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Digital Traffic Lights: UAS Collision Avoidance Strategy for Advanced Air Mobility Services

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Abstract: With the advancing development of Advanced Air Mobility (AAM), there is a collaborative effort to increase safety in the airspace. AAM is an advancing field of aviation that aims to contribute to the safe transportation of goods and people using aerial vehicles. When aerial vehicles are operating in high-density locations such as urban areas, it can become crucial to incorporate collision avoidance systems. Currently, there are available pilot advisory systems such as Traffic Collision and Avoidance Systems (TCAS) providing assistance to manned aircraft, although there are currently no collision avoidance systems for autonomous flights. Standards Organizations such as the Institute of Electrical and Electronics Engineers (IEEE), Radio Technical Commission for Aeronautics (RTCA), and General Aviation Manufacturers Association (GAMA) are working to develop cooperative autonomous flights using UAS-to-UAS Communication in structured and unstructured airspaces. This paper presents a new approach for collision avoidance strategies within structured airspace known as "digital traffic lights". The digital traffic lights are deployed over an area of land, controlling all UAVs that enter a potential collision zone and providing specific directions to mitigate a collision in the airspace. This strategy is proven through the results demonstrated through simulation in a Cesium Environment. With the deployment of the system, collision avoidance can be achieved for autonomous flights in all airspaces.

Keywords: uncrewed aircraft systems; UAS-to-UAS communication; collision avoidance; advanced air mobility; air corridor; air cell; digital traffic light; ground control station

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1. Introduction

The 20th century was a time period marked by numerous life-changing inventions. Travel on horseback, stagecoaches, and trains were once the standard means of travel, however, they stood no chance to the rapid development of more efficient transportation. Henry Ford was a pioneer in the automobile industry and was a leader in the exploration of this new frontier. His greatest contribution and their champion, the Model-T, revolutionized the world and made travel by automobiles affordable and accessible to the masses. With a dramatic influx of drivers came the need to manage the traffic to increase safety and optimize travel. By the 1910s, the United States saw 1.3 million drivers and nearly 4200 traffic-related deaths [1]. One of the first attempts at solving the influx of automobile-related deaths was the electric traffic light created by a Cleveland, Ohio, police officer by the name of Lester Wire. During their assignment to the traffic squad, Lester became concerned about the policemen who would stand in the middle of intersections to direct traffic. This concern led them to invent a device that could manage traffic and be operated from the side of the road [2]. While this electric stoplight only had two stages (stop and go), it revolutionized the infrastructure of American roadways and gave way to future innovations that formed and molded stoplights into what we see today. Humanity has paved roads and built infrastructure, completely transforming the world to make travel more safe and accessible to all, but now a new frontier has emerged.

In the very near future, drones, Uncrewed Aerial Vehicles (UAVs), or Uncrewed Aircraft Systems (UASs) will be sharing the airspace with other crewed and uncrewed aircraft systems in and around cities. Large UAS, such as passenger-carrying vehicles, are expected to fly in skylanes established in the airspace. A skyline is similar to a lane on an interstate highway. With these advancements in technology, there has been an effort to develop collision avoidance systems, similar to Lester Wires' invention, in order to preserve order and safety in the airways. Currently, UAVs are being used to transport goods to civilians. However, in the near future, UAVs will be of much greater use, such as transporting people to specific destinations. Air taxis and air ambulances will provide the opportunity for civilians to commute to locations using the airspace and ambulances to respond to accidents in significantly less time [3–5].

The unique design of the digital traffic light system is an autonomous and robust solution to air traffic management within a rapid and crowded environment. Currently, there are several studies that address algorithmic approaches to airspace management, collision avoidance, and system control. One study uses air route optimization with 3D-trajectory modeling [6], where 3D tubes are used for testing algorithms to determine the optimized solution to a traffic management system. Another study proposes optimal fuel-efficient trajectories [7], where the projected trajectory of an in-route UAV can be altered to effectively avoid a collision with some obstacle while ensuring optimized energy use. These altered trajectories, while maintaining optimized energy, are synchronized and used to provide a traffic management system. Lastly, another study for aircraft trajectory prediction suggests that through the testing of a trial trajectory, the trajectory can be determined based on a trial decision, allowing for the most suitable trajectory to be selected [8]. This allows the testing of the current trajectory to determine if action is required and, if so, will determine if the new trajectory is suitable to avoid an obstacle and be deployed for traffic management. While many studies and scholarly research have defined potential theoretical solutions, this paper presents a complete and research-based prototype that emulates an already working ground-based system in order to provide an appropriate collision avoidance system. Autonomous solutions and UAS-to-UAS communication are used to facilitate a data-driven protocol in order to design a fully acceptable solution in the airspace. This constant communication also allows for nonconforming cases to be addressed directly in place of the system without additional protocols in place. The system also uses a network of Ground Control Stations (GCS) for large-scale applications in order to allow for operation in urban areas with high traffic and buildings in the airspace. Lastly, the system introduces a structured airspace that uses air cells to drive the decisions made by the autonomous vehicles. With these contributions, logistics, emergency support, and transportation in the future will be facilitated in a safe manner due to advanced traffic management.

1.1. Advanced Air Mobility (AAM)

AAM is a major effort led by NASA to facilitate safe, accessible, automated, and affordable air transportation systems (ATS) at low altitudes around 400 m Above Ground Level (AGL) [9]. AAM services are currently in the experimental testing phase. AAM services are intended for passengers and cargo transportation serving urban as well as hard-to-reach rural and tribal locations [9]. Some common terms used within AAM include:

- **Autonomy**—Autonomy is defined as the ability of the aircraft to navigate with minimal or no human intervention [9]. There are multiple types of autonomy, which can be classified within a six-level system. Levels 0 through 2 are more oriented towards little to no autonomy and are used to classify vehicles whose controls originate from human operators [10]. On the other hand, levels 3 through 5 are more oriented toward vehicles with autonomous controls and decision-making capabilities. These vehicles use internal logic or machine learning models for motion control.

- **Detect and Avoid (DAA)**—Detect and Avoid within the scope of advanced air mobility is a system by which unmanned aerial vehicles communicate with each other to avoid collisions and maintain safe flying conditions [9]. Many applications use onboard sensors for detection and avoidance strategies, but the research conducted focuses mainly on UAS-to-UAS communication as a means to detect other UAS and collaborate to avoid collisions.
- **Geofence**—A Geofence is the practice of creating a virtual three-dimensional boundary around an area to maintain control of unmanned aerial vehicles [9]. By applying a Geofence to AAM, we can utilize an algorithmic approach ensuring the control of UAV within the airspace [11].
- **Urban Air Mobility (UAM)**—A component of Advanced Air Mobility for controlling aircraft in an urban environment [9].
- **Unmanned aerial vehicle (UAV)**—Small aircraft that can be remotely or autonomously controlled [9].
- **Vertiport**—Location in an urban environment where unmanned aerial vehicles can land and takeoff [9].

