The SkyLink Express: Structuring Unmanned Aerial Vehicle Transportation: Advancing Autonomous Navigation and Collision Avoidance

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Abstract - *Unmanned Aerial Vehicles (UAVs) hold immense potential to positively impact our world: they can streamline emergency operations, deliver emergency supplies to people in floods, and monitor atmospheric conditions ruined by climate change. However, the existing UAV infrastructure lacks a standardized and efficient system for navigating through airspace. This research paper aims to design an integrated Air Highway System that streamlines UAV operations. The SkyLink Express is structured with organized pathways and airspace, with designated directional highways for each travel direction. Standardization of UAV operations on the SkyLink Express is ensured through the integration of various sensor infrastructure, some of which include LiDAR sensors, Radar-Altimeter sensors, ADS-B modules, and a GPS/INS positioning system. The advanced autonomous navigation algorithm guides UAVs along designated routes with GPS waypoints, and the collision avoidance algorithm maintains a safe distance radius of 5 meters between UAVs, utilizing instantaneous speed information communicated through the ADS-B module and distance data from Lidar sensors. This algorithm adapts to dynamic environments in real-time, ensuring the safety and efficiency of UAV operations by making proactive decisions to avoid collisions. The SkyLink Express represents a transformative advancement in UAV technology, providing a reliable foundation for structured, safe UAV operations across their diverse applications. In conclusion, this system will ensure that the full potential of UAVs are utilized to positively impact communities worldwide.*

Key Words: **Unmanned Aerial Vehicle (UAV), Autonomous Navigation, Collision Avoidance, Geofencing, Flight Controller, Sensor Fusion, Automatic Dependent Surveillance-Broadcast (ADS-B), GPS Waypoints**

1.INTRODUCTION

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have experienced a significant increase in usage across numerous disciplines in the past few decades. They have become crucial resources in various applications due to their ability to perform tasks precisely, reach inaccessible areas, and operate with minimal human intervention. The widespread applications of UAVs are detailed in the table below.

Table -1: UAV Applications

Discipline	Application	Implications
Search and Rescue (SAR)	Use of imaging technology for locating missing people in various terrains	Increased success rates in finding missing people [1], faster response times, ability to access and survey hard-to-reach areas, safer operations for rescue teams [2], improved coordination through real-time data sharing
Border Security	Surveillance and patrolling along national borders	Enhanced detection of illegal crossings and smuggling activities, improved national security, real-time monitoring and quick response capabilities [3]
Military	Reconnaissance and surveillance [4]	Improved situational awareness, real-time intelligence gathering, reduced risk to military personnel, and improved security
Environme-ntal Monitoring	Use of various sensors (LiDAR, NIR, multispectral) for data collection on forest structure, topography, and environmental changes	Higher temporal resolution, ability to operate in adverse weather conditions, detailed and frequent observations of environmental changes [5], improved monitoring of natural resources and disaster management

Agriculture	Crop monitoring, disease diagnosis, water quality inspection, yield estimation	Improved crop management and yield predictions [6], early detection of diseases and pests, optimized use of resources such as water and fertilizers, cost savings compared to traditional methods, increased agricultural productivity and sustainability
Disaster Relief	Damage assessment, search for missing people, delivery of relief goods (food, water, medical supplies) in natural disasters	Faster assessment of disaster impact, timely delivery of essential supplies [7], ability to reach inaccessible areas [8], improved coordination with emergency responders, enhanced safety for human personnel
Fire Rescue	Aerial surveillance of fire zones, deployment of firefighting UAVs to drop flame-retardants	Real-time monitoring of fire spread [9], rapid deployment of firefighting measures, reduced risk to human firefighters, increased effectiveness in controlling and extinguishing fires [10], potential to save lives and property
Commercial Goods Delivery	Package Delivery with UAVs	Faster and more efficient delivery services [11], essential goods delivered to flooded areas/natural disaster destruction, reduced traffic congestion, improved logistics and supply chain management, potential for 24/7 delivery operations
Emergency Resource Dispatch	Rapid delivery of medical supplies and equipment in emergencies	Immediate access to critical resources in medical emergencies [12], potential to save lives, faster response times compared to traditional methods, ability to operate in difficult or hazardous conditions [13]
Geological Survey	Topographical mapping, hydrological modeling, monitoring geological changes	Detailed and accurate data collection, ability to survey large and remote areas [14], cost-effective compared to manned surveys, improved understanding of geological processes, enhanced planning and management of natural resources and infrastructure projects
Imaging	Orthomosaic and elevation data collection, wildfire monitoring, environmental monitoring	High-resolution and real-time data for various applications, ability to operate in challenging weather conditions, detailed monitoring of environmental and ecological changes [15], improved decision-making for conservation and management [16], enhanced ability to detect and respond to environmental hazards

Because of their widespread application, the proliferation of UAVs in the skies brings out significant challenges in managing their countless flight paths. One primary issue is the risk of mid-air collisions with other UAVs and manned aircraft. In addition, the lack of a standardized and efficient system for coordinating UAV traffic can lead to chaotic airspace, reducing operational efficiency and increasing the likelihood of UAV accidents. UAVs are set to become crucial in various industries, necessitating their safe and efficient operation. Without a strong solution, the UAV sector risks inhibiting the many benefits it can deliver.

To address these challenges, this research paper proposes the implementation of an organized Air Highway System designed specifically for UAV management. This system aims to create structured pathways in the sky to streamline the flow of UAVs, decrease collision risks, and optimize airspace usage.

2. LITERATURE REVIEW

2.1 Current Collision Avoidance Systems in Place

Table -2: Current Collision Avoidance System Evaluation

System Name	Key Features	Evaluation
Radar and Guidance Systems [17]	Uses FAA and 3D-specific radars for a comprehensive air picture; Provides visual and audible collision warnings and maneuver guidance; Advanced algorithms estimate collision risks; Operates for various UAS (Unmanned Aerial Systems) sizes without additional onboard equipment	**Benefits:** Enhances safety by detecting potential collisions, allows UAVs to operate in shared airspace, provides accurate tracking and monitoring, reduces human workload **Limitations:** Dependent on radar coverage and quality, high initial setup and maintenance costs, potential inactivity issues in high-traffic areas, requires integration with existing ATC infrastructure
DJI AirSense [18]	Utilizes Automatic Dependent Surveillance-Broadcast (ADS-B) technology to receive signals from nearby aircraft; Provides instantaneous alerts to UAV operators about the presence of manned aircraft; Displays the aircraft's location on the UAV controller's screen	**Benefits:** Enhances situational awareness by providing real-time alerts, easy integration with existing DJI drones, improves safety in shared airspace **Limitations:** Relies on ADS-B signals, which not all aircraft may broadcast; can be limited by the range and accuracy of ADS-B receivers, effective only when other aircraft are equipped with ADS-B transponders
Intel's RealSense Technology [19]	Uses stereo cameras and depth-sensing technology to avoid obstacles; Live 3D mapping of the environment; Uses advanced algorithms for path planning and collision avoidance	**Benefits:** Provides robust obstacle detection and avoidance, effective in a variety of environments, including indoor and outdoor, enhances UAV autonomy and safety. **Limitations:** Requires significant computational power, limited by the range and accuracy of the sensors, may struggle in low-light conditions or with highly reflective surfaces

2.2 Gaps in Current Collision Avoidance Systems

To establish a safe and efficient infrastructure with the widespread use of UAVs, several gaps must be addressed. First, many UAV collision avoidance systems are **not fully integrated with existing ATC infrastructure**. This lack of integration causes communication breakdowns and coordination challenges between manned and unmanned aircraft, leading to potential safety risks. Additionally, UAV collision avoidance systems often **rely on radar or depth-sensing technologies**, which can be limited by range, environmental conditions, and signal reliability. Collisions will also increase due to incomplete coverage or signal interruptions which lead to gaps in the UAV's situational awareness. This high computational power demand may further limit the operational endurance and efficiency of UAVs, more so in smaller models with low battery capacity. Specific environments, such as low light conditions or those with high reflectivity, are challenging for sensor-based collision avoidance. Those types of environments will reduce sensor performance, reducing the detectability and avoidability of obstacles by a UAV.

