AIR CORRIDORS: CONCEPT, DESIGN, SIMULATION, AND RULES OF ENGAGEMENT

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Air corridors are an integral part of the advanced air mobility infrastructure. They are the virtual highways in the sky for transportation of people and cargo in the controlled airspace at an altitude of around 1000 ft. to 2000 ft. above the ground level. This paper presents fundamental insights into the design of air corridors with high operational efficiency as well as zero collisions. It begins with the definitions of air cube, skylane or track, intersection, vertiport, gate, and air corridor. Then, a multi-layered air corridor model is proposed. Traffic at intersections is analyzed in detail with examples of vehicles turning in different directions. The concept of capacity of an air corridor is introduced along with the nature of distribution of locations of vehicles in the air corridor and collision probability inside the corridor are discussed. Finally, the results of simulations of traffic flows are presented.
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1.1. Background and Motivation

Modes of travel and transportation have evolved at a rapid rate over the last few decades. Unmanned aerial vehicles (UAVs) are forms of transportation that can be used for a variety of intriguing purposes. UAVs have the potential to transform our ability to transport packages at low energy and cost due to platform size, advanced technology, and system diversity. UAVs have bright prospects for facilitating package delivery, farming, news gathering, etc. In the near future, (unmanned) air taxis are expected to be deployed in rural and urban areas to transport people and cargo from one place to another. Air ambulances are expected to be deployed to provide emergency services such as 911. The variety of uses of unmanned aerial vehicles (UAVs) making study in this sector exciting.

In the following years, the number of UAS in the airspace is expected to skyrocket. The airspace will become increasingly congested as the number of UAS grows, quickly outstripping the current air traffic control (ATC) system’s capabilities. The creation of the UTM system is an alternative to treating UAS in the same way that manned aircraft is handled. NASA and collaborators have developed UTM to handle UAS traffic upto 400 feet above ground level (3–5). However, unlike commercial flights, UAVs are highly flexible, variable, and have uncertain movement patterns which make UAV traffic analysis more challenging. The introduction of autonomous vehicles into Class B, C, and D airspace necessitates preparation in terms of safety, security, and the protection of human life and habitat, particularly in urban scenarios. Not only regulations but also safety and efficiency are the key concerns of UAS traffic management (UTM) systems. Further, UAV traffic needs to be restricted from flying above private properties, parks, highways, and other heavily populated areas. As a result, pre-defined flight plans, and deterministic flight trajectories are needed because of the limitation of airspace which makes air corridors are an integral part of the advanced air mobility infrastructure.

Air corridors are three-dimensional (3D) volumes of airspace reserved for unmanned air-
craft systems\(^1\) (UASs) for advanced air mobility (AAM) traffic (6; 7). Air corridor design specifications are specific to each country and are defined by its respective federal aviation authority. In the United States, the Federal Aviation Administration (FAA) defines air corridors in class B, C, or D airspace (8). The definition of an air corridor is flexible in nature. FAA has the right to open or close an air corridor. The FAA also defines the expected performance requirements of a UAS flying in an air corridor. The design of air corridors, traffic rules in air corridors, safety requirements, and performance specifications are still evolving. Airspace design concepts, such as the geofence (9), are currently being considered by various research groups. Authors in (10) has introduced a unique drone skyway framework called “CORRIDRONE”. As the name implies, this depicts virtual air corridors for the safe transit of many UAVs from one point to point another. The corridors are not permanent, but can be established on demand.

Air corridors could have multiple routes with different performance requirements, which provide predictability and structure, increase throughput and minimize bottlenecks. Due to the well-defined structure of an air corridor, the overheads such as communication, handovers, traffic management for UAVs flying in an air corridor are minimal as compared to those that are flying outside the air corridor (7). Aircraft systems operating in air corridors follow specific procedures defined for the corridors. Some specific characteristics, such as routes are static but used in a flexible fashion. FAA sets the criteria or decides which routes are open or closed for traffic at any given time. Some design considerations for the route selection include airspace class, noise levels, departure/approach flows, final approach paths, etc. Routes are charted and made available to other airspace users and periodically redefined as operational demand changes (11). This thesis takes a first attempt to the design of air corridors with high efficiency as well as zero collisions.

1.2. Research Contributions

The major goal of this thesis is to formally construct an air corridor suited for UAS operations. The air corridor definition and design is provided as the foundation for this system, allowing UAVs to fly in a collision-free environment. Specific contributions of this thesis are:

\(^1\)In this work, the terms UAS and unmanned aerial vehicle (UAV) are used interchangeably for convenience. However, by definition, a UAS includes a UAV, its ground control station, and a human operator.
• The first development of a multi-layered air corridor model. This model includes a brief explanation of the rules of engagement within the air corridor and V2V communication of the UAVs. Traffic at intersections is also analyzed in detail with examples of vehicles turning in different directions.

• Mathematical definitions of building blocks of air space - air cubes, skylanes, geofences, intersections and air corridors which constitute the airspace.

• Introduced the concept of capacity in terms of number of UAVs of an air corridor. Estimated travel to show the efficiency of this model.

• Discussed probability density function of the vehicle locations in a skylane.

• Derived the probability of collision in the air corridor, and the findings helped to verify this model.

• Presented simulation results comparing different traffic flows which shows the implications of this model.

1.3. Thesis Overview

Air corridors are an integral part of the advanced air mobility infrastructure. They are the virtual highways in the sky for transportation of people and cargo in the controlled airspace at an altitude of around 1000 ft. to 2000 ft. above the ground level. The objective of this thesis is to present fundamental insights into the design of air corridors with both operationally efficient and collision-free.

The primary goal of this thesis is to formalize the construction of an air corridor model. The mathematical definitions of the building blocks of airspace proposed here. Air cubes, skylanes, vertiports, gates, etc. are examples of these building blocks that can be grouped together to form an air corridor structure. A multi-layered model is proposed in which UAVs can fly in a collision-free environment. Before deployment, all UAVs must be equipped with V2V communication and must comply with the engagement regulations outlined in this thesis. For the safety of UAVs flying inside the corridor, the Manhattan mobility model and safety distance restrictions are also taken into account. Some computational modeling such as, capacity calculation, travel time estimation, and collision probability calculation etc are provided to interpret the efficiency of the air corridor
model. Finally, simulations were performed in order to validate the model.

1.4. Thesis Organization

The remainder of chapter 1 outlines the other chapters of this thesis.

The literature review is presented in chapter 2. This chapter gives a brief idea of geofencing, V2V communication, alternative mobility models (such as Manhattan mobility model, Freeway model, City Selection model, etc.), stationary node distribution, and collision probability.

Chapter 3 delves deep inside the problem formulation and introduces a formal definitions of the airspace, for example: air cube, skylane, gate, vertiport. etc and designs a multi-layered model. This chapter also explains the rules of engagement along with vehicle-to-vehicle communication inside the corridor with some flight path examples. Intersection handling technique with some examples is also presented in this chapter.