As AAM continues to develop, there are still some overarching questions: is this safe? How will the airspace be shared? What does this mean for high-density locations such as urban locations (i.e., cities)? In order to effectively incorporate these AAM concepts, a system must be developed for the monitoring of each of these concerns. As UAVs are increasingly being used, it is expected to share the airspace with both manned and unmanned aerial vehicles. This must be done in a safe manner to ensure not only the safety of all vehicles, transported people, and transported goods, but also of the people and infrastructure below that will be subjected to potential accidents. Some of these potential accidents could include packages or UAVs falling out of the sky due to a lack of a collision avoidance system.

1.2. Major Contributions

The invention described here is a method to establish a digital traffic light in the airspace, effectively managing traffic by assigning traffic lights. Currently, there are TCAS systems that manage manned airspace. However, there are no systems for autonomous control of collision avoidance [12]. The digital traffic lights will be established virtually in the airspace and managed on a server located on the ground or in the cloud. This server will be part of the Ground Control Station infrastructure and will allow for autonomous control of the airspace. The representation of a digital traffic light includes its airspace boundary and color (green, red, or yellow) in each direction of traffic flow, including signals for possible turns. Information will be shared with all UASs that are within the vicinity of the traffic intersection through electronic messaging to ensure safe operation. This information will also be shared with the UAS operators, software systems, and partners as needed in real time using UAS-to-UAS communication. Air corridors are virtual highways in the sky that are a vast volume allocated for the travel of aerial vehicles [13]. The proposed digital traffic light system contributes to the ideas of air corridors, air cells, digital flight rules, digital traffic management, and UAS-to-UAS Communications. These contributions help to achieve safety in the airspace, allowing for the development and implementation of AAM.

1.2.1. Digital Traffic Lights

Digital traffic lights is a developed object avoidance strategy that focuses on the contribution of air corridors, air cells, digital flight rules, and UAS-to-UAS communications. The digital traffic lights system will allow for the monitoring of aerial vehicles entering as well as allocating and updating new flight plans for the safe navigation of aerial vehicles through a four-way intersection.

Figure 1 shows a diagram of a four-way intersection managed by a digital traffic light. Here, we can see the UAV going westbound be given a green light color while the UAV heading northbound receives a red light color. The traffic light in the center of the intersection is representative of the role the GCS or cloud server will play and is not physically present in the sky.

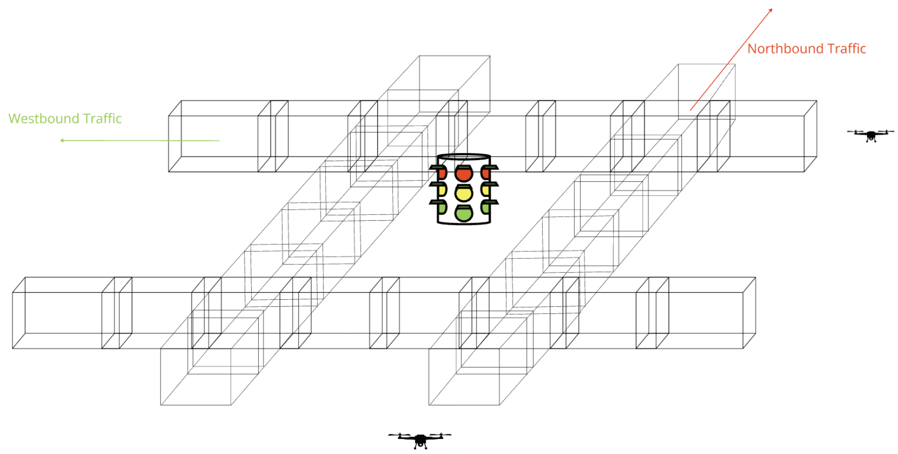

Figure 1. The air cell intersection for digital traffic lights.

1.2.2. Air Corridors

Air corridors are virtual highways in the sky that are a vast volume allocated for the travel of aerial vehicles [13]. These virtual highways are currently being used as a means to integrate airspace management for manned and unmanned aircraft flying at similar altitudes [3]. A four-way intersection is defined as an intersection of four air corridors that will cross in the airspace, providing the potential risk of collision. This potential risk requires the use of a monitoring and rerouting algorithm to safely navigate all aerial vehicles through the intersection.

1.2.3. Air Cells

A 3D volume of an air space can be described and represented by the smallest rectangular prism that encompasses this volume. For the present discussion, this rectangular prism is referred to as an "air cell". Each air cell is uniquely represented by its eight corners (C1 to C8), as shown in Figure 2. Each corner of the air cell can be denoted by its latitude, longitude, and altitude.

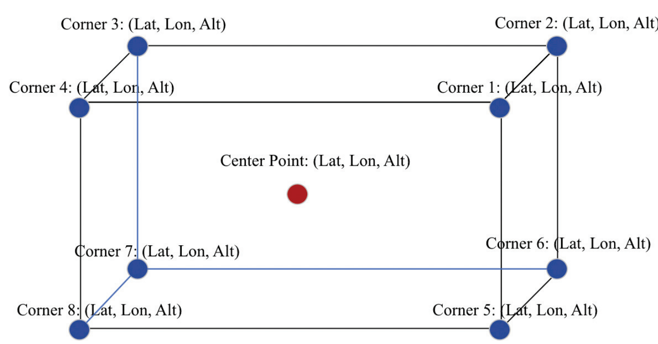

Figure 2. Air cell diagram.

As vehicles are traveling in the intersection of air corridors, they are flying with an operational intent while being monitored by a GCS. This GCS is using air cells to facilitate the digital flight rules concepts. These are a set of guidelines that all vehicles in air corridors are required to follow for sustained use [14]. Air cells monitor what cells are occupied at a specific time and prohibit the entering of other cells by vehicles. Digital traffic lights firstly issue new flight plans to navigate a four-way intersection. These flight plans will include a change of speed depending on the light received by the system. With the evolution of the system, additional constraints may enhance the optimization of flight trajectories provided by input from the AAM community. It then uses the concept of air cells to ensure that while a vehicle is traveling, there will be no collision in the intersection.

1.2.4. Digital Flight Traffic Rules

The implementation (operation and management) of digital traffic lights will be aligned with the implementation of digital flight traffic rules. All UASs are expected to follow the digital flight rules. The state of the traffic light, which includes the direction of allowed traffic flow, will be shared with all UASs within the vicinity of the intersection. A UAS that intends to pass through the intersection will need to verify that the traffic light is green in the direction it is flying before entering the intersection. Other digital flight rules that are being defined for this system include single occupancy, minimum separation distance, and overtaking not occurring in the air corridor [13]. Single occupancy requires that at all times only a single vehicle can occupy a cell at any time. Minimum separation distance prohibits any vehicle from entering any air cell that is one behind an occupied cell. Lastly, there can be no overtaking in the air corridors. These air corridors are only for the sustained use of aerial vehicles with operation intents. These rules are pivotal and will be facilitated by the air cells in the GCS .

