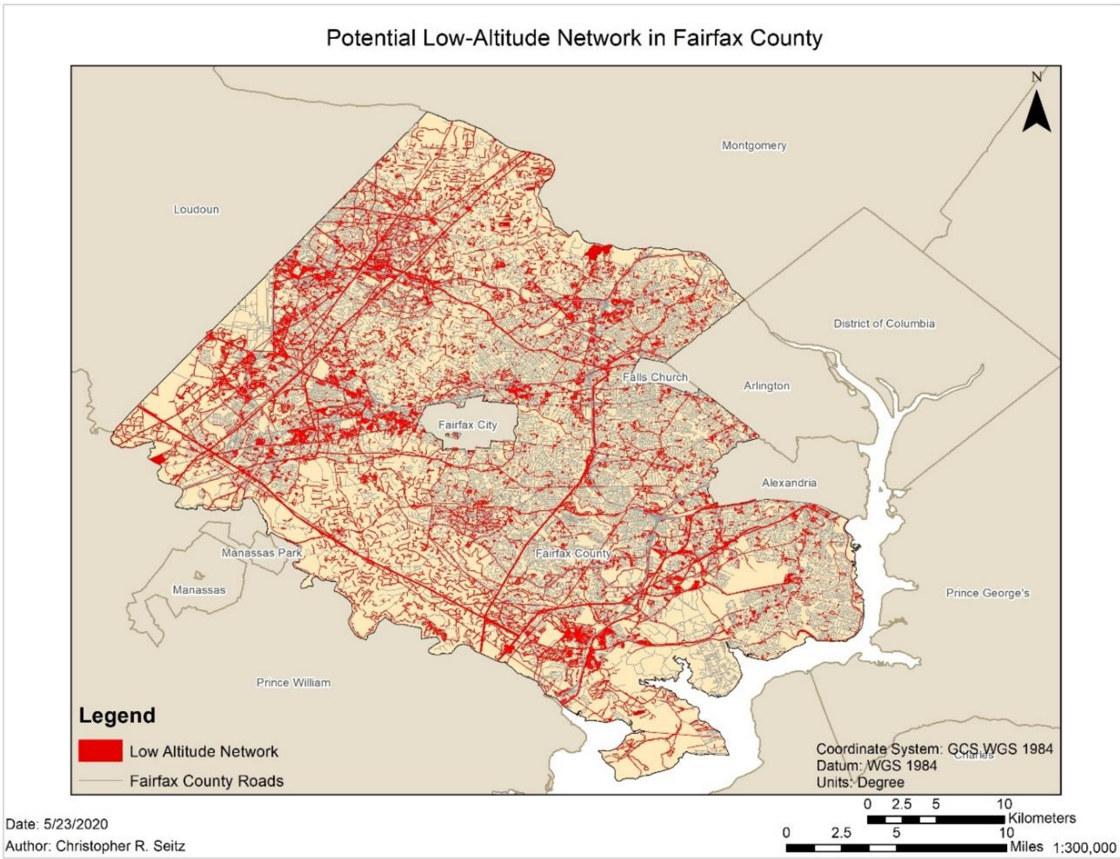


Figure 6: Primary Potential Low Altitude Network in Fairfax County.

The initial purpose of the analysis was to determine what proportion of buildings within Fairfax county would immediately be accessible to a low altitude courier airspace network using corridors and open-air spaces that already exist. Through a synthesis of publicly available data, the analysis was performed through the concatenation of potential low-altitude air corridors comprised of natural gas rights of way, utility ingress and egress easements, above-ground electrical transmission lines, railway corridors, metrorail tracks, and bicycle paths. When considering the easement areas which to exclude, areas such as cemeteries, conservation, preservation and reforestation easements, Fairfax County Park Authority administered land, NoVa Conservation Trust land, scenic areas, open spaces, sidewalks, trails, and traffic control areas were selected against using a definition query, while historic sites and school areas were selected for and clipped against the low altitude network to reduce overflights of populated areas.

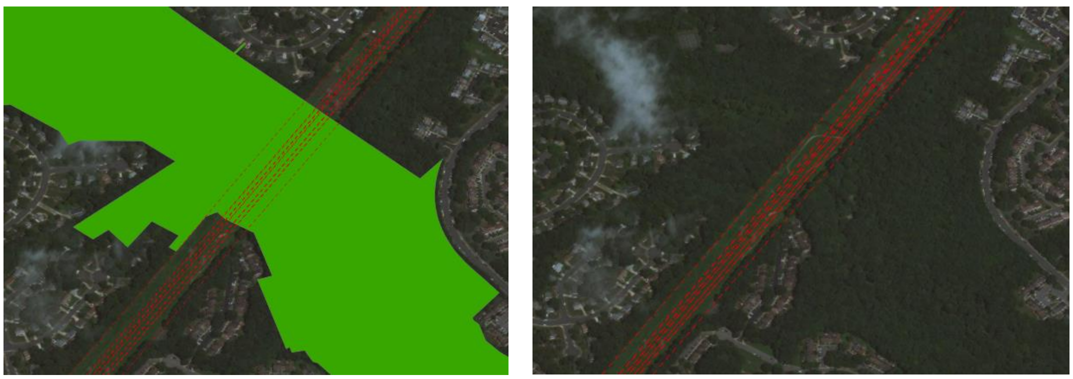


Figure 7: Example of Exception Area for Park Overflight

A particular matter of note when traversals over public parks were concerned, was the decision to include areas where high-voltage transmission lines crossed park lands, where clear cut access easements had been created to accommodate the accompanying utility infrastructure, while lower altitude trails and paths were removed to prevent interference with bystanders. In the selection of areas to exclude from FAA-sourced data, National Security Areas as well as parcels allocated to airports were excluded from traversal as a means of guarding against aerial collision. It was also important to select and remove buildings from these areas by means of an intersect function, as they would be precluded from the network and would skew network access results if they were to be included. Whereas the entire Fairfax County Buildings layer contains 275,560 buildings, the buildings layer used in this study with the restricted areas removed contains 254,403 structures. Likewise, the parcels data set is reduced from 363,712 to 361,283 parcels when accounting for restricted areas.

While developing the initial low altitude airspace network for courier purposes, additional use cases presented themselves. A particular useful niche for UAS, as discussed throughout the literature review is the use of UAS for Infrastructure Inspection and Analysis. When one considers that the purpose of utility infrastructure is to distribute valuable resources across a wide geographic area as efficiently as possible, so accompanies the thought that UAS may be able to inspect such a network to safeguard and maintain its capabilities. When cross-referencing the underlying geography of the developed low-altitude airspace network, a number of use cases can be made for the leveraging of infrastructure corridors in conjunction with minimal ground interference.

Due to the High-Voltage nature of long-range electrical transmission, a significant step-down in voltage would be required to recharge a consumer-grade UAS. As a means of both preserving flight security, as well as maintaining a practical location of charging facilities along major utility corridors that would be leveraged as UAS corridors, an analysis was conducted through ArcGIS Network Analyst to determine whether or not charging facilities located at electrical substations could serve as effective hubs for UAS charging and logistics. Due to their colocation with high-voltage electrical transmission corridors, as well as their secured nature against ground intrusion, charging stations for regulated autonomous flight could be advantageously placed to leverage this unique niche in civil infrastructure, not only as a logistical hub for courier delivery services, but for infrastructure assessment as well. When considering that UAS also have the potential to be outfitted with multispectral sensors which have been found to be sensitive gas leaks in pipelines (Barchin et al., 2017), the natural gas infrastructure of Fairfax County provides an additional corridor for UAS navigation.

In addition to leveraging the corridors developed for utility infrastructure, the corridors for railroads in the form of the Amtrak and freight rail corridors, as well as commuter rail in the form of the Washington DC Metro rail system may be utilized as connective tissue for proverbial “UAS highways”. These Corridors are often precluded from pedestrian traversal by means of access control and were initially designed as a means to connect major logistical hubs. The easements associated with these corridors would allow for their use as a means to connect larger areas of centralized population, as well as allow for the inspection, surveillance, and monitoring of railroad events and current conditions.