Chapter 4 includes all the computational modeling. Capacity of air corridor, travel time estimation, mobility model and node distribution, and collision probability is calculated in this chapter.

Chapter 5 includes all the experiments done and the results of simulation. Finally, conclusion and future works for this thesis are discussed in Chapter 6.
CHAPTER 2

LITERATURE REVIEW

There are numerous applications for UAVs in the military and civilian fields. Sample applications include: (1) providing communication services by serving as base stations (BSs) (12), (13), (2) monitoring air pollution or toxic gas leakage (14), (3) transporting cargo (15), (4) disaster prediction, assessment, and response (12), and (5) providing cost-effective wireless connectivity for devices without infrastructure coverage (16). Unmanned air vehicles are planned to be deployed in rural and metropolitan regions to transport people and freight from one location to another. Besides, emergency services are intended to be provided by air ambulances. As a result, UAS traffic management (UTM) systems are concerned with not only efficiency and regulations but also safety, quality, and reliability.

In (17), authors describe how less structured airspace where flight moves freely, allows for greater capacity and route efficiency. They also point out that free flights require greater technological capabilities and compromise safety. On the other hand, more restrictive structures, such as air corridors enable the operations of less-equipped aircraft at the expense of slightly increased delays. Specified parts of controlled airspace, which is known as air corridor, not only increase safety and ensure compliance but also permit higher-speed Urban Air Mobility (UAM) operations while limiting the effects on other air traffic.

2.1. Air Corridor for Manned Aircraft

An airway, often known as an air route, is specified path along which planes fly from one airport to another and can be defined as segments within a specific altitude block, corridor width, and between fixed geographic coordinates for satellite navigation systems, or between ground-based radio transmitter navigational aids (navaids; such as VORs or NDBs), or the intersection of two navaids' specific radials. Air corridors, on the other hand, are often mandated by military or diplomatic considerations in aviation. For example: During the Berlin Blockade, the commander in charge of the airlift set a highly particular placement inside air corridors, which pilots flying across Soviet-controlled German airspace were required to maintain. During the Cold War, subsequent
aircraft between West Germany and West Berlin, both military and civilian, were forced to stay within their assigned corridor or risk being shot down. (18) A pilot may deviate from airways when conditions permit but compliance with a specified air corridor is mandated.

In contrast, from the perspective of unmanned aircraft system, air corridor is a defined section of airspace in which an aircraft must remain while flying.

2.2. Geofence

Geofence can be defined as virtual three dimensional “boundaries” for UAVs. Each UAS either flies within or avoids a geofence as a no-fly zone (NFZ). (9).

\[
\text{Geofence, } g = \{n, v[], z_f, z_c, m, h[], ids[]\}
\]

In equation (2.1) of geofence, \( z_f \) and \( z_c \) represent minimum floor altitude and maximum ceiling altitude respectively, and a list of \( n \) horizontal vertices is \( v = v_1, ..., v_n \) for each \( v_i = (x_i, y_i) \), \( i = 1, ..., n \) and \( n \geq 3 \). The volume of geofence \( g \) is determined by \( z_f, z_c \) and \( v[] \). The collection of home locations is represented by \( h_i = (\phi_i, \lambda_i, z_i, t_i) \) where \( h[] \) is a list of length \( m \geq 2 \). The latitude, longitude, and altitude of the home location are \( \phi_i \), \( \lambda_i \), and \( z_i \) respectively. The activation time for home location \( i \) for \( 1 \leq i < m \) is represented by \( t_i \). Geofence has also has a deactivation time which is indicated by \( t_m \). The list of unique identification numbers of all the UAVs which has permission to enter and operate within geofence is represented by \( ids \). The volume if geofence is determined in relation to the set of home locations. Although the geofence boundaries are fixed in respect to the home location, the home location may vary.

There are different kinds of geofences. They are classified into two groups based on their permanence over time - static and dynamic. A static geofence is constantly operational and symbolizes unchanging boundaries such as international borders, property lines, buildings, utility poles and lines, and airport final approach and initial departure corridors that are open 24 hours a day, etc. A dynamic geofence, on the other hand, is a geofence that isn’t constantly active, and the home location isn’t always the same. The home location set (\( h[] \)) is used to distinguish between
geofences that are always active, only active for a certain amount of time, or migrate through space over time. Air corridors are classified as static geofences since their boundaries are fixed.

There are two other categories of geofences - keep in and keep out. The following specification specifies which UAS are permitted to fly where. The permissions assigned to a geofence govern whether UAVs interact with the geofence boundaries as a keep-in or a keep-out geofence. If a UAS is given permission to fly within the specified volume, it will classify the area as keep-in. On the other hand, a geofence is classified as keep-out if a UAS does not have clearance to fly within the specified volume. Air corridors can be defined as a keep-in geofence through which all UAVs fly while in transit.

2.3. V2V Communication

A V2V communication system allows two or more aircrafts to communicate directly with one another. V2V communications can be established in three ways: via satellite, via cellular networks, or via direct air-to-air communications (using WiFi or DSRC without the use of infrastructure). V2V communications are useful for sharing real-time information among aircraft and they provide two key advantages in the context of UTM: communication beyond radio line of sight and Collision avoidance between UAVs. In order to implement V2V communication, each aircraft must be identified by a unique ID and an IP address. The Federal Aviation Administration (FAA) and ASTM International (previously known as the American Society for Testing and Materials) recently published Remote ID standards. Remote ID refers to a UAS’s capacity to provide identification information to other parties while in flight. As the Remote ID definition develops, it will become the primary method of identifying a UAS in flight. (19)

2.4. Capacity in Aviation

In aviation capacity is defined by the maximum number of aircraft that the system or one of its components can accommodate in a particular time period. There are many factors that influence an ATS system’s capacity, such as route structure, aircraft using the airspace, weather, available equipment, etc. The natural desire to increase capacity should not result in a decrease in safety. The number of aircraft receiving air traffic controller (ATC) support should not exceed what can
be safely handled. The maximum number of airplanes that can be accepted within the airspace in a given period of time is referred to as ATC capacity. This can be represented as follows:

- **Entry counts**, or the number of aircraft that enter the concerned airspace for a specified period of time.
- **Occupancy counts**, or the number of aircraft that can be served at the same time.
- **Workload**, defined as the sum of all tasks that a controller is expected to complete, should not exceed a time limit.

When the demand for transportation exceeds the capacity, an overload occurs which may result in poorer safety margins since controllers must handle more aircraft than they are supposed to. Sector overflow could be caused by a variety of factors, including: 1) Capacity definition might be inadequate. As capacity evaluation is a detailed procedure involving highly skilled persons, this should not generally occur. However, any traffic assessment system needs balance between simplicity and accuracy, and so a situation may develop for which the model is insufficiently prepared. 2) The traffic forecast might be incorrect. 3) Unpredictable weather condition.