1.2.5. Digital Traffic Management

Each digital traffic light will be represented in a computing system located physically on the ground near the air cell infrastructure (or in the cloud), which will be referred to as a server. This server will be part of the GCS that manages the traffic light. It is possible for one server to manage multiple digital traffic lights. The server gathers information about all UASs within the vicinity of an intersection using UAS to infrastructure communications, where it decides the direction in which traffic should be allowed to flow at any given time. The workflow for this system is as demonstrated in Figure 3. The decision on the direction of traffic flow at any given intersection will be based on the information that the server gathers from a variety of sources. This information includes the priority of the vehicles at the intersection, local weather, and the volume of traffic in each direction, among others. The server dynamically programs the digital traffic light based on the information it gathers from its sources. It shares the state of the digital traffic light with the GCS, the UASs, and their operators, following the industry standards.

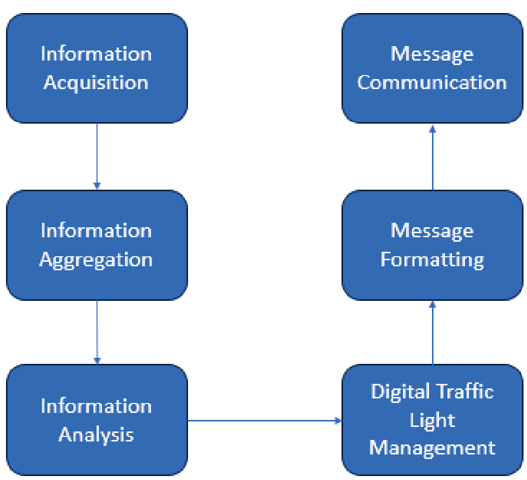

Figure 3. Data exchange for digital traffic management in the airspace.

1.2.6. UAS-to-UAS Communications

The state of a digital traffic light will be communicated with UAS through electronic messaging. The vehicles in the infrastructure will communicate via UAS-to-UAS communications, allowing for the position of other vehicles to be known [15,16]. The state is represented in the form of a data structure which includes the direction of the traffic flow, along with the location of the intersection in which the traffic light is located. In addition to the state and location, the message may include other related information (metadata), such as the beginning and end time of the traffic signals. All messages related to the digital traffic light are sent in real-time through the use of protocol buffers to format and serialize messages and mesh radios capable of utilizing internet protocols. This allows for communication with all the UAS within the vicinity of the intersection. UAS uses UAS-to-UAS communications and leverages the exchange of data to maintain minimum separation amongst one another inside air cell structures [17,18].

2. Problem Statement

As air mobility advances and the skies become more populated, a traffic system is necessary for regulation and flow control of traffic to avoid collision. Currently, there are no solutions for autonomous flights in the airspace. The proposed solution is a digital traffic light system that can monitor the airways and assign traffic light colors to unmanned aerial vehicles (UAV). This system was developed with the intent to increase safety and autonomy for unmanned flights by regulating the flow of traffic. This is achieved by using UAS-to-infrastructure (U2I) and infrastructure-to-UAS (I2U) communication, as well as digital air cells, to assign vehicles entering a four-way intersection a traffic light color that corresponds to a subsequent action that must be taken by the vehicle.

2.1. Concept and Proposed Solution

Digital traffic lights is a system for mitigating traffic using the air corridor concept. In this system, air corridors are made up of two or more lanes, allowing for structured AAM. Lanes are one-directional straight paths used to direct the flow of UAVs. This allows for a series of UAVs to flow in a single direction, reducing the probability of collisions. Each lane is made up of individual air cells that help define the structure of a lane. These air cells are the fundamental building block of the air corridors system. By making use of this hierarchy, digital traffic lights generate a four-way intersection that allows for redirection and an appropriate flow of traffic.

The digital traffic light system works with a GCS that appropriately monitors UAVs. This is achieved by two methods of communication which are broadcast messages and direct messages. The broadcasted message is a form of UAS-to-Infrastructure (U2I) and UAS-to-UAS communications that includes the heartbeat, which is general information on the vehicle, including telemetry data. The direct message is UAS-to-Infrastructure (U2I) communication that takes place between the GCS and the UAV in the air. This direct message is a request for information (RFI) from the GCS in order to receive the vehicle's Operational Intent (OI). As a UAV broadcasts a heartbeat and enters the range of the GCS, the GCS begins to monitor the UAV. Once a vehicle breaks a threshold and enters the four-way intersection, a direct message is sent by the GCS to the vehicle to facilitate the traffic light infrastructure. Once the vehicle responds with its current flight plan, the GCS processes the data and checks for possible future collisions with other UAVs in the intersection. If the GCS identifies more than one drone in the intersection and finds that there is potential for conflict, a system of stoplight colors such as green, yellow, and red is assigned to mitigate this collision. The yellow and red colors effectively slow the drones based on a queue system that allows for safe traversal in the intersection.

2.2. Rules of Engagement

2.2.1. Single Occupancy

At any given time, if there is more than one UAV in a single air cell, there is an increased risk of collision due to the nearby operation of these vehicles. Single occupancy will allow only a single vehicle in an air cell at a time. If a vehicle is attempting to enter an already-occupied air cell, the system will restrict the continuation of the flight and directly reduce the speed of the vehicle to ensure that there will be no two or more vehicles in a single cell. This will ensure the safety of all vehicles in the air space.

2.2.2. Minimum Separation Distance

As a flight operation takes place, it will be vital for the vehicles to maintain a minimum separation distance to ensure collision avoidance. This minimum separation distance will be defined as at least one unoccupied air cell between two flights at all times. Air cells will monitor the in-route flight operations by checking what air cells are actively occupied as well as determining the next air cell to be occupied. If there is an air cell that is occupied and the next air cell for that flight is already occupied, the system will restrict the continuation of that flight due to the potential collision. In response, the speed of the vehicle will be affected, allocating the preceding vehicle a sufficient amount of time to clear the next air cell. Once the minimum separation distance has been restored the speed of the vehicle can be restored. The administration of this digital flight rule will ensure the safety of all in-route vehicles.

2.2.3. Overtaking

As there is no standardized speed at which MAVs and UAVs must travel within air corridors, the potential of entering an occupied air cell and breaking the minimum separation distance is very high. Although, if the speed of one vehicle is much greater than a preceding vehicle, why not overtake it? Overtaking another vehicle is the act of passing a vehicle, which would be done for a multitude of reasons, including faster delivery, less potential of collision, etc. The way overtaking could occur is by allowing the vehicle to diverge from the air cells either above, below, to the right, or to the left of the lanes, depending on the orientation of the drone and how close the vehicle is to other vehicles in other lanes. However, within air corridors, there can be no overtaking. Air corridors are a large stretch of volume allocated for the transportation of aerial vehicles. These volumes do not provide enough space for safe side-by-side travel; additionally, a cell cannot contain more than one occupancy due to high risk. In order to facilitate this process, the digital flight rule of a breakdown lane will be implemented.