This also presents the biggest challenge: standardization among different UAV collision avoidance systems. Without standardized protocols and systems, ensuring that all UAVs will be able to coordinate with one another becomes difficult—increasing the risk of mid-air collisions.

2.3 Overview of Recent Developments in UAV Navigation

Recent advancements in autonomous UAV navigation have significantly enhanced the capability, efficiency, and safety of UAVs. These developments contain a wide range of innovative algorithms and technologies aimed at improving the precision and reliability of UAV operations.

Table -3: Technological Advancements in UAV Navigation

Technology	Development	Impact
Machine Learning (ML) and AI Integration [20]	ML and AI algorithms are being integrated at a growing pace into navigation systems of UAVs. These technologies not only give a UAV the ability to learn from its environment but also increase its decision-making abilities over time.	AI-driven navigation allows a UAV to forecast and respond more efficiently to dynamic obstacles and changes in the environment, thereby enhancing the safety and efficiency of UAV operations.
SLAM (Simultaneous Localization and Mapping) [21]	SLAM algorithms can be used to enable a UAV to build and update a map of an unknown environment while keeping track of its location inside.	This is a critical capability in GPS-denied environments, such as navigation indoors or underground, for autonomous navigation. SLAM increases the ability of the UAV to navigate precisely and avoid obstacles instantaneously.
Path Planning and Optimization [22]	These are advanced path planning algorithms, such as A* and RRT, currently being optimized for use in UAV applications. The approaches enable finding the most effective and collision-free paths that UAVs should fly through.	Improved path planning will therefore enable a UAV to self-navigate efficiently in complex environments, while minimizing energy consumption and travel time, by avoiding obstacles.
Sensor Fusion [23]	Sensor fusion techniques combine data from many different sensors, including LiDAR, cameras, and IMUs, Inertial Measurement Units, providing an understanding of the surroundings of a UAV.	It enhances the accuracy of the navigation system installed in the UAV, making it more reliable through sensor fusion, and thereby provides more accurate obstacle detection and avoidance.
Decentralized Navigation Systems [24]	A decentralized navigation system is a system wherein a number of UAVs could act together without being controlled by one central unit. Distributed algorithms for exchanging information and making collective decisions are used in decentralized navigation systems.	This enhances the scalability and strength of UAV fleets, finally allowing them to execute complex missions and carrying out tasks such as search and rescue or large-area surveillance.

2.4 Gaps in Current Autonomous Navigation Infrastructure

UAVs often **struggle with navigation in diverse and unpredictable environments**. These environments pose significant challenges due to GPS signal obstruction, dynamic obstacles, and complex terrain. Real-time decision-making is critical for collision avoidance and path planning. However, current systems can experience **latency issues**, especially in high-traffic areas or when processing large amounts of sensor data. This latency can reduce the effectiveness of navigation and collision avoidance systems. Current decentralized navigation systems need further development to handle large-scale UAV operations effectively. Ensuring that multiple UAVs can operate in coordination without central control remains a challenge, particularly in terms of **information sharing and collaborative decision-making.** While sensor fusion enhances navigation accuracy, it also comes with limitations. Combining data from various sensors (LiDAR, cameras, IMUs) can be complex and may still result in errors due to **sensor malfunctions, data inconsistencies, or environmental factors** like poor lighting or reflective surfaces. The deployment of autonomous UAVs raises various **ethical and regulatory concerns**, such as privacy, surveillance, and the safe integration into public spaces. Addressing these issues requires comprehensive policies and international cooperation. By identifying and addressing these gaps, advancements in autonomous navigation infrastructure can continue to improve, leading to safer and more efficient UAV operations across various industries and applications.

3. DETAILED OVERVIEW OF THE SKYLINK EXPRESS

3.1 Key Terms

Table -4: Key Terms for the SkyLink Express

Directional Highways	Divided Lanes	SkyLink Express
Directional highways refer to the levels that this highway system contains. These altitude levels were strategically chosen after considering tall structures and commercial planes. East-West (1500-1800 ft) NE-SW (1900-2200 ft) NW-SE (2300-2600 ft) North-South (2700-3000 ft).	Just as in a normal highway, the SkyLink Express has divided lanes on each directional highway for UAVs going in opposite directions. For instance, on the East-West highway, there are divided lanes for UAVs going East-West and vice versa.	Refers to one holistic air highway system, consisting of 4 directional highways and 8 divided lanes (2 on each highway). One SkyLink Express located in every state.

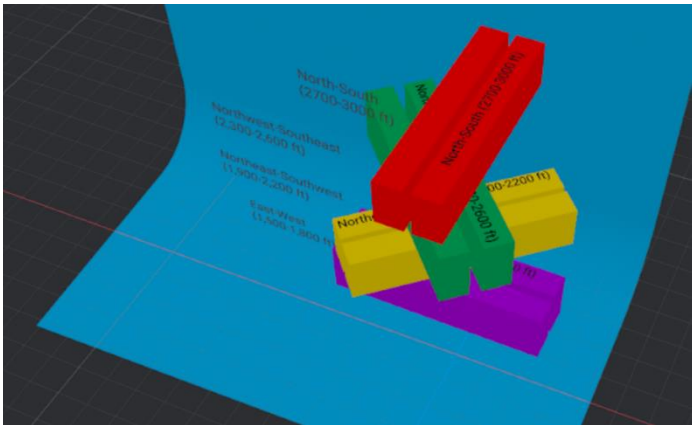


Fig -1: SkyLink Express Structure – Top View

Fig -2: SkyLink Express Structure – Front View

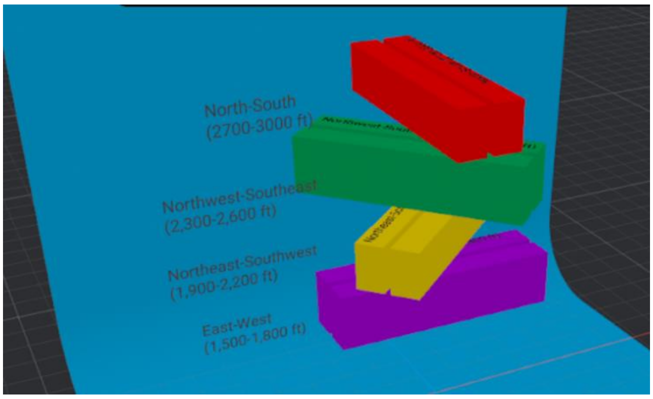


Fig -3: SkyLink Express Structure – Side View

3.2 Regional Organization

Each SkyLink Express is organized regionally by state; SkyLink Expresses will be implemented solely within the United States, but future avenues may involve global expansion. Within each state's SkyLink Express, UAVs may have different applications according to that state's particular UAV needs, but common applications such as delivery and emergency response are commonly applied across all SkyLink Expresses. For instance, rural states such as Vermont may further emphasize agricultural and environmental applications UAVs as compared to a more urban region such as California, which may place more emphasis on commercial delivery. Nonetheless, UAVs are encouraged to travel into neighboring states' SkyLink Expresses, improving connectivity and allowing for farther travel routes.

Fig -4: National Connectivity

3.3 Cooperation with Existing Air Traffic Control Infrastructure

To ensure that UAVs on this system can coexist with existing aircraft infrastructure, a centralized air traffic control (ATC) system is used to streamline UAV navigation and ensure that they are aware when other aircraft travel across the SkyLink Express's directional highways. This centralized ATC system, hosting commercial plane signals **and UAVs** on it, allows for coordinated travel routes that improve safety between the two aircraft's travel paths.