The nature of these easements and corridors means that they are to be allowed to be accessed by personnel representing the respective controlling utility. Often, these inspections are performed by personnel on the ground, operating from moving vehicles and performing visual inspections. The photographic nature of a UAS could potentially mean a brief overflight of a single area, just long enough to capture any imagery or spectral data for later review and move on, whereas an inspector on the ground would potentially take a longer period to traverse the same area, raising the question of whether or not the use of UAS would be any more of a risk to privacy when examining their use in utility inspection.

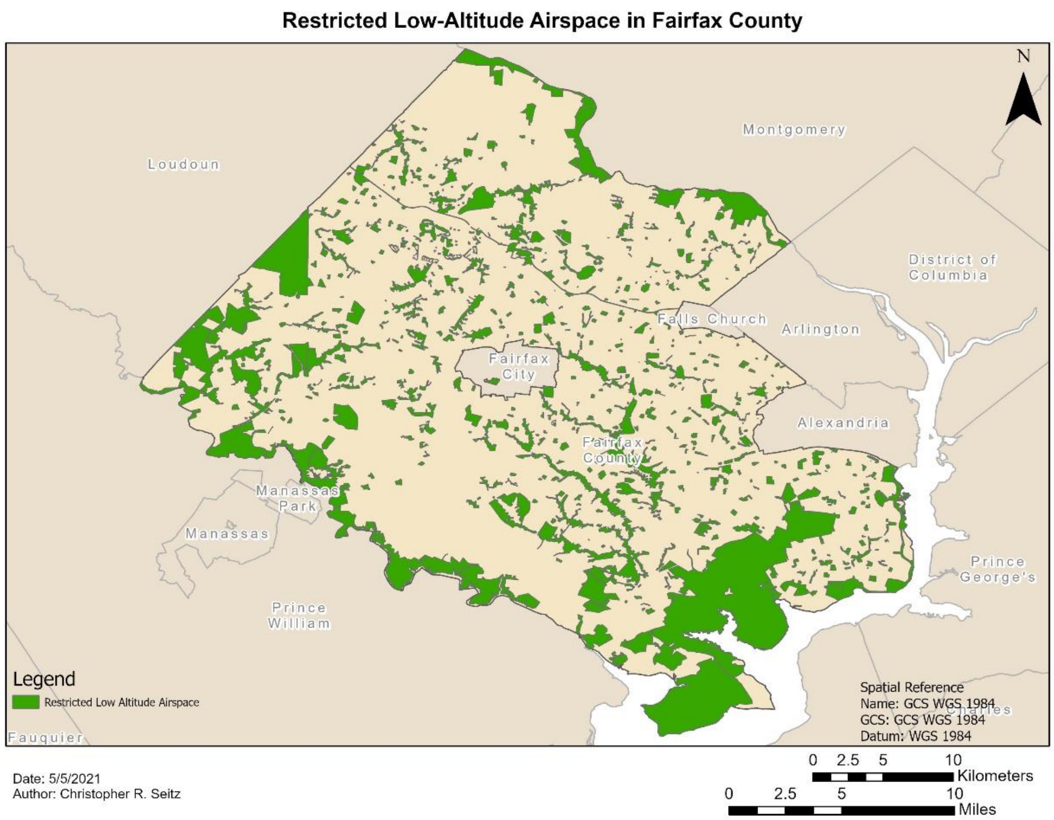


Figure 8: Restricted Airspace Areas

When cross-referencing these data types against one another the desire was to avoid disruption to ground-based transportation networks such as roads as much as possible. It is hypothesized that through using such corridors, the amount of overflight over private dwellings will be minimized, thus reducing privacy concerns, and reducing hazards to bystanders on the ground. For the purposes of comparison, the primary network excludes rights of way associated with roadways, while the secondary network includes the same data, albeit with roadway rights of way appended.