3. System Model

In the initial development of the digital traffic light system, ideal conditions are assumed. This includes airspaces that do not have obstruction, such as birds, unclear airspace due to weather conditions, or other unidentified potential risks that would otherwise deter from the logic developed in the system. Further implementation of the system would allow for more control of exterior variables and allow for other systems to work with the digital traffic light system.

For the development of the digital traffic lights system, the Software-In-The-Loop (SITL) autopilot software PX4-Autopilot [19] was used to simulate the flights of UAVs. A simple API using the MAVLink protocol [20] is used to extract the telemetry data of the software-defined UAVs, which is then transmitted to a test environment developed by the University of North Texas by making use of the CesiumJS environment [21]. This environment allows for all UAVs to be visualized as the logic of the flight rules constantly changes the flight of the UAVs by sending the appropriate MAVLink commands. The digital stoplight system uses the air cell system to generate the rules of engagement, which is also simulated in the CesiumJS environment. Since the air cells are integral to the digital stoplight system, the occupancy of the cell that the drone occupies can be tracked at all times, reducing collisions of UAVs and allowing for safe navigation. The values for the radius and locations of this system were used as proof of concept; these numbers are subject to change based on input from the AAM community. The simple block diagram of the system can be seen in Figure 4.

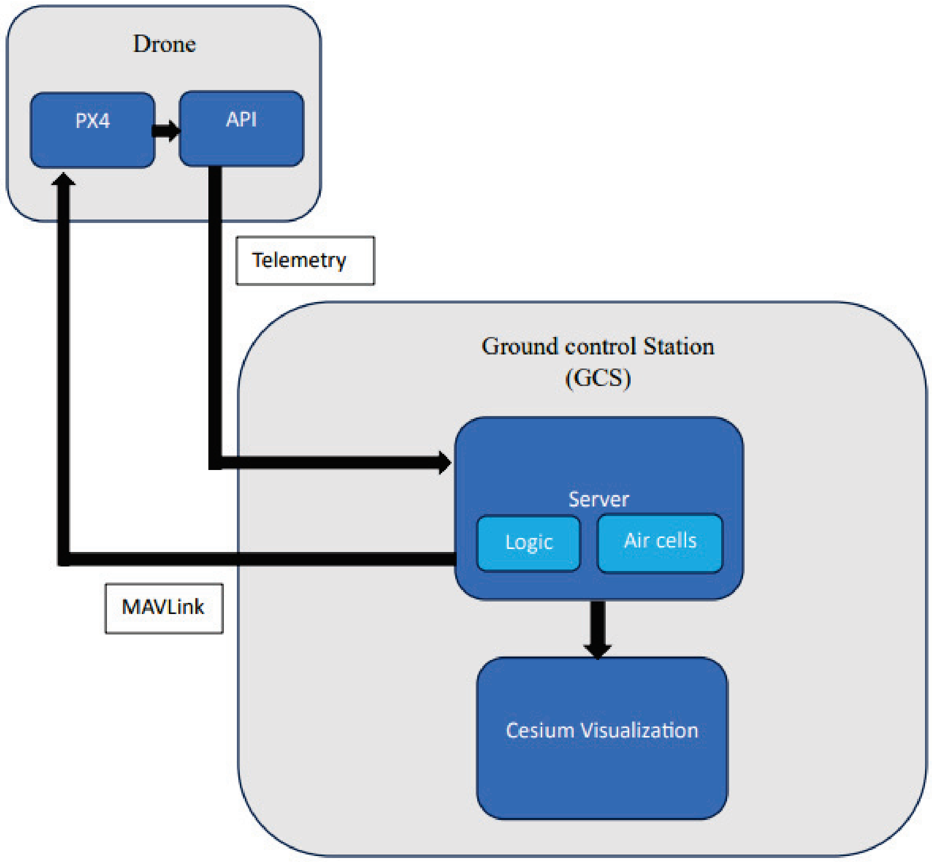

Figure 4. Block diagram scheme for the system.

Air cell digital infrastructure: The intersection for the digital traffic light system makes use of two corridors with two lanes in each corridor. The two corridors are perpendicular to one another, consisting of two lanes parallel to one another that support the flow of traffic in opposite directions. This is to say that there is a corridor that stretches with one lane going north to south and another going south to north. The second corridor stretches similarly, with one going east to west and another west to east. This allows for all directions of traffic to exist, which ultimately requires the digital traffic light system to control the traffic flow. In each lane, a system of cells is interlinked to establish lane structures in the airway. To establish these lanes, the air cells are developed using the dimensional properties of an octagon.

The concept of an octagon allows for lanes to be developed by making use of the points on the polygon directly opposite of one another and connecting them, which effectively creates four lanes. Each lane represents a flow of traffic in all four cardinal directions. These lanes are then divided into cells to create the entire ecosystem of the system that allows for the GCS to monitor the flight of all drones in the intersection.

The digital stoplight architecture uses a circumscribed circle to define the vertices on the octagon by using the circumradius. This simple algorithm uses the center position of the interchange and the circumradius of the system to calculate points in space that represent the vertices of the octagon at every 45 degrees on a circumcircle. The latitude and longitude position for each vertex in the octagon shape can be calculated with the equations below:

$$lat_n = h + R \cdot \cos\left(\frac{n \cdot 360^\circ}{8} + \alpha\right) \quad (1)$$

$$lon_n = k + R \cdot \sin\left(\frac{n \cdot 360^\circ}{8} + \alpha\right) \quad (2)$$

where h and k are the latitude and longitude values, respectively, of the specified center position where the digital stoplight infrastructure is to be generated. In this example, h is equal to 33.25356928863392 and k is equal to −97.1525712200369. This allows for this system to be developed on the spot at any location required. The size of the interchange can be dynamically fitted to any size desired by changing the circumradius R. The algorithm then uses the variable n as the index of the current angle for the vertex that is to be generated. The initial deceleration of the octagon is oriented towards the northwest cardinal direction with a heading of 315 degrees. In order for the interchange to be generated with true cardinal directions, the octagon must face true north. Therefore, the generated octagon must have an offset variable α of 45 degrees. After iterating through each vertex of the octagon and calculating its positions, the plotted positions for each vertex can be seen in Figure 5.