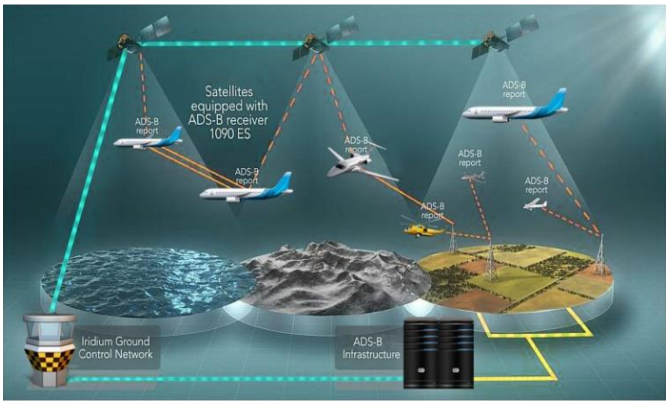


Fig -5: ADS-B Flow of Communication

The primary infrastructure for ATC integration on the SkyLink Express is an emerging technology known as Automatic Dependent Surveillance Broadcast (ADS-B); these transmitters consist of two primary parts: ADS-B Out and ADS-B In. ADS-B Out is a surveillance technology for tracking aircraft - it's what ATC uses to manage traffic [25]. These transmissions are broadcasted once per second [26] at a 1090 MHz frequency [27]. This is the module equipped on the UAV that communicates GPS-derived location, altitude, velocity data once per second. Satellites equipped with ADS-B receivers in low Earth orbit (LEO) capture these ADS-B signals, then relaying this received ADS-B data to ground stations. Ground stations process the ADS-B data and send it to ATC centers for real-time tracking and management of air traffic. Using this instantaneous position data, air traffic controllers can display UAVs on an ATC system using unique identifier codes. The relevant identifier codes used in ADS-B transmission systems are ICAO 24-bit addresses, which are assigned by the International Civil Aviation Organization [28]; each UAV possesses its own unique code in order to be identified. With the information that UAVs provide, ATC's can monitor aircraft flight paths and transmit information to UAVs again in the case of emerging dangerous weather conditions, changing air traffic conditions, or oncoming commercial aircraft traffic. This process allows ATC to regulate air traffic and ensure that the SkyLink Express infrastructure can operate safely alongside commercial aircraft.

ADS-B In receivers are also equipped onto all UAVs, and this involves a UAV receiving transmissions from ADS-B ground stations and/or other UAVs in the surrounding area [29]. UAVs in a concentrated area can receive ADS-B transmissions from other UAVs in the area containing GPS position, velocity, and altitude. By obtaining this information from nearby UAVs, each UAV can determine the relative positions of others, aiding in collision avoidance decision-making; this information is also directly used in the collision avoidance algorithm. When UAVs in a localized area receive messages from ground stations about oncoming commercial aircraft traffic, they follow relevant right-of-way rules, stopping and yielding to the commercial aircraft.

Traditionally, ADS transmissions are processed by pilots aboard the aircraft that uses the module, but in the case of UAVs without pilots, the processing system within their flight controllers will interpret the ADS transmissions and take necessary action. To ensure compliance with current FAA regulations on ADS-B systems, backup UAV remote operators will maintain communication with ATC through the ADS-B transmission.

3.4 Border Security

To prevent UAVs from crossing unauthorized national borders, such as those between the U.S. and Mexico or Canada, there is one horizontal highway lane along the border, solely designated for UAVs securing the border. The SkyLink Express will be compatible with border security UAVs, as they will monitor border security along one designated altitude level across the border. In order to ensure regulatory compliance over borders and other restricted areas, the SkyLink Express utilizes a geofencing management system for border control and designated no-drone zones. Polygonal geofencing is defined by a series of reference points and forms a polygonal shape with multiple vertices [30]. The geofence is created by specifying the GPS coordinates of multiple points in sequence to form the polygon. Specifically, to geofence the border, we are using the latitude and longitude coordinates along the border to create a polygonal geofence. A geofencing management system is used to establish these geofences as part of the UAV's flight controller system [30]. This system, connected to the UAV's control interface, will continuously monitor its instantaneous position relative to the defined geofences. In the case that a violation occurs, the system triggers alerts, and the UAV maintains a distance from the unauthorized area. The parts of a geofence system include the latitude and longitude reference points, which define the boundaries of the geofence, and the software or application used to set and configure these boundaries, as well as to manage the drone's responses when geofencing is activated. Between each border crossing opening, UAVs will go back and forth between the two areas. The specific latitude and longitude coordinates to create the polygonal geofence will be the edge of both border crossing center and into each side of the country. The figure below details the geofencing method to ensure border security.

Fig -6: Geofencing Method

3.5 Navigation System

UAVs on the SkyLink Express utilize a navigation system that relies on a combination of GPS (Global Positioning System) and INS (Inertial Navigation System) technologies. GPS, widely used for its global coverage, is a very reliable navigation source, but its precision can be limited by the number of available satellites within the vicinity of a given GPS receiver. Areas where the GPS signal cannot obtain information from nearby satellites are known as GPS black spots [31]. An Inertial Navigation System uses accelerometers to measure specific forces and gyroscopes to measure rotational rates, updating position, velocity, and orientation from a given UAV's initial starting position; as the UAV starts its flight, the position vectors adjust accordingly. A limitation of this technology is that it can experience integration drift problems due to propagating bias errors [31]–systematic errors or deviations in sensor measurements that accumulate over time. These small errors in calculated acceleration and angular velocity develop over the course of the flight path, causing significant errors in velocity and positioning. To mitigate these drift errors, these drones' INS often rely on external information from GPS technology to substantiate its collected information. Therefore, combining GPS with INS technology helps balance their respective limitations, ensuring a more holistic, reliable navigation system for UAVs in which one can take over when the other isn't properly functioning. In the case that both of these technologies fail, manual override will occur by the UAV's owner/operator. The UAV operator finds the nearest landing area to fix the navigation systems. It is very important that this navigation system is standardized across all UAVs in order to ensure that UAV safety is maximized and collisions are minimized; therefore, these two navigation systems will be required on every UAV that travels on this air highway system.

3.6 Standardization

Standardization between UAVs is essential since they are functioning independently on this air highway system and need to operate safely and be compatible with the necessary autonomous navigation & collision avoidance algorithms. Standardization in the SkyLink Express is ensured through a standardized flight controller and processing software system, while mandating certain sensors to be equipped onto all UAVs. The table below details each aspect of the sensor infrastructure.

Table -5: Standardized Sensor Infrastructure

Sensor Infrastructure	Uses
LiDAR sensor	• standardized sensor for measuring the distance between UAVs, providing precise distance information crucial for our collision avoidance algorithm (see Section 6). • LiDAR's high measurement range and accuracy contribute to

	reliable distance measurements, offering a detailed and dependable dataset for effective collision avoidance strategies [32] • The data collected by LiDAR sensors is processed through our collision avoidance algorithms, enabling real-time decision-making to avert potential collisions and ensure safe navigation.
Radar Altimeter	• The radar altimeter provides accurate altitude measurements, ensuring that UAVs maintain safe flying heights within the designated altitude levels of the highway system. • The immediate and accurate altitude data from radar altimeters facilitate real-time decision-making, enabling UAVs to autonomously stay within the designated highway boundaries outlined by our autonomous navigation program.
ADS-B Out Module	• Every 1 second, these modules transmit UAV positioning information like GPS position, velocity, altitude to ground stations, satellites, and UAVs within the vicinity • This information is useful for air-traffic control management and for yielding to commercial aircraft traffic (see Section 3B for more information on air-traffic control management)
ADS-B In Receiver	• These receivers are used to receive important messages from air traffic controllers about oncoming commercial aircraft traffic. • These receivers also receive ADS-B transmissions from other UAVs about their positioning, allowing each UAV to be aware of other UAVs' relative positions.
GPS Receiver	• These receivers are utilized to process GPS information from satellites and maintain positioning information
Camera Module	• The camera module is used for a variety of applications from search and rescue missions identifying the target to agricultural missions identifying the diseased plants. The specific software needed will be downloaded to work with the camera module based on the UAV operators' needs. • The camera module will also aid during manual override if it comes to it for operators to navigate the airspace and surroundings.
Inertial Navigation System	• This system is used to supplement GPS technology on all UAVS; it involves calculating position vectors based on displacement from a UAVs initial position.

There is no specific standardized flight controller system, but the primary requirement is that the flight controller has to be compatible with the required sensor infrastructure. UAV users will be required to equip UAVs with a flight controller that can integrate the mandated sensor infrastructure. Once a UAV becomes registered onto the SkyLink Express's system and passes all initial checks and inspections for safety, the UAV's user is provided the unique processing system and algorithms needed to operate within the air highway system. These algorithms are then uploaded onto the UAV's flight controller.