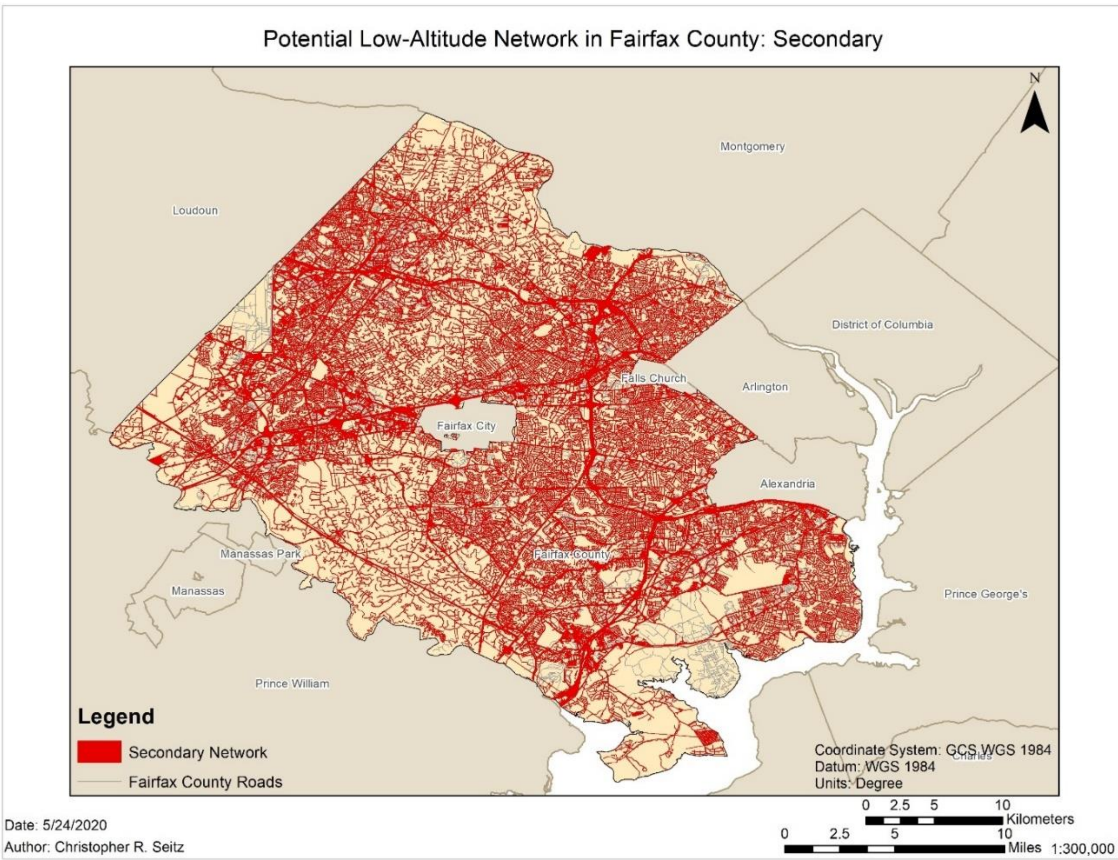


Figure 9: Secondary Low Altitude Network

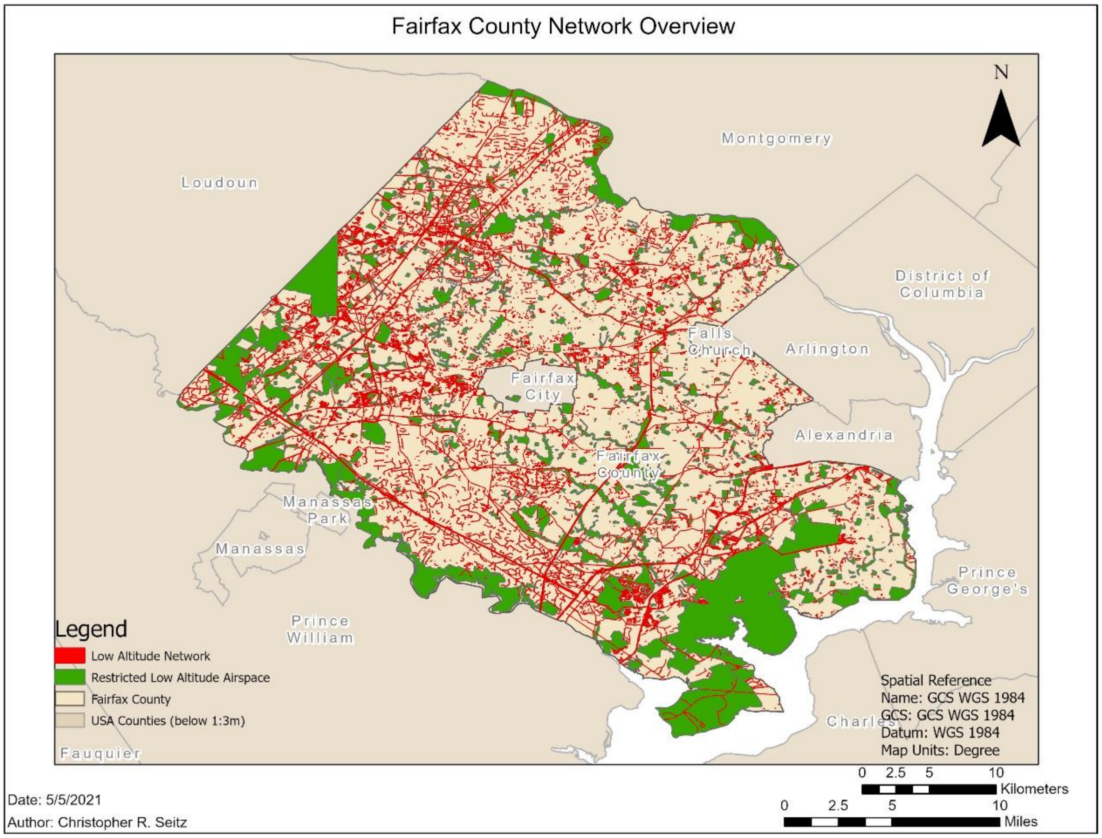


Figure 10: Network and Restricted Airspace Areas in Fairfax County

Processing

The analysis of this low altitude network was conducted through a number of concurrent GIS operations. After an initial clip to remove restricted areas and buildings within them, the remaining linear network data was merged to create two separate potential topological networks across the county, one incorporating public roadway rights of way, and one without. The purpose of generating two separate versions of this network was to determine the effectiveness of such a network without relying on corridors already set aside for and occupied by vehicular traffic on the ground should a UAS not meet FAA specified category 4 flight eligibility. Secondly, two buffers, 100 meters and 200 meters, were generated surrounding this network to model potential access to properties for both entrance into the network and egress out of the network.

Following buffer generation, an intersection between each buffer zone and the underlying structures was conducted to determine what proportion of structures within Fairfax county are served by the creation of such a proposed network. This proportion of structures was then calculated by determining what percentage of Fairfax county structures are accessible within the bounds of both the 100- and 200-meter ingress and egress buffers. A further step of cross-referencing compared the intersection of these networks against the underlying parcel data to determine what percentage of land parcels would be accessible through such a network.

In addition to determining which areas are served by the network, it was also important to determine which areas were not served by the network. Centroids were derived from the Fairfax County structure polygons and their metric distance to the nearest point on both networks was determined through the employment of the 'Near' function. The results of this process were then interpolated using kriging to identify zones that were underserved through the development of the hypothesized networks.

One particular question raised as a result of analysis was that of supporting an unmanned traffic network and how to fuel and sustain the aircraft involved, in order to distribute charging resources in the most efficient manner. According to figures published by DJI in 2021, the maximum speed of a DJI Mavic Air 2 S in terms of speed is assumed to be around 54 km/h airspeed in navigation mode (DJI, 2021), assuming a 20-minute flight time for a UAS, this would put the operational distance of a typical consumer UAS at around 18 kilometers, halved to around 9 kilometers in the event of a return journey. Assuming the existence of a centralized command and control function and the ability of such an overarching command structure to accommodate calculations for battery life and energy consumption, a robust charging infrastructure would allow for long-range flight capabilities leveraging known points within the traffic management system. These characteristics were leveraged in developing the effective range of a UAS operating from a charging station co-located at an electrical substation, in order to determine which areas of the network would be ill-served by such a co-location.