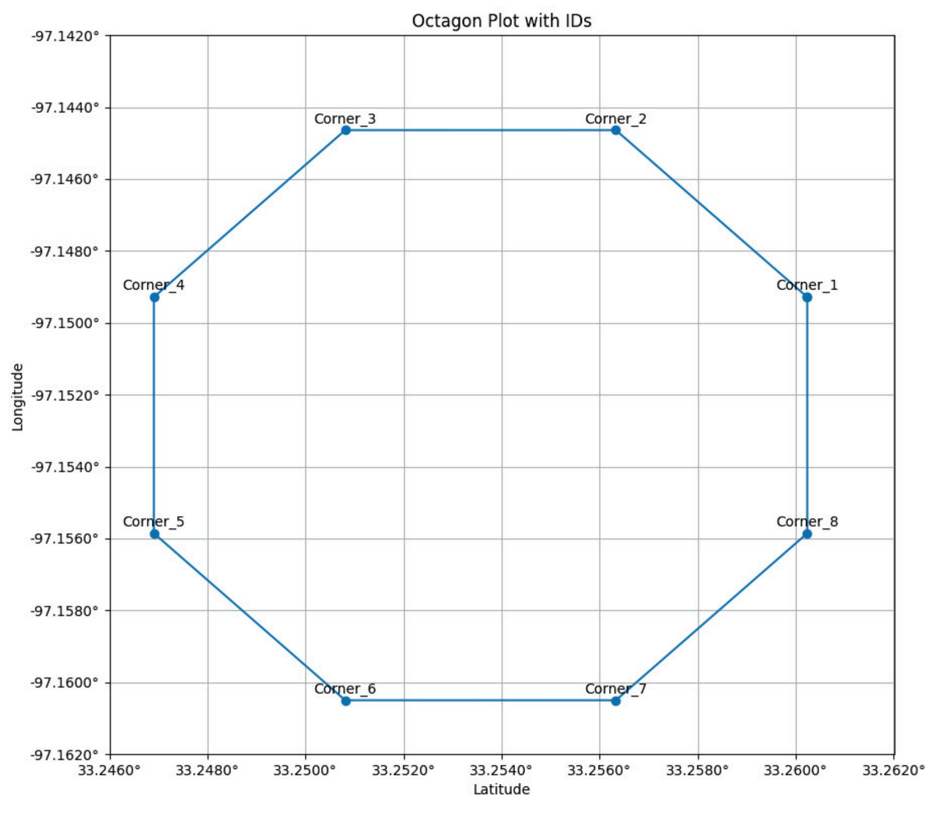

Figure 5. Octagon plot with corner ID.

With the implementation of the algorithm, the octagon structure defines eight vertices used for creating lanes. These lanes are generated by connecting opposite vertices in the polygon to define a line. This creates four different lanes to be used for each direction of traffic. Upon the generation of the lanes, equidistant points are plotted along the lanes, which represent the center positions of air cells. The number of equidistant waypoints can be proportionally scaled to the volume of an air cell. This will allow for a vehicle of N times the size of AAM vehicles to be able to operate in the specified airspace. The plotted center points of the cells can be seen below in Figure 6.

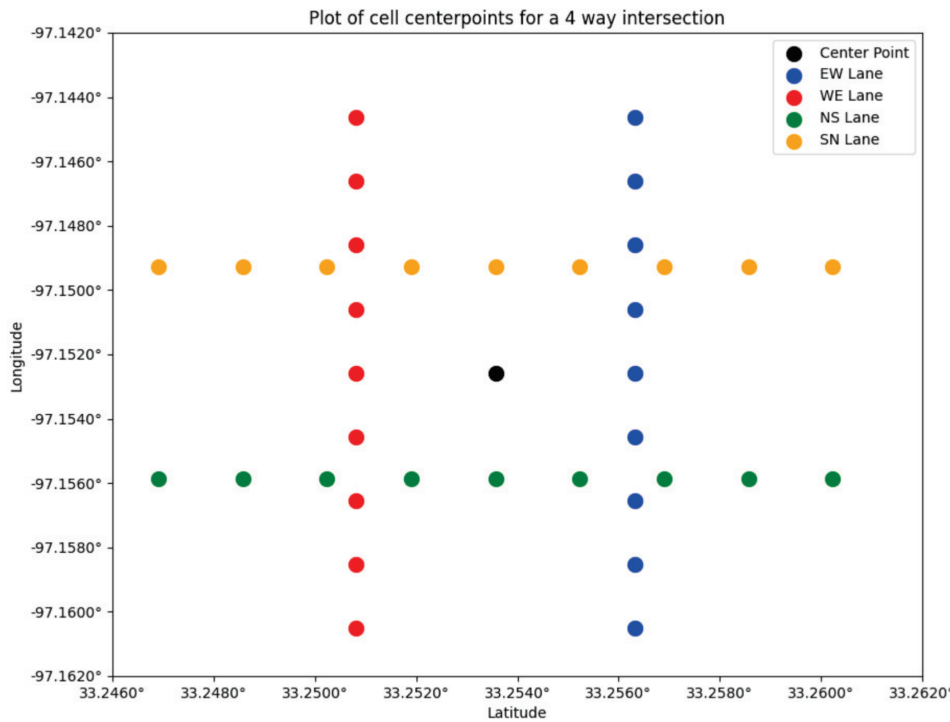

Figure 6. Cell center points plot.

The generated intersection can be seen in Figure 7. After all the center points of the air cells in the intersection are defined, the flight path of each route needs to be derived. To do this, the system utilizes Dijkstra's algorithm [22] to define the most optimal path through the intersection. This allows for all the paths through the intersection, such as straight, right, left, and u-turn, to be defined using the center points of the air cells. Dijkstra's algorithm allows for the routes through the interchange to be generated based on the ingress point and egress point. This allows for all possible paths in the intersection to be defined.