As unanticipated workloads can occur any time, some mitigation measures should be taken to deal with the scenario at least for a short period of time, which includes: 1) rigorous controller training, and 2) refresher controller training.

Rigorous controller training can be accomplished by requiring trainees to work in conditions similar to the sector (or unit) capacity. This is especially effective during simulator training, but the notion can also be used during on-the-job training. As a result, newly licensed controllers can deal with overload scenarios. On the other hand, controllers’ skills deteriorate over time, and it is probable that a protracted period of low traffic levels renders them less effective. This can be minimized by using a simulator for refresher training in settings with workload levels close to the sector capacity. (20)

### 2.5. Travel Time Estimation

Traffic congestion is becoming increasingly common in today’s increasingly crowded metropolitan settings. As the movement of products and people has been increased in past few decades,
understanding complicated city traffic patterns has been designated as a primary goal by twenty-first century urban planners, resulting in a significant rise in the amount and diversity of traffic data collected. For example, taxi companies in a growing number of major cities have begun to store metadata for each individual automobile ride, such as origin, destination, and travel time. One of the primary goals of traffic studies is travel time estimate, which refers to calculate the time required to go from the origin to the destination. This goal is difficult to achieve because travel times are affected by a variety of factors at different timescales, which includes number of lanes on each road, speed limit, weather condition, and so on. In (21), the authors propose a method for estimate travel times for each road in a metropolitan network, providing plausible paths and total trip time estimates for each origin and destination in the network.

2.6. Mobility Models

The fully random mobility models allows random nodes movement over a graph, such as the Random Walk (22) or the Random waypoint (23). The authors of (1) have classified all mobility descriptions as stochastic models that restrict random motions of nodes on a network and discussed different mobility models that limit random node movements.

Davies’s mobility concept (24) for the City Section is an example of mobility model where there model restricts node mobility on a grid road layout, with all edges being bi-directional single-lane roadways. Over the grid, vehicles choose one of the intersections randomly towards their destination and proceed towards it at a steady speed with one horizontal and one vertical movement at most. The vehicle’s speed is determined by the type of road it is going on: high-speed or low-speed road. Each node adjusts its speed accordingly. Because all nearby vehicles travel at the same speed and are allowed to overlap at road intersections, vehicle-to-vehicle interactions are disregarded. There are no specified pauses at intersections or at the end of journeys. Figure 2.1a shows an example of a vehicle journey using the City Section model where the dotted lines represent high-speed roadways. The vehicles go from (1, 4) to (4, 4) in multiple steps.

To investigate the effect of alternative mobility descriptions on several metrics of networking interest, the authors of (25) used a Freeway mobility model and a Manhattan mobility model. The Freeway model is based on the map in Figure 2.1b, which depicts many bi-directional multi-
lane freeways. In the figure, each line indicates a single highway lane. The arrows indicate the direction of vehicular travel. Each node’s mobility is limited to the lane on which it is currently
traveling. Each vehicle begins its travel at the start of a lane and terminates it when it reaches the end of the same lane. Then a new movement is initiated on a randomly picked lane.

As illustrated in Figure 2.1c, the Manhattan mobility model has a grid road topology where each line represents a single-lane road and the arrows indicate the direction of vehicular travel. The Manhattan model is introduced in (26) and this model uses a probabilistic method in the selection of node motions in the City Section, since a vehicle decides to proceed in the same direction with probability $1/2$ and to turn left or right with probability $1/4$ at each intersection. The speed management in the important framework implementation is the same as in the Freeway model, which is more realistic compared to the City Section model, where all vehicles moving on the same lane have the same velocity.

2.7. Stationary Node Distribution

Authors in (2) developed a new random direction mobility model (RD RMM) based modeling and analytical framework. UAVs fly independently in airspace $[0, B]^{2}$ (Figure 2.2) in the independent RD RMM model extensively used in the literature. UAV $i$ chooses a random heading direction $\Theta i[t]$ from $[0, 2\pi)$ at each time instant $1, 2, ..., t$, and travels that direction with a constant heading speed. Thus the probabilistic density function (pdf) of $\Theta i[t]$ is-

$$f(\Theta i[t] = \theta) = \frac{1}{2\pi}$$

The stochastic processes for UAS $i$’s position along the $x$ and $y$ axes are denoted by $X_i[t]$ and $Y_i[t]$.

The joint distribution of UAS locations and heading directions is referred to as node distribution. The stationary node distribution of each UAS is uniform, i.e.,

$$\lim_{t \to \infty} f((X_i[t] = x, Y_i[t] = y, \Theta_i[t] = \theta) = \frac{1}{2\pi B^2}$$

where, $x \in [0, B)$, $y \in [0, B)$, $\theta \in [0, 2\pi)$, and $i = 1, 2, ..., N$.

This paper also proves that regardless of the initial joint node distribution, the stationary joint node distribution of $N$ UAVs is also uniform.
2.8. Collision Probability

The relationship between communications channel failures and the probability of UAV collisions is derived in (27). The authors of this paper looked into two different scenarios: one with direct flight paths and the other with flight paths on a rectangular grid. In both circumstances, collision courses are possible. Two UAVs are said to be on a collision path when they approach each other so close that the required minimum distance of 10 meters is violated.

Communication system is designed in such a way that all relevant information regarding a UAV’s complete flight trajectory is contained in a single beacon message. As a result, if a UAV receives at least one beacon transmission from a possibly colliding UAV in sufficient time before the upcoming collision, it can detect a collision course. The probability of not correctly decoding a specific beacon transmission from a certain UAV is $1 - P_{\text{decode}}$. The probability of not correctly decoding any beacon message from a particular UAV over several successive frames is called missed detection probability and denoted as $P_{\text{miss}}$. Even if $1 - P_{\text{decode}}$ is high, the probability of missing a frame across a large number of frames can be quite low. For example, if $1 - P_{\text{decode}} = 0.5$, 

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**Figure 2.2.** Illustration of a 2-D airspace with UAS mobility captured by the independent RD RMMs. (2)
the chance of not receiving a single message in 30 frames is $P_{\text{miss}} = 0.5^{30} \approx 10^{-9}$ Due to changing interference conditions, $1 - P_{\text{decode}}$ may alter significantly over time. Conflict resolution can be automated if trustworthy trajectory information is available, which is not always the case, such as when an air vehicle collides with a flock of birds.

Aircraft separation in air corridors can assure a very low likelihood of collision. However, collisions can still occur due to position inaccuracy caused by navigation mistakes, atmospheric disturbances, or other circumstances. According to the The International Civil Aviation Organization (ICAO), the Target Level of Safety (TLS) is less than $5 \times 10^{-9}$ collisions per flight hour.