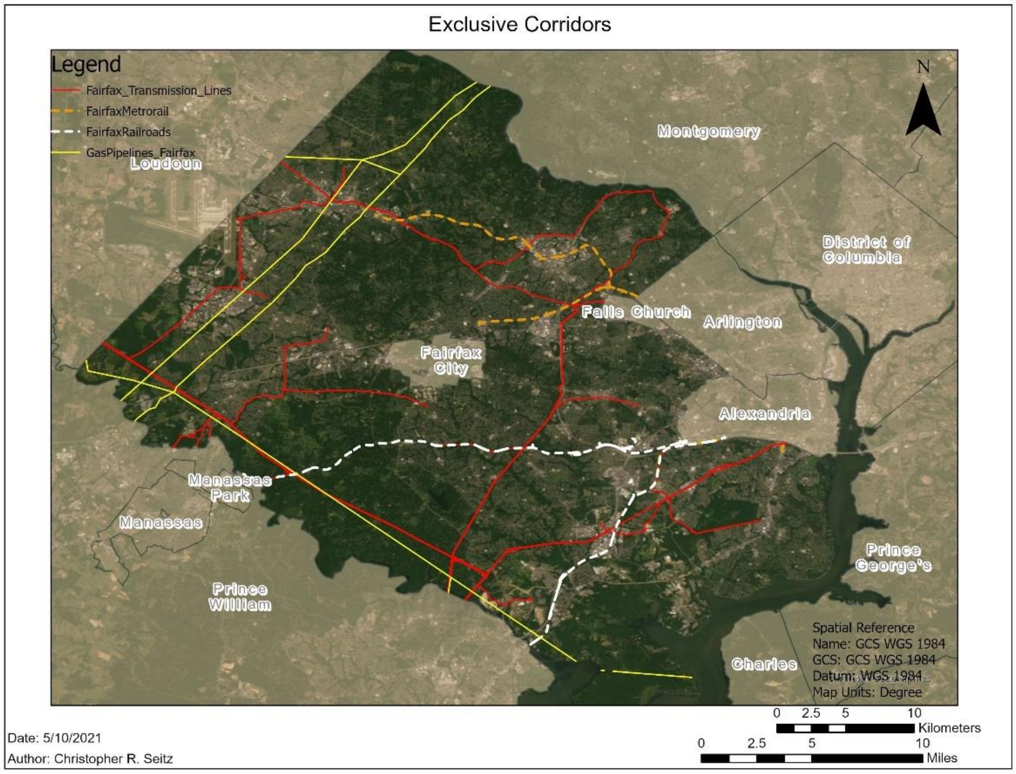


Figure 11: Dedicated Utility and Transit Corridors in Fairfax County

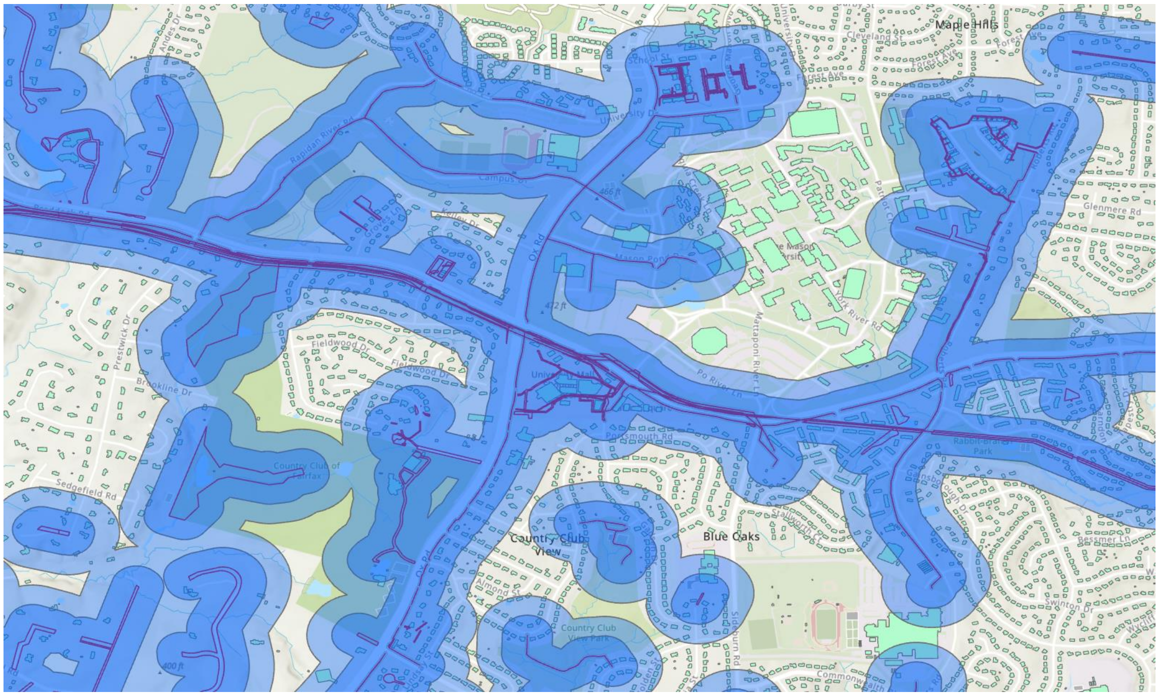


Figure 12: Screenshot of Buffer Generation

CHAPTER FOUR: RESULTS

As covered within the Methodology chapter, in order to study the effectiveness of low altitude unmanned traffic routing, a hypothetical low altitude airspace network for courier delivery, infrastructure assessment, and hypothetical charging hub placement was developed within the boundaries of Fairfax County Virginia. This network was constructed from publicly available polygon and vector data depicting utility easements, bicycle paths, overhear transmission lines, and rail corridors for both freight and commuter rail. Two forms of the network were generated, one without rights of way associated with automobile traffic, and with the rights of way incorporated. It was found that given potential ingress and egress routes of up to 200 meters from a low altitude network would effectively provide a majority of structures within Fairfax County with access to Low Altitude UAS services. When considering parcels separately from structures, ingress and egress routes of just 100 meters would provide access to a majority of Fairfax land parcels. A series of maps depicting the results of this cross-referencing process was generated in order to demonstrate the collected results.

Primary Network Results

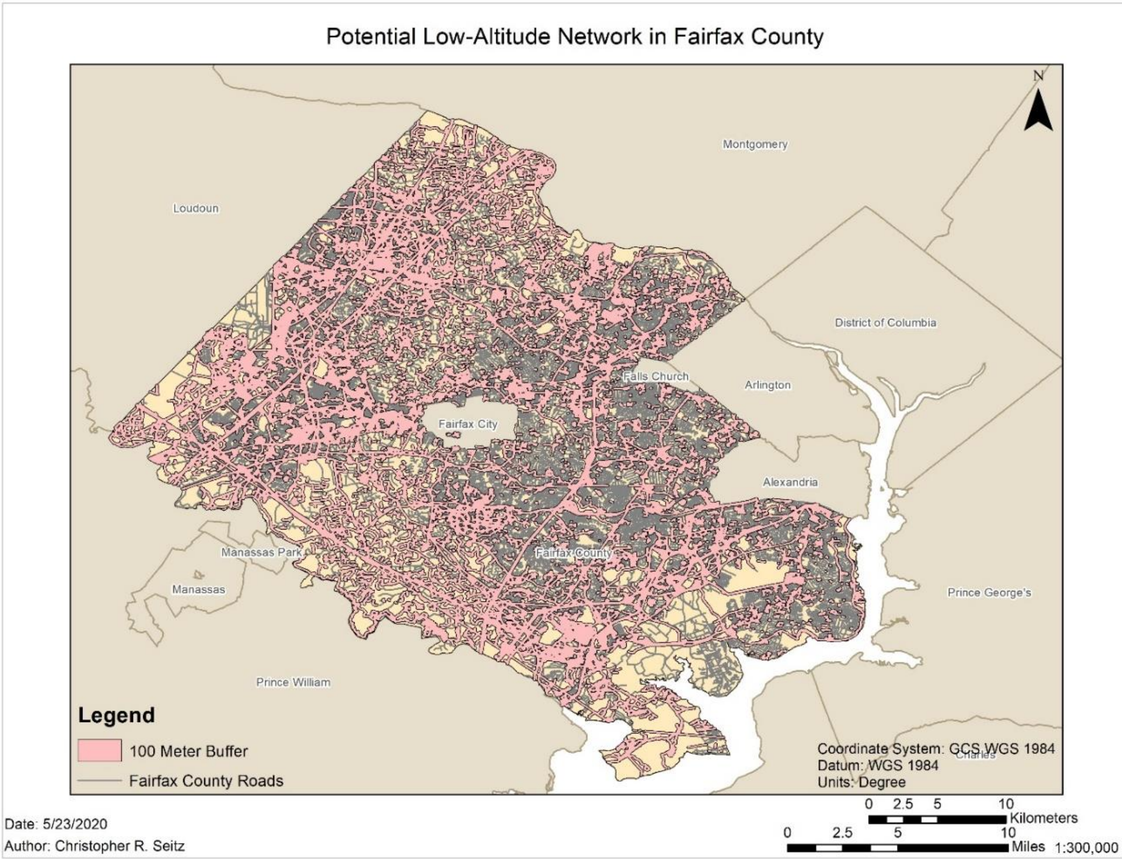


Figure 13: Potential Low-Altitude Network in Fairfax County (100 Meter buffer)

When examining the primary hypothetical network without rights of way incorporated, only 35.23 percent of Fairfax County Structures were accessible within 100 meters of the network however, when examining parcel data against the accessibility of this network, 51.54 percent of land parcels were covered.

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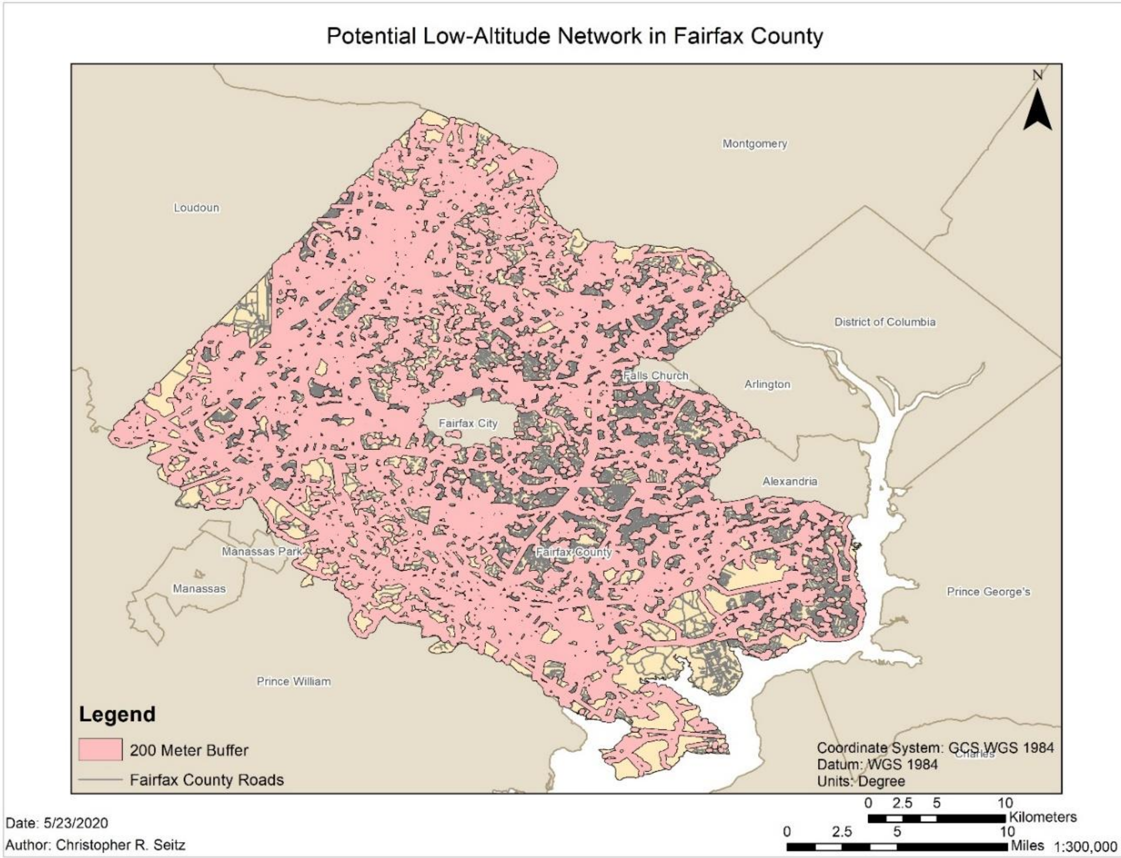

Figure 14: Potential Low-Altitude Network in Fairfax County (200 Meter Buffer)

Upon Expanding this buffer zone to 200 meters, a significant jump in the proportion of structures covered by the primary network is observed with 60.84 percent of structures falling within this extent. When considering parcel data for the same extent, 73.63 percent of land parcels are potentially served by such a network.