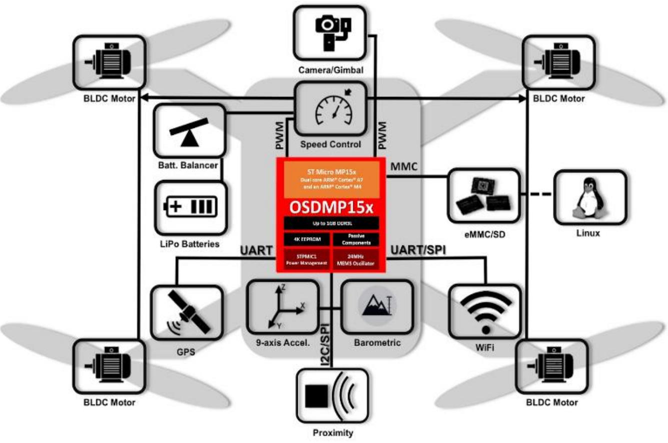


Fig -7: Flight Controller Connections

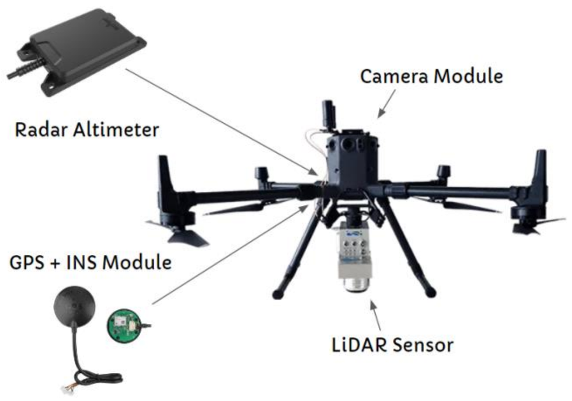


Fig -8: Flight UAV equipped with central SkyLink Express Infrastructure

3.7 UAV Energy Source

Given the urgent need to address global warming concerns, it is crucial that this large-scale use of UAVs utilizes sustainable energy sources to minimize the carbon footprint of UAV operations. However, since a standardized energy source for the entire system is difficult to implement right away, the SkyLink Express aims to achieve full sustainable energy usage by Phase 3 of Implementation (see Section 7 for implementation information).

Space-based solar energy harnesses the Sun's rays from outer space, delivering an intensity approximately 10 times greater than terrestrial solar panels [33]. This system operates through satellites equipped with microwave-transmitting technology, where large mirrors within the satellite reflect sunlight and convert it into an electric current. The converted energy is then beamed to Earth using a targeted laser beam that is received by outdoor solar panels at a facility. These panels transform the laser beam back into solar energy, which serves as a sustainable and efficient power source for UAVs [34]. Lithium-ion batteries within the facilities are directly powered by the transmitted space-based solar energy, providing a continuous and renewable energy supply for UAV operations.

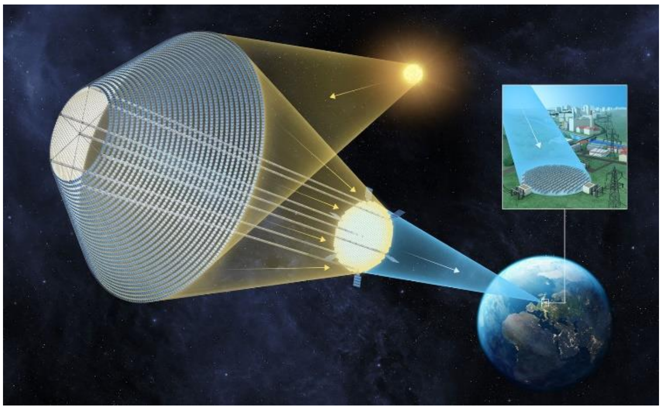


Fig -9: Spaced Based Solar Power

To further enhance sustainability, small wind turbines are integrated into the UAVs' exterior design to harness wind energy at high altitudes. This dual functionality allows the UAVs not only to carry out their operations but also to contribute to sustainable energy practices. The electricity produced by these turbines can be stored for use in other locations, contributing to a more energy-efficient UAV system. The primary part of this energy system that will eventually be required of UAVs is the solar energy powered batteries. This approach aligns with this project's commitment to maximize efficiency and minimize the environmental impact of UAV operations.

4. CODE PROCESSING

Without on board pilots, there needs to be a way for UAVs to process data independently in order to make real-time decisions while navigating airspace. Therefore, a processing system to integrate all of its independent functions is crucial to UAV operations' success. On the SkyLink Express, standardization is necessary to streamline operations across a variety of different UAV models. However, since it's difficult to standardize sensors and every system on the UAV, standardizing the processing software that is then equipped onto UAV flight controllers is more practical. Not only do the flight controllers control the drone's orientation using sensors (gyroscopes & accelerometers) and manage the drone's height using barometric pressure sensors and GPS data, but also will aid in navigation and guidance. While the radar altimeter detects the height the UAV must be, the barometric pressure sensor keeps the UAV hovering at the specific height, ensuring no movement vertically. The flight controller uses Inertial Measurement Units (IMU) to combine accelerometer and gyroscope data to measure the drone's movement and orientation as well as GPS modules to provide location data for navigation and positioning. All data will be stored on the flight controller aiding communication between UAVs, transmitting altitude, speed, battery level, and more data. Because of autonomous control, the flight controller will execute pre-programmed missions or respond to real-time data and sensor inputs autonomously. More of the pre-programmed missions will be discussed in the Autonomous Navigation Infrastructure and Collision Avoidance Program sections.

4.1 Navigation

The SkyLink Express's navigation system relies on positioning data from GPS (Global Positioning System) and INS (Inertial Navigation System) to navigate flight paths. The GPS provides accurate positional data (latitude, longitude, and altitude) by receiving signals from satellites. INS uses accelerometers and gyroscopes to track the UAV's position, orientation, and velocity. This is crucial for providing continuous navigation data, especially when GPS signals are weak or unavailable (see section 3.4). The flight controller integrates data from these 2 navigation sources to form a comprehensive understanding of the UAV's current position and movement. Algorithms within the flight controller process this data to continually update the UAV's position. Based on the data, the flight controller calculates an efficient route to the UAV's next waypoint/destination. Utilizing the geofencing polygons, the autonomous navigation system stores these coordinates as unauthorized areas and will adjust UAV paths to avoid these areas.

4.2 Autonomous Navigation

The autonomous navigation infrastructure of UAVs involves sophisticated systems to ensure safe and efficient flight paths without human intervention. The processed data sources include GPS waypoints which are pre-programmed coordinates that the UAV follows to reach its destination and altitude data (obtained from barometric sensors and GPS modules) which determines the UAV's altitude level; these sources of information are needed for avoiding collisions and following designated directional highway and lane constraints. The flight controller receives signals from GPS satellites to determine its current position. Based on the waypoints and altitude data, the flight controller adjusts the UAV's flight path and altitude based on the autonomous navigation program. The variables in the program altitude level and waypoint functions trigger these signals to run in the flight controller. The autonomous navigation algorithm ensures that the UAV follows its pre-programmed route while dynamically adapting to changes in the environment, such as avoiding obstacles.

4.3 Collision Avoidance

Effective collision avoidance is critical for the safe operation of UAVs. The data sources for processing are ADS-B (Automatic Dependent Surveillance-Broadcast) which provides real-time data about nearby aircraft, including their speed and position and other sensors such as radar, LiDAR, and cameras, which detect obstacles in the UAV's path. The flight controller processes data from ADS-B and other sensors to identify potential collision threats. In the program, the variable UAV1.speed will collect data from ADS-B for UAV2's speed and this will signal the collision avoidance algorithm to assess collision risk and calculate necessary evasive maneuvers in the flight controller. The flight controller prompts the UAV to change its altitude, speed, and direction to avoid the obstacle as the program prompts.