In the scenario of aircraft flying at the same speed along parallel tracks in the same direction, the probability of coincidence can be defined as the upper bound for the collision probability per unit distance. In the case of two aircraft flying at a constant separation, at least three probabilities of coincidence can be calculated -

1. The maximum probability of coincidence at the most likely point
2. The cumulative probability of coincidence integrated along the flight path
3. The cumulative probability of coincidence integrated across all space

The authors of (28) have applied these three probabilities of coincidence to both of the old standard (2000 ft) and new reduced vertical separations of 1000 ft, for comparison with the ICAO TLS and to assess their usefulness as safety measures. They have found that the possibility of supplementing the ICAO TLS $5 \times 10^{-9}$ per hour, which is appropriate for the cumulative probability of collision, with two additional safety metrics is raised-

1. One per hour flown squared, which is appropriate for comparison with the maximum joint probability density of collision
2. Another times hour flown, which is appropriate for comparison with the three-dimensional cumulative probability of coincidence

These measures have various dimensions, provide diverse information, and may serve as substitutes or supplements.
CHAPTER 3

AIR CORRIDOR FOR UNMANNED AIR VEHICLES

3.1. Introduction

The term air corridors are used in aviation that refer to virtual roads in the sky. From the perspective of a UAS, air corridor is a 3D volume of airspace that will be used by the (unmanned) aircraft throughout its journey. Other airspace construction components, such as an air cube, skylane, gates, vertiport, intersection, and so on, are integrated to make an air corridor. Air corridors will be established between 1000 and 2000 feet above ground level and will be utilized to transport people and packages. As a result, when designing air corridors, safety and efficiency would be the top priorities.

3.2. Definitions and Notations

Airspace is organized in terms of its building blocks - air cubes, skylanes, intersections and air corridors which constitute the airspace. Mathematical definitions of these building blocks will be discussed in this section. Unmanned aircraft systems (UASs) also require vertiports for takeoff and landing operations.

**Definition 3.1 (Air Cube).** An air cube \( c \) is a building block for a skylane in 3D airspace. An air cube is a static geofence in its most simplified form of a cube. All air cubes in one skylane are similar in size. An air cube is exclusively reserved space for an UAV in transit at any given time. According to Mid-Air-Collision (MAC) avoidance rules, the standard safe distance between two UAV’s is 500 ft. or 152.4 meters (29). In our model, the side length \( s \) of each air cube is set to 200 meters.

\[
c[cid] = \{cid, center, s, direction\}
\]

In equation 3.2, \( cid \) represents air cube identifier. Each air cube has a unique identifier \( cid \) which helps the UAVs to understand the cube occupancy information while moving. \( center = \{\phi, \lambda, z_c\} \), indicates the center point of the air cube, where \( \phi, \lambda, z_c \) represents latitude, longitude and ceiling
altitude respectively. From the side length (s) and the center of the air cube, the overall volume and position of air cube can be determined. Direction indicates the traffic flow direction ([East to West], [West to East], [South to North] or [North to South]) inside the cube.

**Definition 3.3 (Skylane or Track).** Skylane (S) can be defined as a volume consisting of a number of cubes which have same directions. In other word, skylane is formed by arranging a number of

![Diagram of Skylane Structure](image)

**Figure 3.1.** Skylane structure. Blue boxes represent variables that define the data elements of skylane. Green boxes represent variables that define movement directions of vehicles inside the skylane.
cubes in the same direction. An unmanned aircraft must fly within the skylane during its transit. An entrance gate is used to enter the skylane and one exit gate is used to exit the skylane. Gates are defined in 3.8.

\[(3.4) \quad S[\text{sid}] = \{\text{sid, direction, nc, c[cid], gates}\}\]

where, \(\text{sid}\) represents the unique identifier of the skylane, direction represents one of the the four directions of travel [East to West], [West to East], [South to North] or [North to South]. This paper considers three layered air corridors in a typical urban or rural setting, each layer consisting of two skylanes. The top layer contains two one-directional skylanes: South-to-North and North-to-South. The bottom layer contains two one-directional skylanes: East-to-West and West-to-East. The middle-layer is used by UAVs to take turns.

Figure 3.1 illustrates a data structure of an skylane where blue boxes represent variables that specify skylane data items such as air cube, gate, and so on. Green boxes represent variables that specify vehicle movement directions within the skylane. Length of an skylane, \(L\) is equal to \(n_c \times s\), where \(s\) is the side length of an air cube defined in meters and \(n_c\) is the number of air cubes.

**Definition 3.5 (Intersection).** An intersection is the junction where one skylane crosses another in the horizontal plane. In the skylane, it is the place where vehicles take turns or change their direction. In order to avoid collisions, an intersection is designed to include three layers. The middle layer is used for a temporary hovering before a UAV actually takes the intended turn.

**Definition 3.6 (Vertiport).** A vertical airport or vertiport (V) is a place for take-off and landing for UAVs.

\[(3.7) \quad V[\text{vid}] = \{\text{vid, v[ ], z_c, ids[ ]}\}\]

Each vertiport has a unique identifier \(\text{vid}\). The volume of a vertiport is defined by its horizontal vertices \(v[(x_1, y_1), (x_2, y_2), (x_3, y_3), (x_4, y_4)]\) and its maximum ceiling altitude \(z_c\). The array \(\text{ids[ ]}\) is the sequence of identification numbers of the UAVs that are permitted to land or take off from the
vertiport. This identification number will help other UAVs to know the occupancy information of the vertiport.

**Definition 3.8 (Gate).** A gate is a connection between a skylane and a vertiport. It regulates the takeoff and landing operations of the UAVs. Vehicles need to go through the gates to enter or exit the skylanes.

**Definition 3.9 (Air corridor).** An air corridor is a 3D volume of airspace reserved for UASs. The term 'air corridor' refers to the complete airspace structure which includes all skylanes, intersections, vertiports, and gates. Vehicles (unmanned) must travel within the air corridor at all times. As a result, air corridor can be defined as static geofence with keep-in boundaries.

3.3. Multi-layered Model Design and Rules of Engagement

Travel and transportation modes have evolved at a rapid pace over the previous few decades. Unmanned Aerial Vehicles (UAVs) are modes of transportation that can be employed for a variety of innovative applications. Among them the introduction of autonomous vehicles into Class B, C, and D airspace to carry people and cargo, requires preparation in terms of safety, security, and the protection of human life and habitat. Air corridor design, traffic restrictions in air corridors, safety standards, and performance specifications are all constantly evolving. Several research organizations are now researching airspace design concepts.

In this section, the design of a multi-layered air corridor, traffic coordination, and the rules of engagement in air corridors are described. The communication between UAVs is also presented here. This section also illustrates through few examples how UAVs can safely take turns at intersections.