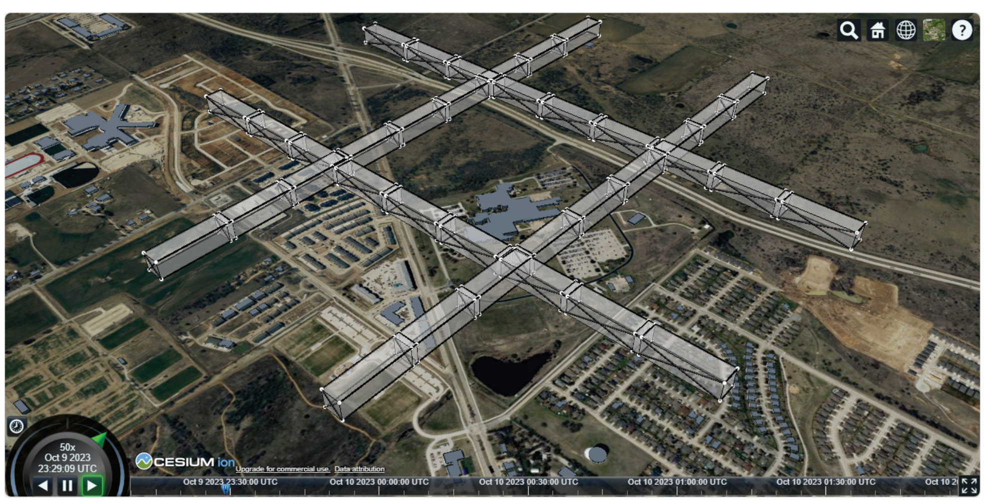

Figure 7. The generated intersection

Routing algorithm: When a vehicle enters the intersection, it must be able to efficiently traverse through while conforming to the flow and direction of traffic. To achieve this, an algorithm was developed that utilizes Dijkstra's algorithm to generate a route through the intersection for the UAV. The algorithm takes into consideration the UAVs ingress and egress direction to determine the lanes the drone must travel through. The air cell interchange only allows for the direction of traffic to flow in one direction, and thus, only the lanes that will allow the UAV to conform to standard road rules are considered, while the other lanes are ignored. For example, if the ingress is north and egress is east, only the north–south and west–east lanes will be used for the UAV to traverse through. To generate the route, the center points of all the air cells in each lane are inserted into a graph. The source node, in this case, is the first air cell in the ingress lane, and the target node is the last air cell in the egress lane. Once the graph is created and the source and target nodes are declared, edges are created between the nodes, with the weights being equal to the distance. Once the edges are created, Dijkstra algorithm is then used to generate the shortest path from the source node to the target, which then generates the path the UAV needs to traverse through the intersection.

Traffic light color assignment: When one or more UAVs enter the intersection radius defined as 800 m from the center point, the newly generated flight plans from Dijkstra's algorithm are queued. The distance is determined by taking the received heartbeats from the UAV and measuring the real position of the UAV asynchronously to the center point of the intersection, as seen in Figures 3–7. Once the UAVs are queued, their flight plans through the interchange are compared to determine the number of possible collisions. This is achieved by using the waypoints in a mission and creating a line string from it. Once the missions can be represented as a line string or a path, the number of possible intersection points and locations of those intersections can be derived. The intersection of two line strings here is indicative of an inborn collision between two UAVs. The returned values are used to assign each UAV a light color (green, yellow, or red), which will directly vary their speeds to ensure no collisions. The UAV with the least amount of intersections is given the green light due to the least chance of collision. Similarly, the light colors are distributed (with respect to green, yellow, and red) in increasing order of number of intersections. The UAV with the most intersection points will be assigned a red light, and the UAVs that fall in between in terms of intersections will be assigned yellow lights, instructing them to reduce their speed. If the UAV leaves the radius of the intersection, it is removed from the queue, allowing for the remaining UAVs in the intersection and any new UAVs that enter the radius to get a new light distribution.

The distance of the green drone to the point of collision of the subsequent yellow drone is used with the speed of the green drone in order to determine the amount of time expected to reach that point. Once this time zone has been determined, the speed of the yellow drone can be determined in order to ensure that the green drone gets to the collision point before the yellow drone changes its color to green and increases its speed to the same speed as the first green drone. This same process is completed for the yellow and red color drone speeds. Since the system only allows for four vehicles to enter the intersection at a time, there is a possibility for multiple instances of the same light color. The relationship still remains the same, just as color 1 and color 2 for defining when they can speed up for any color. This allows for no collisions utilizing the digital traffic light system with a fast and accurate processing capability.

In order to queue a UAV and make use of Dijkstra's algorithm, the 800-m radius is used from the center point of the interchange. The equations for determining if the UAV is in the radius make use of the Haversine formula. The Haversine formula is the equation used to precisely calculate the distance between two objects on the surface of a sphere, and in this case, it takes into account the curvature of the earth [23]. In Equations (3) and (4), the difference in the latitude and longitude between the UAV position and the center of the interchange is taken. These are known as the d_{lat} and d_{lon} values, and they are used in the calculation for the square of half the chord length known as "a" seen in Equation (5).

After a is defined, the angular distance in radians on the sphere is calculated, known as constant "c", as seen in Equation (6). Finally, the distance is calculated in Equation (7) by multiplying the angular distance c with the radius of the Earth:

$$d_{lat}(radians) = Center_{lat} - UAV_{lat} \tag{3}$$

$$d_{lon}(radians) = Center_{lon} - UAV_{lon} \tag{4}$$

$$a = \sin\left(\frac{d_{lat}}{2}\right)^2 + \cos(UAV_{lat})\cos(Center_{lat})\sin\left(\frac{d_{lon}}{2}\right)^2 \tag{5}$$

$$c = 2 * atan2(sqrt(a), sqrt(1-a)) \tag{6}$$

$$distance(meters) = c * 6371000.0 \tag{7}$$

4. Simulation and Results

In order for a smooth operation of the working digital traffic light system, consistent communication between all entities must be maintained. By utilizing the simulation environment CesiumJS, a three-dimensional intersection was developed in order to define the bounding areas of operation. This area represents the air corridor, which is constructed of air cells. This is what is referred to as a Geo-referenced environment. Utilizing this environment, users can see the real-time tests and flights of any UAVs in the airspace. This required generating digital operating UAVs by using the flight controller PX4 and transmitting the heartbeat of the UAVs on a 1Hz frequency. This flight controller allowed for the actual SITL implementation of these vehicles in order to fly along the predefined paths that go along the intersection corridors. For testing purposes, two UAVs are started from the ground, and both approach the intersection. Once the UAVs are in the defined radius, they begin to conform to the air cell infrastructure. Further implementation of the digital traffic light system may allow for a smoother transition as the corridors may extend further in all directions, and the control of the flight plans will be defined in entirety. In order for the full test to take place, a GCS is implemented and monitors and accepts all flights of drones. Once the UAVs are flying in the air, the exact WGS84 positions are tracked and stored in the GCS. This allows for the exact air cell that the UAV is in to be known. By extrapolating based on the initial flight plan, the next cell can be determined and compared with the other vehicles in the air space. Using the information known about the UAVs operating in the airspace, decisions and actions can be taken to prevent air collisions. In this case, the digital traffic light system assigns a color that represents the speed throughout the intersection and maintains communication in order to traverse the corridors. This is a dynamic assignment that can change based on the UAVs potential collision point. All of this happens simultaneously, and no collisions are seen. This allows for a visualization of UAVs in the environment and can seen below in Figure 8. The images used to suggest our system works are purely used to show the collision avoidance that is achieved by reducing the speed while utilizing the assigned traffic light colors. While this is the first iteration of the design, it is understood that the other portions of the digital traffic light system will be implemented in further development in order to achieve the full working system as described in this research.

In Figures 8–10, a fully constructed air cell intersection with two UAS traversing safely through can be seen. These vehicles were both confirmed to fly in the airspace with initial flight plans and fly as specified. Once a large number of vehicles congest the airspace, the problem of collision begins to become a major problem for the vehicles in the air and the people or entities below on the ground. This is where this assignment of the speeds through the interchange allows for a novel solution to the problem. Below, in Figure 9, a new perspective of the flying vehicle with different traffic light colors can be seen. This is a representation of how the traffic light system would operate from a ground perspective that allows for an interpretation from a bystander's perspective, showing the safety a person can feel knowing a solution to collisions in the airspace is presented.