Secondary Network Results

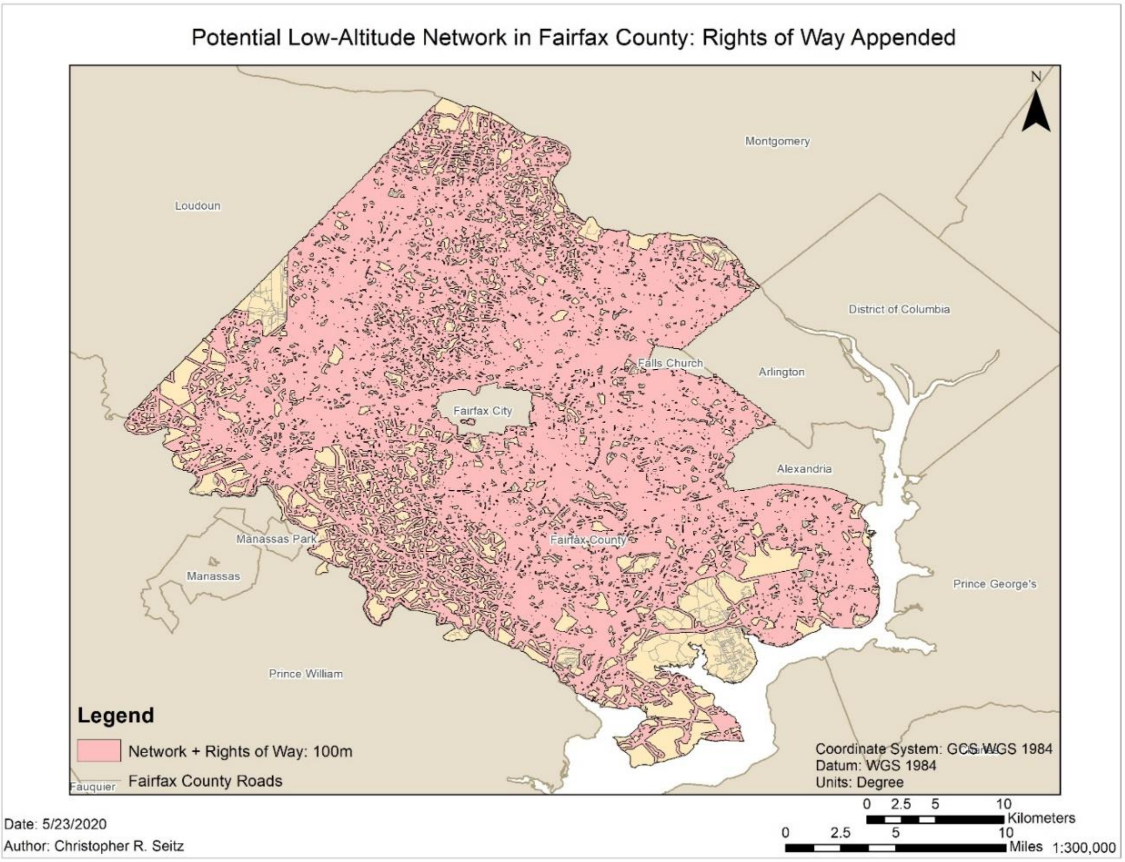

Figure 15: Potential Low-Altitude Network in Fairfax County (Rights of way Appended, 100m)

Whereas the initial network focused on avoiding the incorporation of roadway rights of way, a secondary network was generated to determine what differences would be observed when incorporating such data. Due to the nature of roadways as connective infrastructure, a much larger proportion of 97.5 percent of structures was found to lie within the 100-meter buffer, while 97.66 percent of parcels were found to be accessible within that same distance.

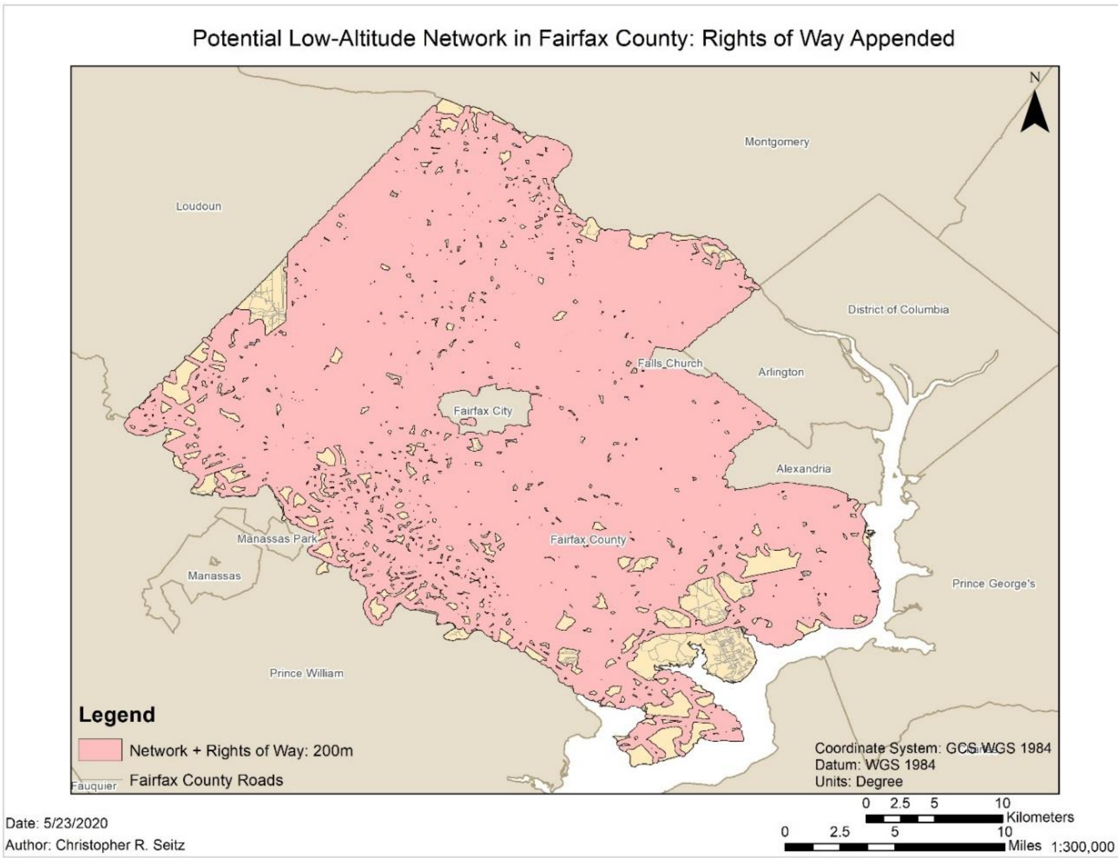

Figure 16: Potential Low-Altitude Network in Fairfax County (Rights of way Appended, 200m)

Generating a 200-meter buffer surrounding the secondary network yielded the highest proportion of structures and parcels observed. This buffer zone encompassed 99.65 percent of structures, with over 99.92 percent of parcels connected to the network.