3.3.1. Multi-layered Air Corridor Design

In a multi-layered air corridor model, the airspace is divided into two layers throughout the airspace except at intersections (Fig. 3.2). The top layer accommodates southbound and northbound traffic whereas the bottom layer accommodates eastbound and westbound traffic. The places where these two layers crosses each other are known as intersections. At intersections, there is also
Table 3.1. Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S[]$</td>
<td>List of skylanes</td>
<td>sid</td>
<td>Skylane identifier</td>
</tr>
<tr>
<td>ids[]</td>
<td>List of identification numbers of the permitted UAVs</td>
<td>$gc$</td>
<td>Gap between UAVs in terms of number of cubes</td>
</tr>
<tr>
<td>$V[]$</td>
<td>Vertiport</td>
<td>$vid$</td>
<td>Vertiport identifier</td>
</tr>
<tr>
<td>c[]</td>
<td>List of air cubes</td>
<td>cid</td>
<td>Air cube identifier</td>
</tr>
<tr>
<td>nc</td>
<td>Number of air cube</td>
<td>s</td>
<td>Side length of air cube</td>
</tr>
<tr>
<td>g</td>
<td>Geofence</td>
<td>$h_i$</td>
<td>Home location</td>
</tr>
<tr>
<td>n</td>
<td>Number of vertices in geofence</td>
<td>$v$</td>
<td>list of vertices in geofence</td>
</tr>
<tr>
<td>$z_f$</td>
<td>Minimum floor altitude</td>
<td>$z_c$</td>
<td>Maximum ceiling altitude</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Latitude</td>
<td>$\lambda$</td>
<td>Longitude</td>
</tr>
<tr>
<td>$z_i$</td>
<td>Altitude</td>
<td>$t_i$</td>
<td>Activation time</td>
</tr>
<tr>
<td>C</td>
<td>Capacity</td>
<td>N</td>
<td>Number of UAVs</td>
</tr>
<tr>
<td>l</td>
<td>Number of skylanes</td>
<td>L</td>
<td>Length of a skylane</td>
</tr>
<tr>
<td>T</td>
<td>Travel time</td>
<td>$T_{delay}$</td>
<td>Delay time</td>
</tr>
<tr>
<td>SD</td>
<td>Safety distance</td>
<td>$\alpha$</td>
<td>Acceleration</td>
</tr>
<tr>
<td>$u_{max}$</td>
<td>Maximum speed</td>
<td>$u_{min}$</td>
<td>Minimum speed</td>
</tr>
<tr>
<td>$u_i$</td>
<td>Speed of vehicle i</td>
<td>$x_i$</td>
<td>Position of vehicle i</td>
</tr>
</tbody>
</table>

a middle layer which is used by the vehicles for hovering while taking turns. Each layer of an air corridor is represented by its floor and ceiling altitudes $[Z_f[k], Z_c[k]], k=1,2,3.$

3.3.2. Rules of Engagement

The directions of the skylanes are fixed in top and bottom layers. As a result, the vehicles could move only in the predefined directions in these two layers. If a vehicle wants to change its direction, it needs to come to the middle layer, change its direction, and then go to the desired layer. If the air cube at the desired level is occupied, the vehicle has to wait in the middle layer.
(A) Side view of an air corridor: Skylanes on level 1 (East-West) are black, skylanes on level 3 (North-South) are blue, and level 2 is yellow.

(b) Top view of an air corridor: skylanes in level 1 (East-West) are in black color, skylanes in level 3 (North-South) are in blue color, and red boxes represent vertiports.

**Figure 3.2.** Design of a multi-layered air corridor.
briefly until the air cube becomes available. The main purpose of middle layer is to avoid collision while vehicles are taking turns.

This design puts the burden of collision avoidance on the vehicles. As long as the following rules of engagement are enforced, collisions can be avoided:

1. At any given time, a cube can be occupied by only one vehicle.
2. A vehicle needs to make sure that the air cube it is entering at time \((t+1)\) is going to be empty at time \((t+1)\).
3. Overtaking doesn’t occur in air corridor. If one UAV slows down, the UAVs at the rear need to slow down.

3.3.3. Communication

The UAVs are expected to be sufficiently autonomous to maneuver on their own, and equipped with detect and avoid (DAA) and vehicle-to-vehicle (V2V) communication capabilities. Vehicle-to-vehicle communication also includes vehicle-to-ground communication. Air corridor operations, on the other hand, do not entail contacts with Air Traffic Control (ATC). The communication range of UAVs within the corridor is 1 km or 5 cubes (considering the side length of each cube is 200m). The communications system is designed such that all UAVs communicate all required information about the entire flight trajectory (location, heading direction, velocity, and so on) within a radius of 1Km or 5 cubes. Communication allows the UAVs to know the velocity, position, direction of other vehicles; which helps them to maintain safe distance and avoid potential collision courses. Because of its detect and avoid (DAA) capability, UAVs can also avoid uncertainty in the sky, such as colliding with a flock of birds.

3.3.4. Flight Path from One Vertiport to Another

If a vehicle wants to travel from the south vertiport to the west vertiport, it will use the skylane from south to north at level 3, travel to an intersection, change its altitude to level 2 and heading direction towards west. The communication system will allow the UAV to acquire the occupancy information of five neighboring cubes in the next time step. If level 1 is empty at (next) time instant \((t+1)\), then the vehicle will go to level 1 switching to the westbound skylane to reach
its destination. Otherwise, the vehicle will hover in the middle layer until the level 1 becomes empty. The route is indicated in green color in Figure 3.3.

![Figure 3.3. Flight path from south vertiport to west vertiport in multi-layered air corridor.](image)

3.4. Intersection Handling

Intersections are the places where skylanes of top and bottom crosses each other. Intersections contain three levels to support vehicles while changing the direction of flight. When a vehicle needs to take a turn, it first goes to the middle layer (level 2), change its heading and then goes to the desired level. Before going to the desired level, the vehicle will check the occupancy of its desired level at the next time step. If the desired level (1 or 3) is occupied by another UAV at that time, then the UAV hovers in the middle layer until the desired level is empty.

Intersection is the only location in the air corridor which contains three levels. As a result, it is critical to handle intersections in a systematic manner in order to avoid potential collisions.
This section includes an example in which four UAVs take turns at the same time. Two scenarios are considered for this example: 1) the desired level is empty, and 2) the desired level is occupied.

![Diagram of traffic intersections in air corridors.](image)

**Figure 3.4.** Designing traffic intersections in air corridors.

Three level intersection in which each level contains four air cubes is illustrated in Figure 3.4. The four cubes in level 1 are 1A, 1B (for westbound vehicles), 1C and 1D (for eastbound vehicles); cubes in level 3 are labelled as 3A, 3C (for southbound vehicles), 3B and 3D (for northbound vehicles); Cubes in level 2 are 2A, 2B, 2C, and 2D and these cubes are used for hovering. Traffic pattern at intersections is illustrated with four examples in Figure 3.5 and Figure 3.6. In Figure 3.5, four UAVs are simultaneously turning at the intersection: (1) UAV 1 is turning from north to east, (2) UAV 2 is turning from north to west, (3) UAV 3 turning from south to east, and (4) UAV 4 is south to west. Figure 3.6 illustrates how the UAVs need to communicate to negotiate their position if the desired level is occupied by other UAVs. For simplicity, gap \( g \) between cubes is ignored, i.e., it is set to zero, in this example.