4.4 Air Traffic Control Infrastructure

UAVs must interpret and respond to signals from air traffic control (ATC) to safely navigate shared airspace. UAVs equipped with ADS-B receivers can interpret signals from ATC, including commands for altitude changes or course corrections. The flight controller decodes these signals and responds to ATC commands using the UAV's navigation system. The UAV then adjusts its flight path or altitude as directed by ATC to avoid conflicts with manned aircraft or other external circumstances. The processing system ensures that UAVs adhere to airspace regulations and respond appropriately to ATC commands. UAVs require ADS-B Out to broadcast their position and ADS-B In to receive data from other aircraft and ATC. This capability ensures comprehensive awareness and compliance with regulatory requirements. By standardizing flight controllers and integrating sensors and processing algorithms, UAVs can navigate complex airspaces autonomously, avoid collisions, and adhere to ATC instructions effectively.

5. AUTONOMOUS NAVIGATION INFRASTRUCTURE

5.1 Overview of Autonomous Navigation Infrastructure

Unlike traditional transportation systems, where visible markers such as signs and roadways guide vehicles, UAVs operate in three-dimensional airspace without physical boundaries. Since they are unmanned, UAVs require programmed coordinates to ensure that they remain on their routes and complete their missions successfully. The SkyLink Express's autonomous navigation infrastructure is critical to ensuring that UAVs remain on their pre-programmed routes, contributing to enhanced operational efficiency, safety, and coordination. To stay on its flight path, UAVs on the SkyLink Express follow programmed GPS waypoints, which serve as reference points to navigate their routes. GPS waypoints are specific geographic locations defined by precise latitude and longitude coordinates, which are recorded with a precision of 5 decimal places in order to reach precise building/location coordinates. These waypoints are pre-programmed into the UAVs' navigation system, creating a path that the UAV must follow to reach its destination. Since each directional highway dictates different travel directions, the program considers the altitude level changes necessary for the UAV to reach its final destination.

To ensure safe operations, these waypoints are generated using emerging AI technology that has been on the rise in ATC applications: demand prediction [35], a key component of this AI technology, is used to forecast the number of aircraft that will be flying in specific airspace at a specific time. This information is crucial for setting safe GPS waypoints that can help UAVs proactively avoid collisions with other aircraft. By analyzing historical ADS-B transmissions (which include GPS positioning & altitude data) to the ATC center and real-time data from UAVs on specific altitude levels, AI algorithms predict future demand on directional highways and Expresses to accordingly adjust UAV paths. Time series analysis is one method by which AI is utilized for demand prediction in ATC: this technique involves analyzing historical data on flight schedules, passenger demand, and climate patterns to identify trends, which can then be used to predict future demand. By using machine learning algorithms such as neural networks, we can analyze large amounts of data and trends that are not easily visible to humans. AI is also integrated with UAVs' Automatic Dependent Surveillance-Broadcast (ADS-B) modules to provide real-time data on aircraft positions, allowing for more accurate demand predictions and optimized UAV path planning.

5.2 Autonomous Navigation Program Methodology

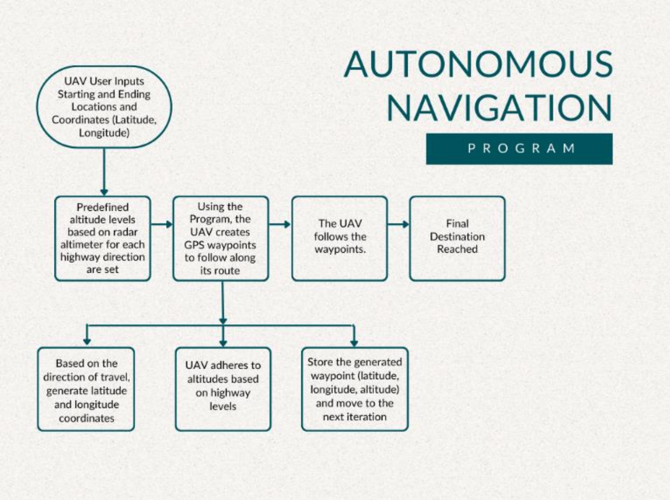
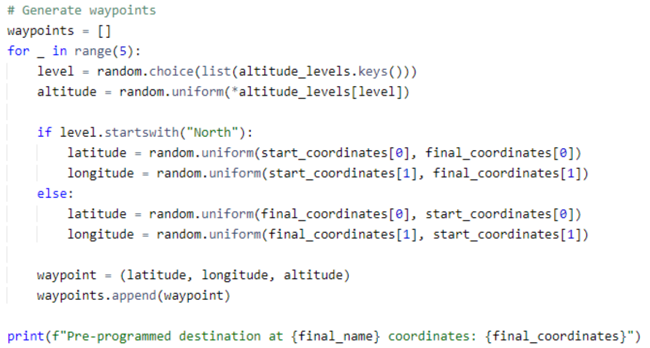


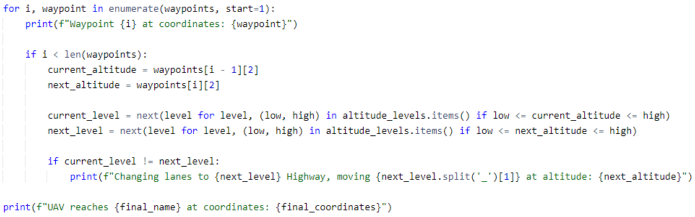
Fig -10: Autonomous Navigation Program Methodology

The program computes different altitude levels for UAVs to maintain safe separation from other UAVs traveling in opposite directions and obstacles such as tall buildings. As previously mentioned, these altitude levels are associated with specific directional highways (e.g., East-West, North-South) as explained in Section 3. Based on the start and final (latitude and longitude) coordinates inputted by the user, the program determines the primary direction of travel. The waypoints between the start and final coordinates are then generated with AI demand prediction information, adding variability to the UAV's path while maintaining the overall direction. Each waypoint is assigned an altitude within the range of the designated directional highway, determined by the direction of travel. This ensures that the UAV follows a designated altitude level, helping to manage airspace effectively. As the UAV travels between waypoints, the program monitors altitude changes and acts when a lane change is required, which involves transitioning between different directional highways on the system to maintain the correct direction and avoid collisions. The UAV continuously tracks its position using GPS and INS, adjusting its course as necessary to stay on the pre-programmed path. Key parts of the program (generating waypoints and the for loop conditional) are shown below.



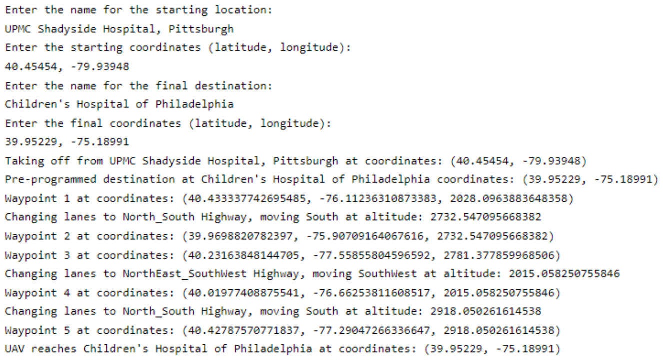
```
# Generate waypoints
waypoints = []
for _ in range(5):
    level = random.choice(list(altitude_levels.keys()))
    altitude = random.uniform(*altitude_levels[level])

    if level.startswith("North"):
        latitude = random.uniform(start_coordinates[0], final_coordinates[0])
        longitude = random.uniform(start_coordinates[1], final_coordinates[1])
    else:
        latitude = random.uniform(final_coordinates[0], start_coordinates[0])
        longitude = random.uniform(final_coordinates[1], start_coordinates[1])

    waypoint = (latitude, longitude, altitude)
    waypoints.append(waypoint)

print(f"Pre-programmed destination at {final_name} coordinates: {final_coordinates}")
```