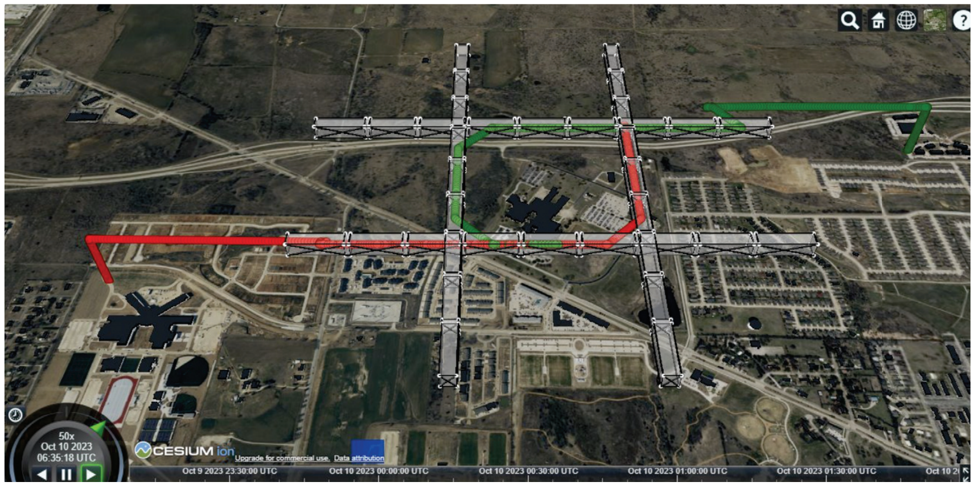

Figure 8. The air cell intersection—overhead view.

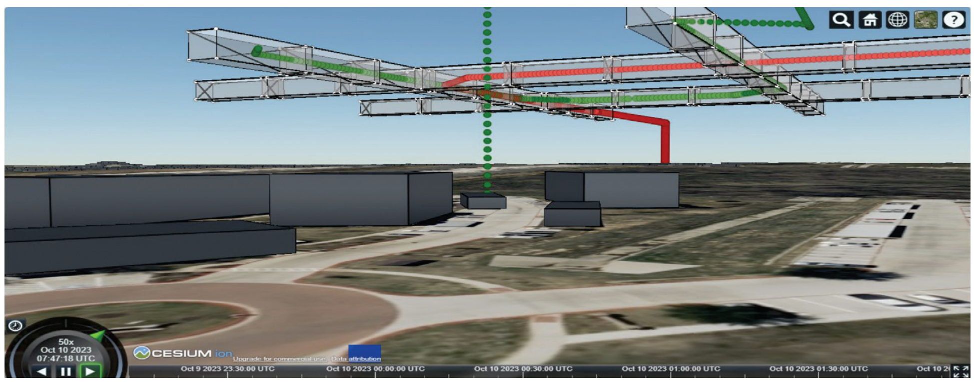

Figure 9. The air cell intersection—ground level view.

Lastly, in Figure 10, a close-up view of the air corridor can be seen. Each green dot inside the corridor represents the real-time telemetry of the UAV flying through the air space. It can be seen that at all times, the position of the UAV is known and is within the projected flight plan. With this information, the next point it intends to go to can be extrapolated, and collision can be detected. This allows for an intelligent understanding of how the vehicles will operate in the air space, suggesting the successful implementation of the digital traffic light system.

Overall, the testing of the digital traffic light system with the SITL-defined vehicles, GCS, and communication methods was a large success, which proved to provide a working solution to the projected congestion and expected collision in the airspace. This simulation allows for a real-time visualization of the flying UAVs, ensuring the system is working. Further testing may include the use of real UAVs in the airspace along with the working GCS, which will show the flying UAVs on the ground along with all the perspectives seen above in the SITL test.

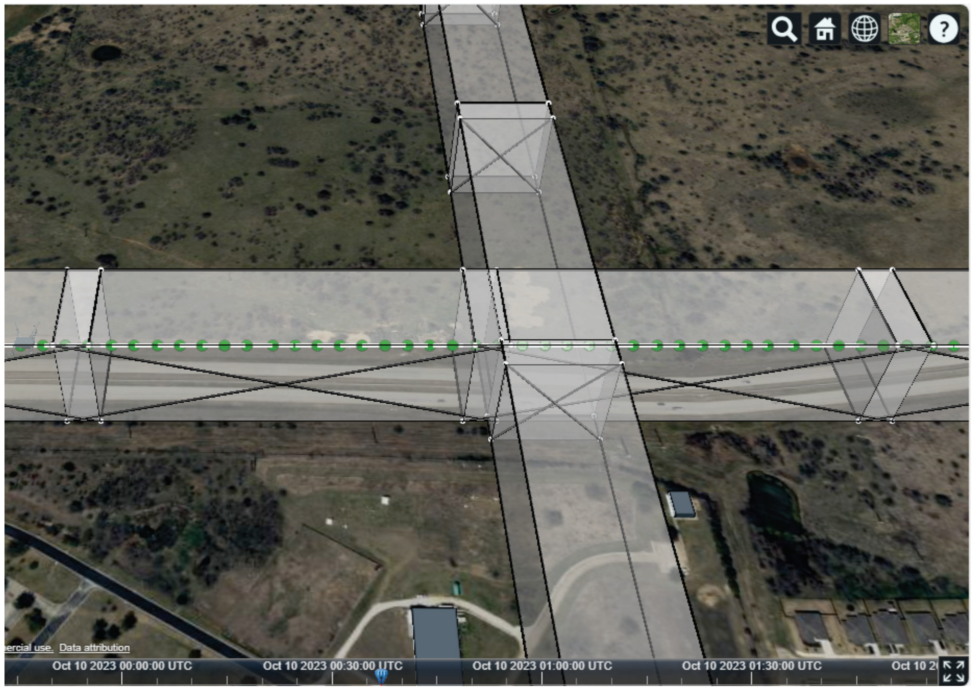

Figure 10. The air cell intersection—close-up view.

5. Conclusions and Future Work

As the efforts towards advanced air mobility are rapidly developing, there is a demand for safe transportation of goods and people. This paper proposed a new and novel solution for increasing safety and autonomy in the airways, known as the digital traffic light system. Utilizing a fully autonomous system, colors with associated speed are delineated in order to appropriately navigate an area in which a traffic intersection occurs. The system is developed using the fundamental theory of stoplights to structure and manage traffic in urban air spaces by enforcing calculated pathways to circumvent collisions. The proposed solution presented here was visualized using SITL programming efforts to demonstrate successful collision-free flights. This SITL demonstration can easily be applied to HITL UAV flights for effective control within an intersection at all times. With consistent testing and integration of the digital traffic light system, a perfected collision avoidance system will be implemented in real-world AAM applications, allowing for safe and fast transportation of goods and services.