Traffic management at intersection is outlined in the following four steps.
Figure 3.5. Traffic management at intersections: first Illustration.
(1) Time step 1: At time $t_1$, only two vehicles are inside the intersection: UAV 1 in cube 3A and UAV 4 in cube 3D (Figure 3.5a).

(2) Time step 2: In step 2 ($t_2$), all vehicles move one cube further. Thus, 3A and 3C are occupied by UAV 2 and 1 respectively. Similarly, UAV 3 and 4 go to cube 3D and 3B respectively (Figure 3.5b).

(3) Time step 3: In this step, all vehicles will change their heading direction to take a turn. At time step 3 ($t_3$), all four UAVs will change their altitude and move to level 2 from level 3 (Figure 3.5c) assuming level two is not occupied by other UAVs.

(4) Time step 4: Two possible scenarios arise in step 4. In the first scenario, UAVs observe that all cubes in level 1 are empty. So, the UAVs will go to level 1 at time step 4 (Figure 3.5d).

In the second scenario, assume that cubes 1B and 1D in level 1 are occupied by UAV 5 and UAV 6 respectively, at time step 4. So the negotiation between UAVs can be carried out in two possible ways. In the first approach (Figure 3.6a), both UAV 3 and 4 will stay in level 2 (in cubes 2D and 2B), and UAV 1 and UAV 2 will move to level 1 (to cubes 1A and 1C) at step 4. At time step 5; UAV 2, UAV 5, and UAV 1 will move one cube further. Thus UAV 5 and UAV 1 will be at cube 1A and 1D respectively, which gives UAV 4 the opportunity to move to cube 1B. UAV 3 will still be hovering in second level at time step 5. UAV 3 will move towards level 1 at time step 6. In this negotiation procedure whoever gets empty cube first, will go first.

In the second approach (Figure 3.6b), UAV 1, UAV 3, UAV 4 will stay at level 2 (in cubes 2A, 2D, and 2B) and UAV 2 will move to level 1 (1A) at time step 4. At next time step, each UAV will move one step further. Thus cube 1A will be occupied by UAV 5 but other cubes inside the intersection will be empty which gives UAV 4, UAV 1, and UAV 3 to move to level 1 at time step 5 and keep moving towards their destination at the following time steps. In this negotiation procedure UAVs at the front get priority over the ones that are behind.
Figure 3.6. Traffic management at intersections: second illustration.
4.1. Capacity of Air Corridor

The notion of capacity of a corridor captures the idea of how many vehicles can safely fly in a given volume of airspace. In this section, the concept of capacity of an air corridor is introduced and analyzed. Estimated travel time inside the corridor is also calculated here.

4.1.1. Capacity

**Definition 4.1 (Capacity).** Capacity of an air corridor is defined by the maximum number of vehicles that can fly in the corridor maintaining minimum safe distance among them.

Many factors, such as route structure, weather conditions, established habits, available equipment, etc. can have an impact on capacity. Although it is natural to desire to enhance capacity, safety must not be compromised, and hence the number of aircraft should not exceed what can be safely managed. The maximum number of flights that can be safely accommodated should be calculated in a suitable manner.

Consider a unit cube with 1 unit volume and assume that it is divided into smaller cubes of side length $s$. If one UAV is allowed in each smaller cube, the capacity of the unit cube is would be $\frac{1}{s^3}$ where $s << 1$. In the three-layered air corridor model described in Section 3.3.1, the top and bottom layers are utilized for traffic and the middle layer is used for hosting the vehicles preparing for turns. In this model, the available space in the air corridor is limited to two layers. Hence the capacity of the air corridor is $\frac{2}{3 \times s^3}$ where $s << 1$. If one considers a skylane, the available airspace depends on on the length of the skylane ($L$), the side length of the air cube ($s$) and the minimum gap between the UAVs in terms of number of cubes ($gc$). Thus, the capacity ($C_{skylane}$) a skylane can be computed as

$$C_{skylane} = \left\{ \frac{L}{(gc + 1) \times s} \right\}.$$
For example, if the length of a skylane is 10 km, the side length of each cube is 200 m, and the gap between two vehicles is one cube, the capacity of the skylane is going to be 20.

4.1.2. Travel Time Estimation

Traffic congestion is becoming more widespread in today’s increasingly congested metropolitan environments. Understanding traffic patterns becomes a key urban planning problem as the movement of goods and people grows. One of the basic purposes of traffic studies is to estimate travel time, which entails evaluating the time necessary to get from one location to another.

Assuming that length of a cube $s$ and there are $nc$ number of cubes in a route, time per cube can be determined by dividing the length of the cube $(s)$ by the speed of the UAV $(u)$. Thus, the travel time for a UAV to complete the route is given by,

$$(4.3) \quad Travel\ Time, \ T = \frac{s \cdot nc}{u} + T_{\text{delay}},$$

where, the $u$ represents the vehicle speed, and $T_{\text{delay}}$ takes into account delays during take-off, landing, and waiting time during the travel. In estimating the travel times, It is convenient to consider intervals rather than fixed values for vehicle speeds and delays. For example, the speed of a vehicle $u \in [u_{\text{min}}, u_{\text{max}}]$ and the flight delay $T_{\text{delay}} \in [T_{\text{delay-min}}, T_{\text{delay-max}}]$.

For example, if the side length of cube $(s)$ is 200m, number of cubes $(nc)$ to travel between vertiport is 28, velocity $u(t) = [10, 100]$ m/s, delay $T_{\text{delay}} = [1, 5]$s; time per cube would be $[1.999, 20]$ seconds and total travel time is going to be $[56.99999, 565.00]$ seconds.

4.2. Mobility Model and Node Distribution

Mobility models describe the movements of mobile users in terms of position, velocity, and direction across time. The distribution of vehicle locations plays an important role in many computations related to traffic modeling. Estimation of vehicle location distribution requires a mobility model. From among the existing mobility models, the Manhattan Mobility Model (1) is the most suitable for modeling traffic in air corridors.
4.2.1. Manhattan Mobility Model with Safety Distance Rules

Figure 4.1 illustrates the Manhattan mobility model in an air corridor with four skylanes. South-north directional vehicles are colored in blue and east-west directional vehicles are colored in green. The intersection and vertiports are shown in yellow and red color respectively. At a given time instant $t$, vehicle $i$ is at position $x_i(t)$, and the speed of vehicle $i$ is $u_i(t)$. The vehicles in front and back of vehicle $i$ are represented as $(i+1)$ and $(i-1)$ located at $x_{i+1}$ and $x_{i-1}$ and their velocities are $u_{i+1}$ and $u_{i-1}$ respectively. The distance between $i$ and $i+1$ is $\Delta x_i$. Similarly, $j$ represents another vehicle moving from west to east and the vehicles in front and back of $j$ are $j+1$ and $j-1$ respectively. The distance between $j$ and $j+1$ is $\Delta x_j$.