This section of the code first creates an empty list 'waypoints' and initializes it to store the generated waypoints. The loop runs 5 times, generating 5 waypoints from the course of the first location to second as UAVs are traveling within their state. If longer tracks occur, the for loop will adjust and generate more waypoints to fit the course. A random altitude level (1 of the 4 designated altitude ranges) is then chosen from the 'altitude_levels' dictionary keys in order to set the UAVs starting altitude in the corresponding level. Depending on whether the selected level's name starts with "North" or not, the latitude and longitude are chosen from different ranges. For "North", latitude and longitude are chosen within the range from start_coordinates to final_coordinates. For other directions, the range is from final_coordinates to start_coordinates. For other directions, the range is reversed to accurately represent their respective travel directions. A tuple (latitude, longitude, altitude) is created and appended to the waypoints list to create the waypoints.



```
for i, waypoint in enumerate(waypoints, start=1):
    print(f"Waypoint {i} at coordinates: {waypoint}")

    if i < len(waypoints):
        current_altitude = waypoints[i - 1][2]
        next_altitude = waypoints[i][2]

        current_level = next(level for level, (low, high) in altitude_levels.items() if low <= current_altitude <= high)
        next_level = next(level for level, (low, high) in altitude_levels.items() if low <= next_altitude <= high)

        if current_level != next_level:
            print(f"Changing lanes to {next_level} Highway, moving {next_level.split('_')[1]} at altitude: {next_altitude}")

print(f"UAV reaches {final_name} at coordinates: {final_coordinates}")
```

The next section of code prints each waypoint with its index number. For each waypoint, the current and next altitudes are retrieved from the ‘waypoints’ list. The altitude levels corresponding to the current and next altitudes are then determined. If the current and next levels are different, a lane change message is printed, indicating the direction and altitude of the change. The code output for this program is shown below. Let us take an example of an emergency delivery from the UPMC Shadyside Hospital in Pittsburgh to the Children’s Hospital of Philadelphia.



```
Enter the name for the starting location:
UPMC Shadyside Hospital, Pittsburgh
Enter the starting coordinates (latitude, longitude):
40.45454, -79.93948
Enter the name for the final destination:
Children's Hospital of Philadelphia
Enter the final coordinates (latitude, longitude):
39.95229, -75.18991
Taking off from UPMC Shadyside Hospital, Pittsburgh at coordinates: (40.45454, -79.93948)
Pre-programmed destination at Children's Hospital of Philadelphia coordinates: (39.95229, -75.18991)
Waypoint 1 at coordinates: (40.433337742695485, -76.11236310873383, 2028.0963883648358)
Changing lanes to North_South Highway, moving South at altitude: 2732.547095668382
Waypoint 2 at coordinates: (39.9698820782397, -75.90709164067616, 2732.547095668382)
Waypoint 3 at coordinates: (40.23163848144705, -77.55855804596592, 2781.377859968506)
Changing lanes to NorthEast_SouthWest Highway, moving SouthWest at altitude: 2015.058250755846
Waypoint 4 at coordinates: (40.01977408875541, -76.66253811608517, 2015.058250755846)
Changing lanes to North_South Highway, moving South at altitude: 2918.050261614538
Waypoint 5 at coordinates: (40.42787570771837, -77.29047266336647, 2918.050261614538)
UAV reaches Children's Hospital of Philadelphia at coordinates: (39.95229, -75.18991)
```

As seen, the program displays the waypoints the UAV follows as well as the change in altitude levels when a different direction is needed, printing the coordinates. It successfully travels from its starting coordinates to final coordinates with the program’s methodology.

6. COLLISION AVOIDANCE PROGRAM

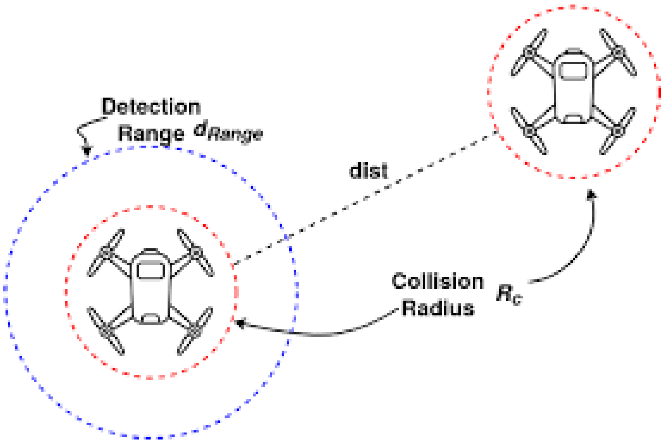


Fig -11: Detection Range for Collision

Table -6: Key Terms for Program Understanding

Term	Definition
UAV 1	• self UAV (itself)
UAV 2	• approaching obstacle UAV; can approach from the top, bottom, left, right, front, or back directions
Obstacle Direction	• the direction from which UAV 2, the obstacle UAV, is approaching UAV 1 • determined using information from the 6 LiDAR sensors placed on different parts of every UAV (front, back, top, bottom, left, right)
Collision Avoidance Direction	• the direction UAV 1 travels in to avoid collision with UAV 2
Speed Multiplier	• the adjustment to UAV 1’s current speed in order to avoid collision with UAV 2 • this multiplier can be greater than or less than UAV 1’s current speed (Iteration 1 & 2 take UAV 2’s speed into consideration when determining the necessary speed multiplier)
Speed Ranges (m/s)	• Low Speed: 9 <= x <= 13 • Medium Speed: 14 <= x <= 27 • High Speed: 27 <= x <= 36
ADS-B In Receiver	• receiver module equipped on every UAV within this system that receives ADS-B transmissions from other UAVs in its vicinity • all received transmissions contain other UAVs’ GPS position, velocity information, altitude, etc. • relevant information for the collision avoidance algorithm is the velocity information; used to make necessary speed multiplier adjustments to avoid collisions

The primary objective of the collision avoidance program is to ensure the safety of UAVs operating within shared airspace. This involves processing sensor data, recognizing obstacles, and executing avoidance maneuvers without human intervention. By preventing collisions, the program aims to protect both UAVs and any individuals or property on the ground. The program is designed to manage the flow of UAV traffic efficiently by setting different speed ranges and allowing UAVs to accordingly adjust their individual flying speed in order to avoid collisions, ensuring that UAVs can complete their missions without unnecessary delays or reroutes. The 3 speed ranges are as stated in the table above.

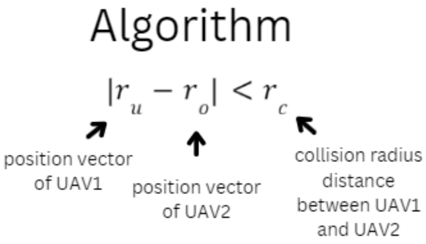
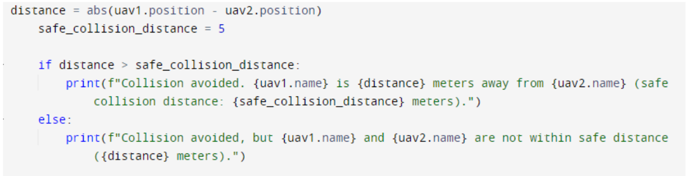


Fig -12: Program Algorithm

The collision avoidance uses the sense and avoid method which adapts to specific constraints. This algorithm gives a specific constraint for the distance between UAVs to be less than the collision radius which for safety is 5 meters; our program incorporates this algorithm through a conditional statement.



```
distance = abs(uav1.position - uav2.position)
    safe_collision_distance = 5

    if distance > safe_collision_distance:
        print(f"Collision avoided. {uav1.name} is {distance} meters away from {uav2.name} (safe
            collision distance: {safe_collision_distance} meters).")
    else:
        print(f"Collision avoided, but {uav1.name} and {uav2.name} are not within safe distance
            ({distance} meters).")
```

This code turns the sense and avoid algorithm into code by taking the absolute value of the distance between the two UAVs, and if above a safe collision distance of 5 meters, the program detects no collision warning. Otherwise, a distance warning occurs and collision avoidance is performed. The program relies on LiDAR sensors and ADS-B In transmissions to communicate distance and speed data from UAV to obstacles. Because the ADS-B Out transmissions are broadcasted once per second, ADS-B In receivers mounted on every UAV are continuously receiving GPS and velocity information from UAVs in their surrounding vicinity. With this positioning information, every UAV can create a mental map of the UAVs around it and be aware of any UAVs that are coming within 5 meters of distance. This program's methodology begins with UAV 1 sensing UAV 2 within 5 or fewer meters of distance. This is followed by UAV 1 determining UAV 2's instantaneous velocity in order to appropriately adjust its own speed to avoid the collision with UAV 2. UAV 2's instantaneous velocity is determined using information from ADS-B transmissions received by the ADS-In receiver. This then triggers both UAVs at risk of collision to act using the collision avoidance methodology, which is displayed below.