Table 1:Depiction of Buffer Analysis Results

Network	Buffer Distance	Structures	Structure Percent	Parcels	Parcel Percent
Primary	100	89628	35.23	186226	51.54
Primary	200	154781	60.84	266043	73.63
Road Access	100	248053	97.50	352851	97.66
Road Access	200	253515	99.65	361021	99.92

Spatial Interpolation

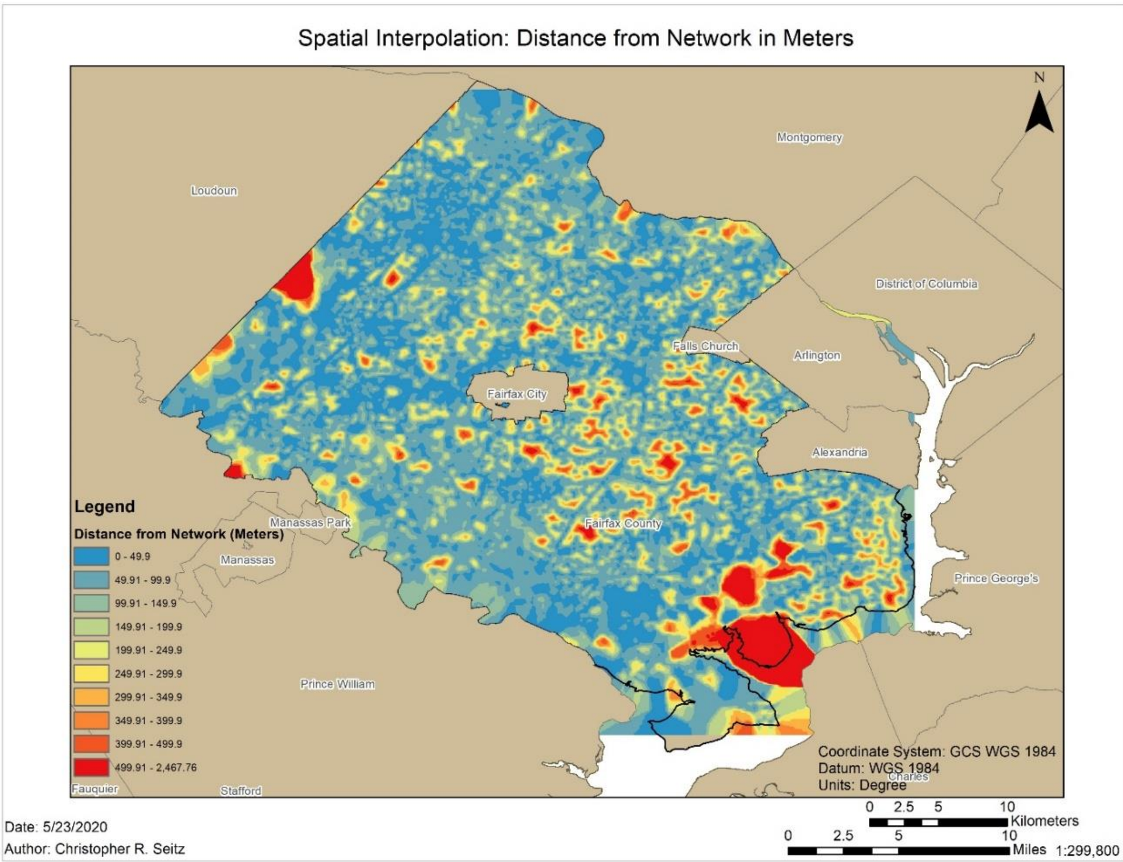

Figure 17: Spatial Interpolation of the Primary Network

In addition to determining which areas are served by the network, it was also important to determine which areas were not served by the network. Through determining the proximity of each building to the network and spatially interpolating the results through kriging, a map of which areas are underserved by the network was able to be developed. Through this process, it was discovered that the primary network featured and average structure-to-network distance of 143 meters, while the secondary network featured and average structure-to-network distance of only 37.5 meters. Of particular note, the large sectors of inaccessibility in the northwest and southeast portions of the county are comprised of the runways at Dulles International Airport, and the restricted airspace of Ft. Belvoir respectively. Also of interest were areas that were underserved by the network, yet still outside of the National Security Areas and easements set aside from public parks. It was found that the parcels with largest distances between the UAS network and its containing buildings were golf courses and privately owned recreation areas not owned or operated by the Fairfax County Parks Authority, thus raising additional questions over the role of private ownership in determining the overarching airspace of a property.

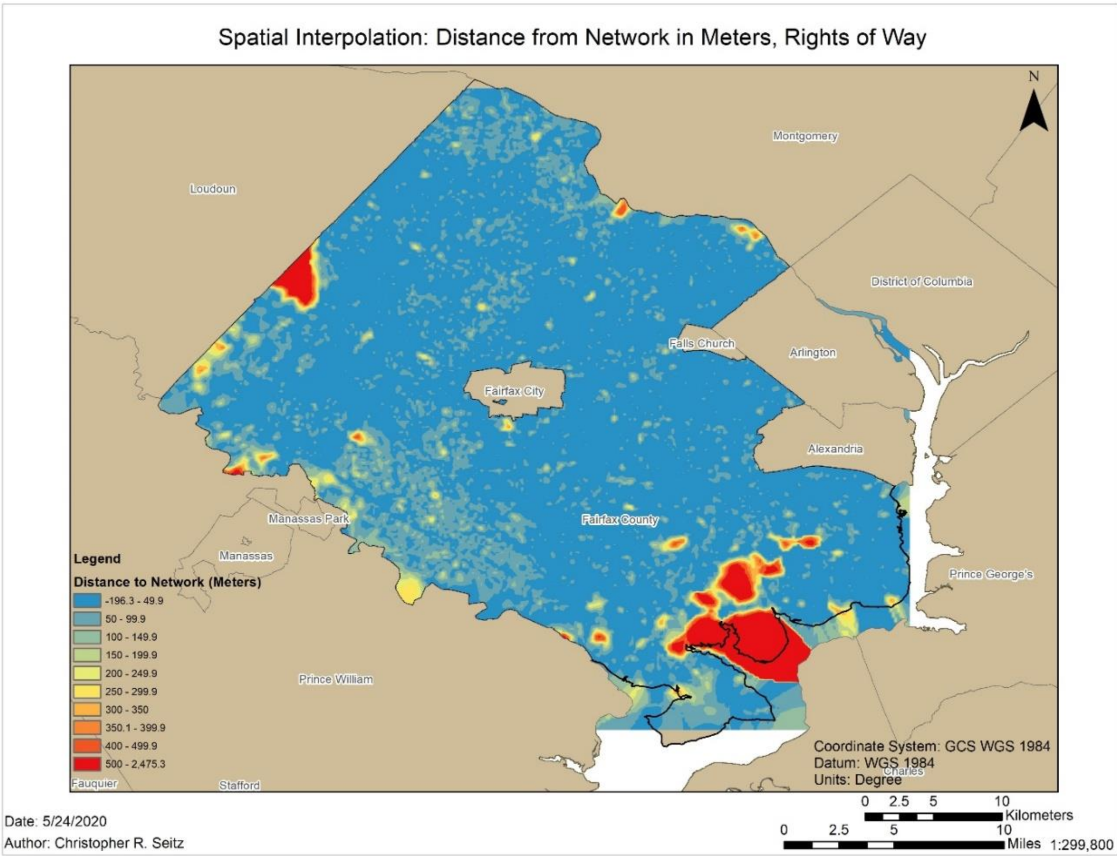

Figure 18: Spatial Interpolation of the Secondary Network

A number of real-world considerations would need to be examined in addition to the results portrayed by this study. In addition to possible pushback by property owners with regard to a potential 100-meter ingress and egress intrusion from the low-altitude airspace network, National Security concerns particular to the Fairfax County area may complicate UAS operations. When examining the results of this study, the extension of the network from 100 meters to 200 meters represents a major difference in terms of UAS accessibility, but also in terms of UAS being a potential nuisance to bystanders on the ground. When examining the difference between the two networks, the inclusion of roadway right of ways would prove to be a significant boon to the proportion of properties and structures served. When examining how a traveling UAS may access a particular structure or property, potential navigation constraints could take into account a number of factors: The location of a building within a land parcel, the shortest path across private property from the network to the destination building, as well as avoidance of other structures while traversing non-destination private property.