![Figure 4.1](image.png)

**Figure 4.1.** North-south skylanes are represented in blue color, east-West skylanes are represented in green color, intersections are shown in yellow color, and vertiports are colored in red. Indices $i-1$, $i$, and $i+1$ represent three vehicles in level three and the distance between any pair of vehicles is $\Delta x_i$. Similarly, $j$, $j+1$, and $j-1$ represent three vehicles in level one and the distance between any pair of vehicles in this level is $\Delta x_j$. 

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Manhattan mobility model includes a minimum safety distance (SD) requirement between vehicles which is implemented in the lanes. Let $\eta$ be a random variable (RV) uniformly distributed in $[-1, 1]$ which adds randomness to the vehicle speed. The speed ($u_i$) of vehicle $i$ is also a uniform RV in the interval $[u_{min}, u_{max}]$ and $\alpha$ denotes the acceleration of vehicles.

\[ u_i(t + \Delta t) = u_i(t) + \eta \alpha \Delta t \]  
\[ (4.4) \]

If $u_i(t) > u_{max}$, then $u_i(t) = u_{max}$; 
\[ (4.5) \]

If $u_i(t) < u_{min}$, then $u_i(t) = u_{min}$; 
\[ (4.6) \]

If $\Delta x_i(t) \leq SD$, then $u_i(t) = u_{i+1}(t) - \alpha/2$; 
\[ (4.7) \]

Equation 4.4 represents vehicles speed where $\eta$ adds some randomness. Equation 4.5 and 4.6 limits the vehicles speed inside the corridor in the interval of $[u_{min}, u_{max}]$. Equation 4.7 provides the safety distance rules. If two UAVs become closer than the minimum SD, then the UAV at the rear slows down.

4.2.2. Probability Density Function of UAV Locations

The probability density function (PDF) of the location ($X[t]$) of UAVs, is given by,

\[ \lim_{t \to \infty} f(X[t] = c[cid], 1 \leq cid \leq nc) = \frac{1}{nc} \]
\[ (4.8) \]

where, the length of each skylane is represented in terms of number of air cubes is $nc$. Expressed in terms of distance, the length ($L$) of a skylane is the product of number of cubes ($nc$) and the side length of a cube ($s$), i.e., $L = nc \cdot s$. From (4.8), it can be deduced that the probability of an air cube being occupied by a UAV is given by $\frac{N}{nc}$, $N \leq nc$, where $N$ is the total number of UAVs. Lemma 1 suggests that the node distribution of UAV locations remains uniform as long as there are no obstacles in the skylane.

Lemma 4.9. Manhattan grid model leads to uniform distribution of locations of vehicles in a skylane. Traffic may be slow or fast, but, it always flows as long as there are no obstacles in the skylane.
The proof follows the Manhattan mobility Model with SD requirement described in (4.4) and the uniform distribution of both $u(t)$ and $\eta$.

4.3. Collision Probability

**Definition 4.10 (Collision Probability).** Collision is the situation when there are two or more UAVs in a cube at the same time.

Collision probability is the probability of one cube occupied by more than one UAV at the same time. One way to avoid any potential collision is to enforce the rule that there can be only one vehicle in a cube. This can be accomplished with the safety distance rule described in the mobility model (4.4). However, collision can occur for many unforeseen situations including congestion at intersections, vehicle failures, communication failure, weather condition etc. Lemma 4.11 estimates the probability of no collision probability as a function of number of UAVs present in a skylane.

**Lemma 4.11.** Assume that there are $N$ number of UAVs and $nc$ number of cubes in a skylane and $N << nc$. Then, the probability of no collision ($P_{\text{no-collision}}$) is given by:

\[
P_{\text{no-collision}} = \frac{(nc) \times (nc - 1) \times (nc - 2) \times \ldots \times (nc - (N - 1))}{(nc)^N} \sim \frac{(nc)^{nc-N+1/2}}{e^N \cdot (nc-N)^{nc-N+1/2}}
\]

**Proof**

With the restriction that only one UAV can be present in one cube at any given time, the number of ways $N$ UAVs can be in $nc$ number of cubes is given by:

\[
ncP_N = \frac{nc!}{(nc - N)!}
\]

This expression forms the numerator for the first expression on the right hand side of (4.12). If any UAV is allowed to occupy any cube without restriction, then the number of ways $N$ vehicles
occupy nc air cubes is given by \((nc)^N\). This forms the denominator for the first expression on the right hand side of (4.12). If both \(N\) and \((N - nc)\) are large numbers, we can use Sterling’s formula
\(n! \sim \sqrt{2\pi n} \left(\frac{n}{e}\right)^n\) to approximate the factorials. With this approximation, we can rewrite (4.14) as follows:

\[
ncP_N = \frac{nc!}{(nc-N)!} \sim \frac{(nc)^{nc+\frac{1}{2}}}{e^N \cdot (nc-N)^{nc-N+\frac{1}{2}}}
\]

(4.15) Probability of no collision = \(\frac{\text{Number of options with restriction}}{\text{Number of options without restriction}}\)

\[
= \frac{ncP_N}{(nc)^N}
= \frac{nc!}{(nc-N)!}
= \frac{(nc)^{nc-N+\frac{1}{2}}}{e^N \cdot (nc-N)^{nc-N+\frac{1}{2}}}
\]

Figure 4.2. Probability of collision \((P_{\text{collision}})\) and Probability of no collision \((P_{\text{no-collision}})\) vs. number of UAVs \((N)\) assuming number of air cubes \((nc = 100)\).
Figure 4.2 illustrates the collision probability with $nc$ set to 100. It also suggests that enforcing the rule that there can only be one UAV in one cube is best way to avoid collisions.
5.1. Overview

This section discusses the results of discrete-time simulations carried out to demonstrate the long-term distribution of UAV locations within a skylane as a function of system parameters such as the velocity of the UAVs, traffic volume, and length of time steps. For simplicity of the simulation, the skylane is considered as a one-dimensional grid. Vehicles can move from one cube to another at a time in one direction. Since vehicles have varying speeds, some vehicles may reach the next cube between time steps and some vehicles may not. Vehicles moving at the maximum speed may advance at most one air cube per time step.