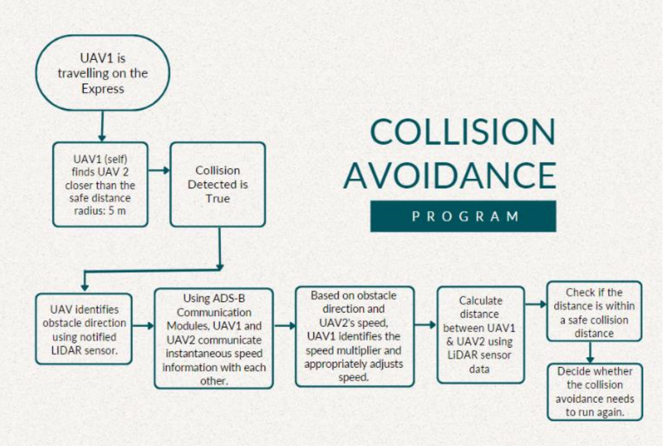


Fig -13: Collision Avoidance Program Methodology

6.1 Original Program

With this program methodology of the original program, the program generalizes all the different speed combinations and UAV 1 adjusts its speeds by the same multiplier regardless of whether UAV 2's speed is low, medium, or high speed. Therefore, this initial algorithm was not specific enough to each unique case of speed combinations between UAV 1 & 2. Specifically, if UAV 2 coming behind UAV 1 is traveling twice as fast as UAV 1, UAV 1 should move twice its current speed to adjust and UAV 2 should slow down to half its current speed. Although it includes different cases for each direction, these generalized speed multipliers were not specific enough to successfully avoid collisions. Therefore, the efficiency success rate for the original program was very low (~ 30%).

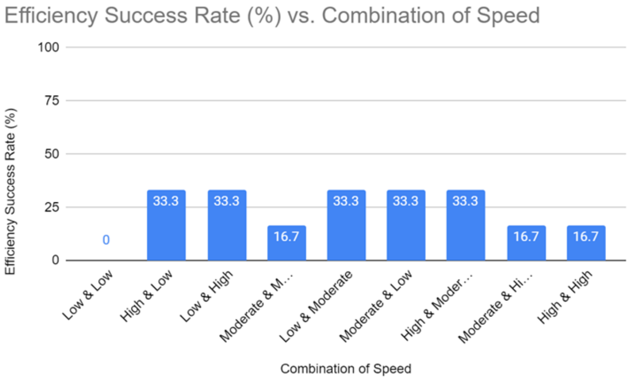


Fig -14: Efficiency Success Rate vs. Combination of Speed for Original Program

These low results for different speed combinations between the obstacle and UAV show the failure in the original program to efficiently avoid collisions. Additionally, the directional efficiency is displayed below, showing failure in left, right, top, and bottom obstacle directions.

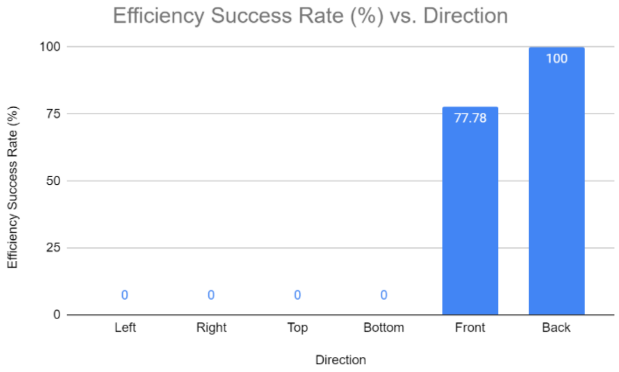
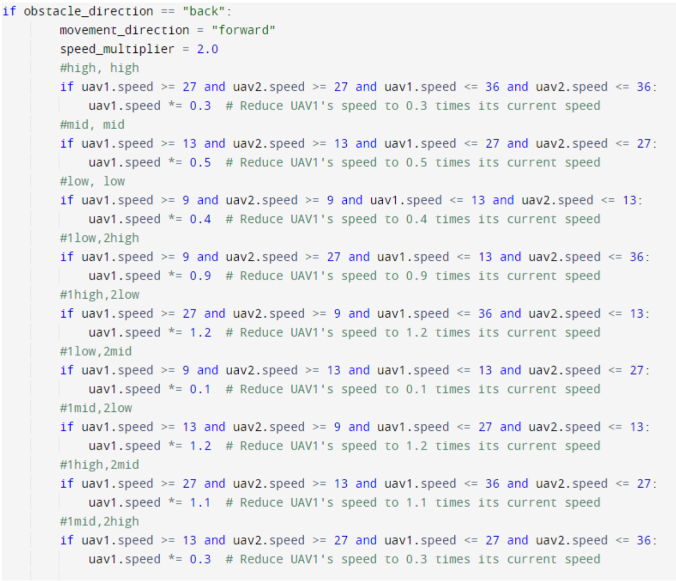


Fig -15: Efficiency Success Rate vs. Direction for Original Program

This is due to the program keeping the obstacle avoidance direction to the opposing directions of the obstacle. Specifically, if UAV 2 is approaching UAV 1 from above when switching into a lower directional highway, UAV 1 cannot simply move down as it cannot go too far into the directional highway below, making it an unsuccessful maneuver to avoid the collision. This issue was addressed in Iteration 1 by standardizing all collision avoidance directions to forward.

6.2 Iteration 1

To increase the efficiency success rate, a case by case approach based on each direction and specific combination of speeds of the 2 UAVs was implemented. This involves assigning unique speed multipliers based on UAV 2's speed range (low, medium, & high). This increases the program's efficiency as the speed multiplier depends on a much more specific scenario which yields more accurate results. Below is one direction which implements this method; this is also done for all 6 directions which represent the LiDAR sensors detecting the collision.



```
if obstacle_direction == "back":
        movement_direction = "forward"
        speed_multiplier = 2.0
        #high, high
        if uav1.speed >= 27 and uav2.speed >= 27 and uav1.speed <= 36 and uav2.speed <= 36:
            uav1.speed *= 0.3  # Reduce UAV1's speed to 0.3 times its current speed
        #mid, mid
        if uav1.speed >= 13 and uav2.speed >= 13 and uav1.speed <= 27 and uav2.speed <= 27:
            uav1.speed *= 0.5  # Reduce UAV1's speed to 0.5 times its current speed
        #low, low
        if uav1.speed >= 9 and uav2.speed >= 9 and uav1.speed <= 13 and uav2.speed <= 13:
            uav1.speed *= 0.4  # Reduce UAV1's speed to 0.4 times its current speed
        #1low,2high
        if uav1.speed >= 9 and uav2.speed >= 27 and uav1.speed <= 13 and uav2.speed <= 36:
            uav1.speed *= 0.9  # Reduce UAV1's speed to 0.9 times its current speed
        #1high,2low
        if uav1.speed >= 27 and uav2.speed >= 9 and uav1.speed <= 36 and uav2.speed <= 13:
            uav1.speed *= 1.2  # Reduce UAV1's speed to 1.2 times its current speed
        #1low,2mid
        if uav1.speed >= 9 and uav2.speed >= 13 and uav1.speed <= 13 and uav2.speed <= 27:
            uav1.speed *= 0.1  # Reduce UAV1's speed to 0.1 times its current speed
        #1mid,2low
        if uav1.speed >= 13 and uav2.speed >= 9 and uav1.speed <= 27 and uav2.speed <= 13:
            uav1.speed *= 1.2  # Reduce UAV1's speed to 1.2 times its current speed
        #1high,2mid
        if uav1.speed >= 27 and uav2.speed >= 13 and uav1.speed <= 36 and uav2.speed <= 27:
            uav1.speed *= 1.1  # Reduce UAV1's speed to 1.1 times its current speed
        #1mid,2high
        if uav1.speed >= 13 and uav2.speed >= 27 and uav1.speed <= 27 and uav2.speed <= 36:
            uav1.speed *= 0.3  # Reduce UAV1's speed to 0.3 times its current speed
```

This code excerpt displays how the program identifies the speed ranges from low (9 to 13), mid (14 to 27), and high (28 to 36). Based on the speed combinations, collision avoidance differs: if UAV 2 approaching from the back is traveling twice the speed of UAV 1, UAV 1 will need a greater speed multiplier to avoid the collision. As the scenario differs for each situation, this program is specifically avoiding collisions based on different speed combinations as well as the different obstacle directions. This results in a much higher efficiency success rate shown below.