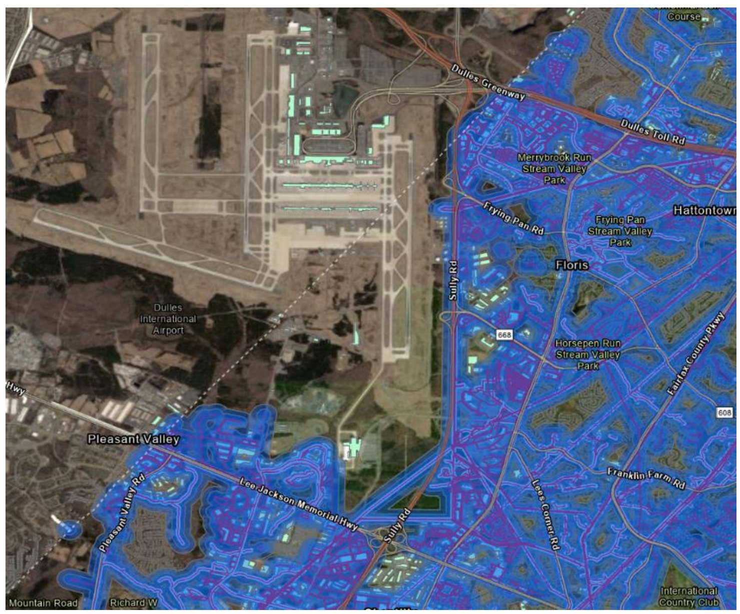

Figure 19: Inaccessible Region near Dulles Airport

Figure 20: Inaccessible Region near Ft. Belvoir

Utilizing high-voltage electrical corridors for transit provides not only allows for the development of infrastructure for immediately available power for UAS to recharge on longer journeys, but the major electrical transmission lines throughout Fairfax County only intersect 991 structures, broken down into 11 transportation facilities, 76 Industrial Facilities, 88 commercial facilities, and 785 buildings classified as “Building General” of which 297 are transformers lying within the easements owned by Virginia Electric & Power Company and an additional 295 are controlled by Dominion Virginia Power. One problematic exception to this convenient colocation of corridor and utility is a section within the Annandale sector of Fairfax County, where the high-voltage utility line splits from the large easement-line corridors and submerges underground. When intersecting the natural gas network and accompanying easements against residential structures, 346 instances of overlap occur. Of these instances, 30 may be classified as either commercial, industrial, or commercial retail facilities, while 293 single family residences are intersected, the remainder being offices and multi-use facilities.

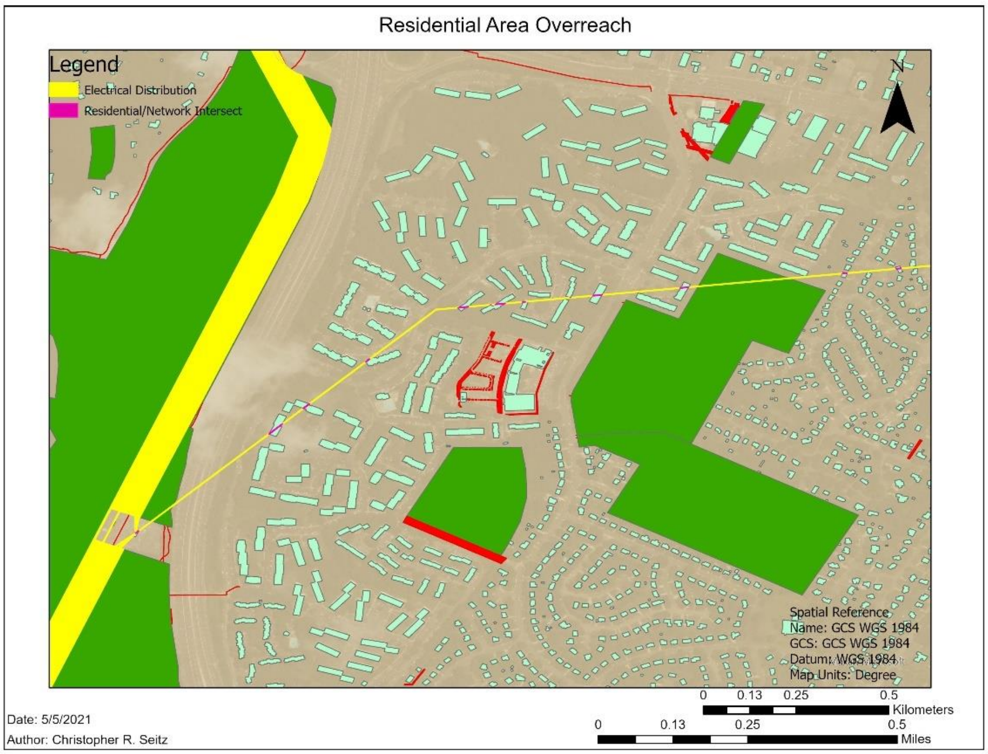

Figure 21: Network Overreach of Private Property in Annandale

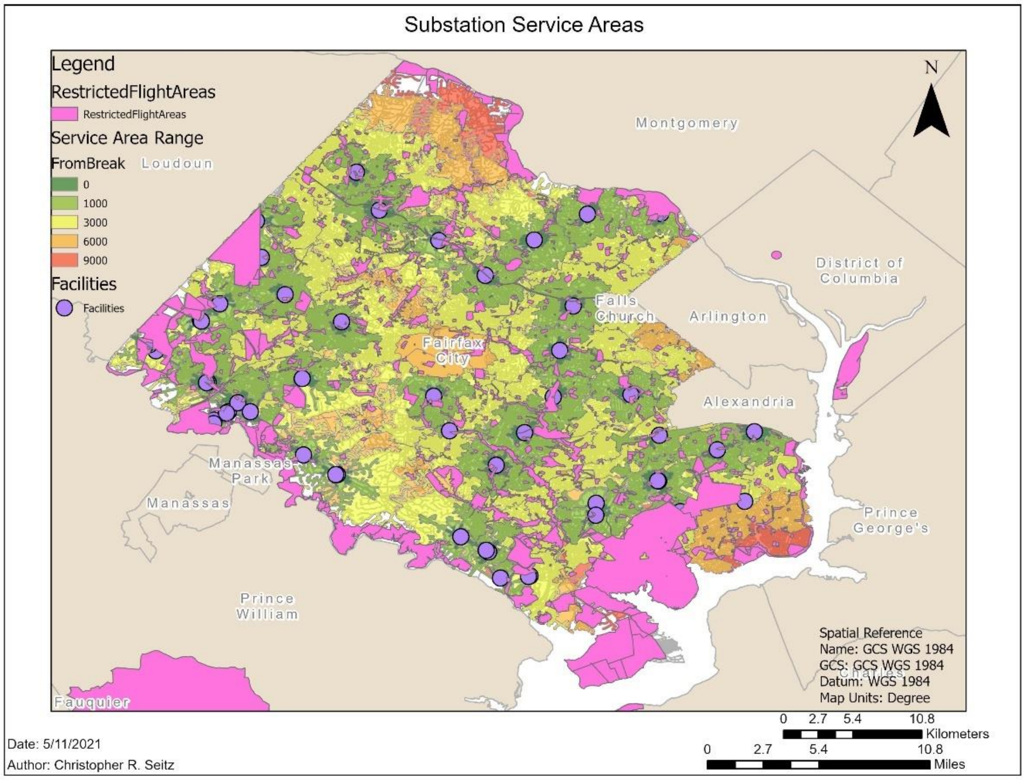

Figure 22: Substation Service Areas within Fairfax County

When determining the effectiveness of co-locating UAS charging station at electrical substations throughout Fairfax County, it was found that a vast majority of properties would be served by such a system with 2.26% of structures and 2.05% of parcels not served by the network beyond a network range of 9 km from a charging station. Many areas underserved by the charging network are in the vicinity of otherwise restricted airspace, which could lead to a possible explanation in routing difficulty.