Figure 5.1 depicts the skylane with $nc$ air cubes. Traffic flows from the left to the right, starting from cube 0. A new vehicle can enter cube 0 only when it is not occupied. Every vehicle leaves the skylane from cube $nc - 1$ and presence of obstacles is not taken into account. The Manhattan mobility model allows vehicles to move forward with a given probability ($P_{move}$) if the next cube is vacant. For a vehicle $i$ in cube $a$ at time $t$, the probabilities for the next time step $t + 1$ are:

\[
P_{i, t+1}(x = a + 1) = \begin{cases} 
0, & \text{if } a+1 \text{ occupied} \\
{P_{move}}, & \text{otherwise} 
\end{cases}
\]  

(5.1)
5.2. Simulation Comparing Different Velocities

Instead of simulating variations in vehicle’s velocity, the transition probabilities ($P_{stay}$ and $P_{move}$) for a vehicle to advance to the next cube are defined. Higher probability of vehicle staying in the same cube ($P_{stay}$) indicates that the traffic is moving slowly. Similarly, lower probability of vehicle staying in the same cube ($P_{stay}$) indicates that the traffic is moving fast. For fast moving vehicles, the probability of staying in one cube $P_{stay}$ is in the interval of [0.001, 0.050] and for slow moving vehicles $P_{stay}$ is in [0.20, 0.90]. The probability of a vehicle moving to the next cube, $P_{move} = 1 - P_{stay}$. The simulation was run for 100,000 time steps considering 20 vehicles in a skylane consisting of 100 air cubes.

5.2.1. Convergence

The simulation results at Figure 5.2 show that the standard deviation for the probability density function is much greater for slow traffic (Figure 5.2b) and the simulation takes much longer to converge compared to the fast traffic (Figure 5.2a).

5.2.2. Vehicle Distribution along the Skyclane

Simulation results depicts the occupancy information of 100 cubes having 20 UAVs. The simulation results show that in the case of slow traffic the cubes at the end of the skylane are less likely to be occupied (Figure 5.3) even with more simulation steps (Figure 5.4).

5.2.3. Trajectories

Simulation results (Figure 5.5) show how the vehicles move along the corridor in horizontal axis. The vertical axis depicts the time. Unlike road traffic, overtaking does not occur in air corridor. As a result, even a single slow vehicle impacts the traffic flow. Cubes at the end of the skylane becomes occupied soon in the case of fast moving UAVs (Figure 5.5a). On the other hand, Figure 5.5b depicts that the end of the skylane needs more time to become occupied if the UAVs are moving slowly.
5.3. Simulation Comparing Different Traffic Volumes

Traffic volume, i.e. ratio of vehicles to air cubes in skylane ($\frac{V}{NC}$) is analyzed here. Simulation results are shown for 10 and 50 UAVs in 100 air cubes which correspond to the ratios of vehicles to cubes 0.1 and 0.5 respectively. The simulation was run for 100,000 time steps.

5.3.1. Convergence

For low traffic volume, the standard deviation of the probability density function is substantially higher, and the simulation takes much longer to converge (Figure 5.6a). Higher traffic volume, on the other hand, requires less time to converge (Figure 5.6b).

5.3.2. Vehicle Distribution along the Skylane

Figure 5.7 shows that vehicle location distribution along the skylane is going to be stationary for different traffic volumes.

5.3.3. Trajectories

Higher traffic levels mean more UAVs, therefore the trajectory is more crowded than at lower traffic volumes. (Figure 5.8).

5.4. Probability Density

The vehicle distribution along the skylane for different traffic volumes is shown here. The horizontal axis in Figure 5.9 depicts the number of cubes, while the vertical axis represents the number of UAVs. The number of UAVs is represented by the color density. The fewer the UAVs, the deeper the color. The simulation results show that the probability density along the corridor is uniform despite the variances in traffic volume. For Each vehicle the likelihood to be in any cell should be equal.
Figure 5.2. Convergence of FAST vs SLOW moving vehicles.
Figure 5.3. Location distribution of FAST vs SLOW moving vehicles with 100,000 time steps.
Figure 5.4. Location distribution of FAST vs SLOW moving vehicles with 10,000,000 time steps.
Figure 5.5. Trajectories of FAST vs SLOW moving vehicles. (Only the first 200 time steps are shown.)
(a) Low traffic volume; i.e. Ratio of vehicles to air cubes in skyline \(\frac{N}{nc}\) = 0.1

(b) High traffic volume; i.e. Ratio of vehicles to air cubes in skyline \(\frac{N}{nc}\) = 0.5

**Figure 5.6.** Convergence for different traffic volumes.
(a) Low traffic volume; i.e. Ratio of vehicles to air cubes in skylane \((\frac{N}{nc}) = 0.1\)

(b) High traffic volume; i.e. Ratio of vehicles to air cubes in skylane \((\frac{N}{nc}) = 0.5\)

**Figure 5.7.** Location distribution for different traffic volumes.
(a) Low traffic volume; i.e. Ratio of vehicles to air cubes in skylane \( \left( \frac{N}{nc} \right) = 0.1 \)

(b) High traffic volume; i.e. Ratio of vehicles to air cubes in skylane \( \left( \frac{N}{nc} \right) = 0.5 \)

**Figure 5.8.** Vehicle trajectory analysis for different traffic volumes. (Only the first 200 time steps are shown.)
(a) Low traffic volume; i.e. Ratio of vehicles to air cubes in skylane \( \frac{N}{nc} \) = 0.1

(b) High traffic volume; i.e. Ratio of vehicles to air cubes in skylane \( \frac{N}{nc} \) = 0.5

Figure 5.9. Probability density analysis.
CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1. Conclusion

This thesis is concerned with the integration of unmanned systems into controlled airspace. Formal definitions for air corridor and its constituent building blocks including air cubes, skylanes, intersections, vertiports, and gates are provided in this thesis. A three layered air corridor model is designed to ensure effective traffic flow and rules of engagement for the collision-free traffic inside the corridors with an example is discussed. Traffic management at intersections is illustrated with few examples. The notion of capacity of skylane as a function of number of cubes and gap size between UAVs is presented. The travel time of an unmanned aerial vehicle (UAV) through a skylane is predicted using intervals for vehicle speeds and delays. Probability of collision and probability density of locations of vehicles in air corridors are also discussed. Finally the simulation results are presented for different traffic flow. Traffic simulations in air corridors show that vehicle density remains constant despite changes in traffic volume. The simulation findings also show that slower traffic and lower traffic quantities take longer to converge than quicker traffic and greater traffic volumes. Slower traffic has an effect on vehicle distribution and trajectory occupancy as well. They are, however, unaffected by differences in traffic levels.

6.2. Future Work

The notion of a "air corridor" provides various areas for further research. Firstly, More extensive research should be conducted on the communication protocol used within the corridor.

Another area of future work is the improvement of intersection handling. While the given approaches found a solution in the majority of situations, other scenarios, such as fixed rotor UAVs, were not satisfactorily addressed. An improved intersection handling method would increase the percentage of instances that could be solved.

The hardware requirements, such as vertiports for takeoff and landing, communication configuration, the aircraft itself, equipped with adequate sensors and components of required capacity,
make the task more difficult.

The air corridor model given here should be integrated with current airway for manned aircraft to better evaluate and verify air corridor in a UTM system. Such data is important for testing airspace management since, in the future, the air corridor for unmanned aircraft will most likely align with the airway for manned aircraft.

Finally, the air corridor must be implemented on a variety of UAS systems. Flight testing will help to confirm the design choices, as well as to indicate areas for additional research that may not be evident through modeling.
REFERENCES


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