Future works include overtaking, breakdown lanes, and response systems for emergency vehicles. These further implementations would allow for all of the airspace to be appropriately managed for all autonomous UAVs. These further protocols and future implementations could be implemented with machine learning applications in order to develop smart and more efficient ways of assigning colors. The testing would then be completed in a physics-based engine such as Unreal Engine or Unity in order to test the real application of the PX4 SITL in the airspace. Lastly, the system would be deployed to a large-scale network that utilizes many GCS. These GCS would maintain their own respective digital stoplight intersections while being interlinked with other types of air cell structures [24].

6. Patents

Due to the significance and relevance of this work, the digital traffic light system has been filed for patent under Application No. US 18/756,973 titled “METHOD AND APPARATUS FOR CREATING AND MANAGING DIGITAL TRAFFIC LIGHTS IN THE AIRSPACE”. This invention will address the expected collisions due to high trafficked areas in the near future from large investments and high volume use of UAVs in urban air spaces.

This will improve the air traffic and collaboration of UAVs and allow for a safe environment and easy integration for large-scale applications for a wide range of industries, including transportation, logistics, and medical emergency implementations [4,5].

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References

1. National Safety Council. Deaths and Rates. Available online: https://injuryfacts.nsc.org/motor-vehicle/historical-fatality-trends/deaths-and-rates/ (accessed on 11 July 2024).
2. Utah Department of Transportation. Happy Birthday, Lester Wire! Available online: https://udot.utah.gov/connect/2016/09/02/happy-birthday-lester-wire/ (accessed on 11 July 2024).
3. Namuduri, K. Digital Twin Approach for Integrated Airspace Management With Applications to Advanced Air Mobility. *IEEE Open J. Veh. Technol.* **2023**, *4*, 693–700. [CrossRef]
4. Goyal, R.; Cohen, A. Advanced Air Mobility: Opportunities and Challenges Deploying eVTOLs for Air Ambulance Service. *Appl. Sci.* **2022**, *12*, 1183. [CrossRef]
5. Johnson, W.; Silva, C. NASA concept vehicles and the engineering of advanced air mobility aircraft. *Aeronaut. J.* **2022**, *126*, 59–91. [CrossRef]
6. Durand, N.; Gianazza, D.; Gotteland, J.-B.; Alliot, J.-M. *Metaheuristics for Air Traffic Management*; Wiley: Hoboken, NJ, USA, 2015.
7. Pawelek, A.; Lichota, P.; Dalmau-Codina, R.; Prats, X. Fuel-Efficient Trajectories Traffic Synchronization. *J. Aircr.* **2019**, *56*, 481–492. [CrossRef]
8. Mondoloni, S.; Rozen, N. Aircraft Trajectory Prediction and Synchronization for Air Traffic Management Applications. *Prog. Aerosp. Sci.* **2020**, *119*, 100640. [CrossRef]
9. NASA. What is Advanced Air Mobility? A Student Guide. Available online: https://www.nasa.gov/wp-content/uploads/2020/05/what-is-aam-student-guide_0.pdf?emrc=482a27#:~:text=The%20vision%20of%20AAM%20is,reach%20urban%20and%20rural%20locations (accessed on 13 July 2024).
10. Alsadik, B.; Nex, F. The Rise in UAV Inspections for Civil Infrastructure. *GIM Int.* **2021** . Available online: https://www.gim-international.com/content/article/the-rise-in-uav-inspections-for-civil-infrastructure (accessed on 1 September 2024) .
11. Fu, Q.; Liang, X.; Zhang, J.; Qi, D.; Zhang, X. A Geofence Algorithm for Autonomous Flight Unmanned Aircraft System. In Proceedings of the 2019 International Conference on Communications, Information System and Computer Engineering (CISCE), Haikou, China, 19–21 July 2019; pp. 65–69. [CrossRef]
12. National Business Aviation Association. Traffic Collision Avoidance System (TCAS). Available online: https://nbaa.org/aircraft-operations/communications-navigation-surveillance-cns/tcas/ (accessed on 30 September 2024).
13. Muna, S.I.; Mukherjee, S.; Namuduri, K.; Compere, M.; Akbas, M.I.; Molnár, P.; Subramanian, R. Air Corridors: Concept, Design, Simulation, and Rules of Engagement. *Sensors* **2021**, *21*, 7536. [CrossRef]
14. Wing, D.; Lacher, A.; Ryan, W.; Cotton, W.; Stilwell, R.; Maris, J.; Vajda, P. Digital Flight: A New Cooperative Operating Mode to Complement VFR and IFR. *Tech. Memo.* **2022** . Available online: https://ntrs.nasa.gov/citations/20220013225 (accessed on 11 July 2024).
15. Darbha, S.; Konduri, S.; Pagilla, P.R. Benefits of V2V communication for autonomous and connected vehicles. *IEEE Trans. Intell. Transp. Syst.* **2019**, *20*, 1954–1963. [CrossRef]
16. Mandapaka, J.S.; Dalloul, B.; Hawkins, S.; Namuduri, K.; Nicoll, S.; Gambold, K. Collision Avoidance Strategies for Cooperative Unmanned Aircraft Systems using Vehicle-to-Vehicle Communications. In Proceedings of the 2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring), Florence, Italy, 20–23 June 2023; pp. 1–7.
17. Namduuri, K.; Mandapaka, J.S.; Kidane, M. The Philosophy of UAS-to-UAS Communications; ThinkMind: Coimbatore, Tamil Nadu, 2024. Available online: https://www.thinkmind.org/index.php?view=article&articleid=mobility_2024_1_10_70007 (accessed on 15 May 2024).
18. Al-Rubaye, S.; Tsourdos, A.; Namuduri, K. Advanced Air Mobility Operation and Infrastructure for Sustainable Connected eVTOL Vehicle. *Drones* **2023**, *7*, 319. [CrossRef]

19. Lorenz Meier, Thomas Gubler, and Contributors. PX4 Autopilot. Open Source Project. Available online: https://px4.io/ (accessed on 30 September 2024).
20. Lorenz Meier, MAVLink Contributors. MAVLink: Micro Air Vehicle Communication Protocol. Open Source Project. Available online: https://mavlink.io/en/ (accessed on 30 September 2024).
21. CesiumJS, Contributors. CesiumJS: A JavaScript Library for 3D Globes and Maps. Open Source Project. Available online: https://cesium.com/cesiumjs/ (accessed on 30 September 2024).
22. Dijkstra, E.W. A Note on Two Problems in Connexion with Graphs. *Numer. Math.* **1959**, *1*, 269–271. [CrossRef]
23. Karney, C.F.F. Algorithms for geodesics. *J. Geod.* **2013**, *87*, 43–55. [CrossRef]
24. Dalloul, B.; Mandapaka, J.S.; McCorkendale, L.; Nicoll, S.; Namuduri, K. Merging in Air Corridors Using Vehicle-to-Vehicle Communications. In Proceedings of the ICC 2024—IEEE International Conference on Communications, Denver, CO, USA, 9–13 June 2024; pp. 3894–3900.