CHAPTER FIVE: CONCLUSION

Through an examination of how airspace may be re-conceptualized at low altitudes within areas infeasible for safe manned aerial operations, a new perspective on how Unmanned Aerial Systems may be integrated into our daily lives has been gained. As individuals on the cutting edge of consumer UAS technology continue to push the boundaries of their platforms both technologically and operationally, there will be a growing momentum for more in-depth integration of UAS into the airspace system. With such diverse uses ranging from agriculture to emergency services, the use of Unmanned Aircraft Systems provides further geospatial analyses of existing topology, infrastructure, and airspace will need to be carried out to ensure that this integration does not come at a cost of not only safety, but human dignity as well. The challenge of determining where UAS may be best leveraged and in what fashion will continue to be an inherently geospatial undertaking, leveraging the computational power of networked digital technology, while simultaneously guiding computerized platforms through 3-dimensional airspace.

Regarding the widespread societal acceptance of drones into civil society, there are significant differences into how unmanned systems compare against manned aircraft in terms of their perception by the general public. Key concerns found by researchers at the Human-Computer Interaction center at Aachen University included interviewed subjects' concerns over privacy, particularly over the inability to determine whether a drone was filming, overflights of their personal property, ambiguity of flight purpose, and operator anonymity (Lydinia, et al., 2018). Despite these concerns, subjects interviewed in this same study also agreed that drone technology is useful and should be operated by private persons. Researchers at the Queensland University of Technology in Australia discovered similar perceptions to drones, although finding the risks involved with drones to be similar to those of manned aircraft, while also echoing similar concerns including questions regarding the capability of UAS technology, privacy, safety, and security issues (Clothier et al., 2015). These perceptions may persist in comparison to manned aircraft due to the ability to identify the operating entity and purpose of a manned craft due to size and the legibility of an FAA mandated tail number, whereas the identity and purpose of a UAS operation may be more difficult to perceive due to the small size and pilotless nature of UAS.

Due to the complicated regulatory nature of the airspace surrounding the US Capital Region, the selection of Fairfax County as the study area only enunciates the requirement and need for unmanned traffic management systems to determine areas where these powerful tools of innovation may be utilized to their full extent in a safe manner. The current regulatory framework wherein UAS are constrained to line-of-sight operations is seen by many to be a temporary placeholder as both the FAA and NASA attempt to develop a comprehensive mechanism for leveraging these powerful systems. Perhaps particular challenges for future researchers may center around the availability and quality of local level geospatial data for developing transport networks, as it was rather fortuitous in this instance of being able to access high-quality GIS data from Fairfax County.

In overcoming the difficulties surrounding UAS airspace management, society will face numerous challenges beyond the technical limitations of UAS. These challenges are ethical, legal, and political in nature. While the capabilities of UAS outstrip the regulatory frameworks designed to hold them in place, UAS will continue to present challenges to enforcement agencies and airspace authorities alike. The technical capabilities of low cost and high mobility present a double-edged sword of high utility in public safety and economic affairs, and unpredictability or danger in the hands of the untrained or malevolent. The lower cost and higher spatial resolution of UAS will prove to be attractive options for geospatial researchers in several disciplines ranging from human geography to wildlife ecology. Industrial use of UAS to quickly capture data of crumbling infrastructure has the potential to save considerable amounts of resources on inspections over manned inspection duties in both time and safety equipment required to reach potentially dangerous locations. This capability to probe for weaknesses in infrastructure also poses a security risk when UAS are employed for malevolent means, resulting in potential sabotage or espionage against valuable National Security Assets for the United States. Combatting ill-intentioned use of UAS will continue to prove itself as a thorn in the side for enforcement agencies as counter-UAS technologies struggle to keep up and match consumer UAS in terms of ubiquity and effectiveness. The potential of UAS to hold not only the public to account by public safety officials, but the public safety officials in turn held to account by the public demonstrates the complicated nature of UAS ubiquity. This give and take of possible surveillance and counter surveillance brings forth the classic idiom from the Roman poet Juvenal, "*Quis custodiet ipsos custodes?"* or "Who will watch the watchmen?" In order to reap the most from UAS integration without a deterioration in quality of life and privacy, proactive measures need to be taken in order to balance a need for public safety against the development of a national surveillance panopticon and prevent as much unwanted intrusion into private life as possible.

Standards for a common UAS communication backbone and data storage and transmission must be developed to ensure lapses in communication do not occur and that data collected incidentally does not fall to potential misuse by both public and private interests. The development of alternative sectors of airspace may potentially spawn a radical re-imagining of the 3-dimensional space close to the ground that all people live in and occupy. Through identifying and modifying corridors through which UAS may travel, there is the potential for an increase in air-traffic without major disruption to ground vehicular traffic and pedestrians on the streets. Through the development of effective low-altitude airspace networks, UAS have the potential for integration without radical changes in existing topology, connecting people through UAS services by leveraging the utilities that already connect us.

The importance of high-quality Geospatial Data cannot be understated with regard to the development of this study. As autonomous UAS flight will operate on a foundation of geospatial data, spatial accuracy and temporality will prove to be crucial in determining one has the most relevant and correct data. Due to the constantly changing regulatory landscape with regard to UAS policy and the sensationalism regarding UAS stories within news media, it is critical to be aware of any changes that may occur based on FAA advisory circulars and regulations. As the Federal Air Regulations rely on FAA policy determinations that are mandated by legislation, but not enacted by congress directly, they are subject to change without immediate prior announcement. UAS-specific data provided and regularly refreshed by the FAA will prove to be a key asset to researchers and industry partners alike.

The encoding of Part 107 into the Federal Air Regulations is an important milestone not only in the history of UAS, but in aviation itself. As the technical capacities of UAS platforms have advanced by leaps and bounds, the regulatory framework put in place to constrain their ill-use has struggled to keep pace. Despite this somewhat sluggish regulatory response to the sea-change in aviation that UAS represents, the FAA has made some strides in coping with this disruptive technology. From the initial limitations curtailing UAS usage to line-of-sight operations and waiver requirements in controlled airspace, to the rollout of LAANC and the development of additional regulations standardizing remote identification mechanisms for assuring accountability in UAS operations, there are promising trends towards full integration of UAS into the National Airspace System.

As the possibility exists for FAR Part 91 General Aviation license holders to operate UAS in emergency Tactical Beyond Visual Line-Of-Sight conditions, there is promise that through the exploration of these situations, there is the potential for more widespread use of UAS in a similar manner. In situations where this line-of-sight requirement is waived, perhaps operations must be conducted by an individual with a higher degree of aeronautical understanding, such as a pilot already possessing a Part 91 license, or an amended part 107 exam which focuses on Instrument Flight Rules (IFR) operations required by General Aviation pilots.

As UAS undoubtedly become more common, changing the airspace and landscape before our eyes, so too will our perceptions and solutions change to accommodate this new technology. With data collection techniques such as Volunteered Geographic Information becoming ever more prominent, perhaps crowd-sourced data collection of potential low altitude airspace corridors could be tested. General thoughts on the development of crowdsourcing and distributed information sharing communities by Goodchild et al. (2005) and Rice et al. (2012), anticipated this possibility, among others. Another potential direction for future research would be an examination into how a UAS courier system may not only deliver goods to a client site but retrieve goods for shipment. How would these transactions take place between man and machine? A particular insight gained during the course of this research has been a consideration of where and how a property owner may establish a known location for pick-up and drop-off of UAS transported goods, establishing a "Droneport" akin to the establishment of a mailbox on other private properties. How would homeowners be able to determine where and how these points are established? The development of standards and methodologies to adapt to the sea change in technology that UAS represent will not always need to be guided by a series of trial and error, but through insights into how humans interact with their surrounding geography through technology. As the National Airspace System has continued to adapt to new technologies introduced throughout the years, so too will UAS and their operators find their niche within the world's most heavily traversed aerial network.

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