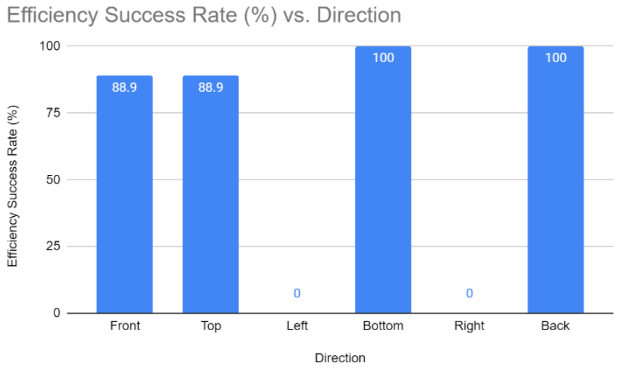


Fig -16: Efficiency Success Rate vs. Direction for Iteration 1

High results were yielded for all directions except left and right due to the obstacle directions in the left and right directions being the opposing directions. This issue was focused on in Iteration 2.

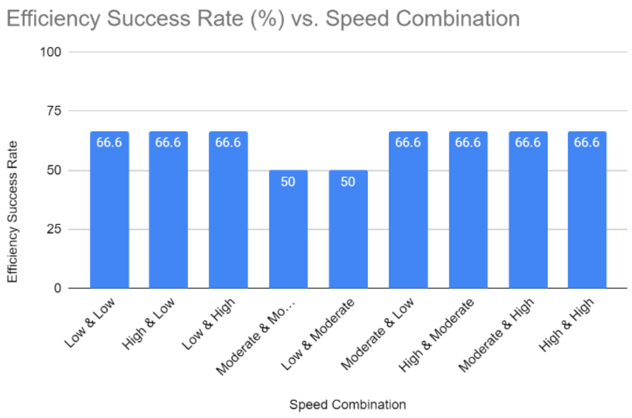


Fig -17: Efficiency Success Rate vs. Speed Combination for Iteration 1

6.3 Iteration 2

The issue of directional efficiency was mostly addressed in Iteration 2. The left and right obstacle directions were causing the UAVs to move in the opposite directions and resulted in the UAVs risking going outside the horizontal boundaries of the highway. Therefore, all collision avoidance directions were changed to forward to avoid the obstacle efficiently. Additionally, the case by case approach was enhanced by fine tuning the speed multipliers for each speed combination case through thorough testing of data and analysis of results.

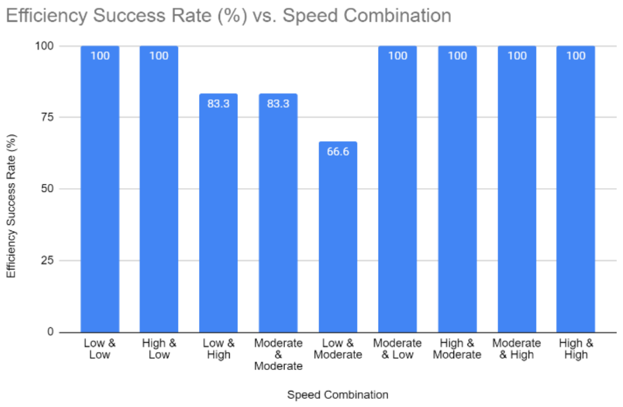


Fig -18: Efficiency Success Rate vs. Speed Combination for Iteration 2

These results shot up from the previous speed combinations with many combinations yielding 100 percent and the lowest being 66.6 percent.

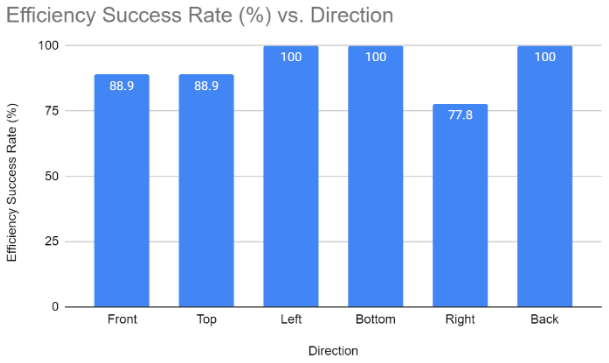


Fig -19: Efficiency Success Rate vs. Direction for Iteration 2

No results no longer yielded 0% success rates, and the collision avoidance direction change to forward overall strengthened the results.

Overall, the improvements to this program have greatly improved the efficiency success rates through changing the collision avoidance directions as well as fine tuning the data for each speed combination case. Additionally, with the AI demand prediction with past data trends, precautions are taken to decrease the change of UAVs going on the same routes and encountering commercial vehicles. This greatly improves the efficiency success rate by decreasing the chance of collisions occurring in the first place on top of this avoidance strategy.

7. IMPLEMENTATION

In trying to integrate the SkyLink Express into our existing airspace infrastructure, there are various regulatory and social factors to consider.

7.1 Regulatory Implementation

Despite the developed autonomous navigation and collision avoidance algorithms, the immediate implementation of these programs for UAVs are in violation of certain FAA regulations. Therefore, in order to comply with such regulations and strategically implement this transformative technology, the SkyLink Express infrastructure will be implemented in phases.

7.2 Phase 1

Table -7: Addressing Regulation for Phase 1 Implementation

Regulation	Addressing Regulation
UAV Flight Altitude [36] UAVs must generally fly below 400 ft above the ground.	The most prominent FAA regulation that this air highway system violates is the 400 ft flying altitude limit. However, due to the large architecture present, establishing this system below 400 ft is unrealistic. Therefore, the altitude levels are strategically chosen to be above standing architecture and below commercial aircraft traffic. Through collaboration with the FAA and the U.S government, this system can utilize higher altitude levels above the current limit if the regulations are able to be amended.
107.19: Remote Pilot-in-Command [37] A remote pilot in command must be designated before or during the flight of the small unmanned aircraft. (b) The remote pilot in command is directly responsible for and is the final authority as to the operation of the small unmanned aircraft system. (c) The remote pilot in command must ensure that the small unmanned aircraft will pose no undue hazard to other people, other aircraft, or other property in the event of a loss of control of the small unmanned aircraft for any reason. (e) The remote pilot in command must have the ability to direct the small unmanned aircraft to ensure compliance with the applicable provisions of this chapter.	This first phase of implementation will involve all UAVs being constantly monitored by a remote pilot-in-command using camera modules equipped on the UAVs. These cameras allow remote pilots to view the UAV throughout its flight path and make necessary adjustments to its travel direction. During this initial phase, UAVs will not utilize the autonomous navigation program but will rely on remote pilot navigation to ensure compliance with current safety regulations.
§ 107.29 Operation at night. [38] **§ 107.39 Operation over human beings. [39]**	Additionally, UAV operation throughout the night and over people requires specific waivers, which will be necessary for all UAVs traveling on the system. The process for obtaining these waivers will involve close collaboration with the FAA to ensure all safety standards and regulations are met.
§ 107.37 Operation near aircraft; right-of-way rules. [40] (a) Each small unmanned aircraft must yield the right of way to all aircraft, airborne vehicles, and launch and reentry vehicles. Yielding the right of way means that the small unmanned aircraft must give way to the aircraft or vehicle and may not pass over, under, or ahead of it unless well clear.	To adhere to 107.37, the right-of-way will be granted to large commercial aircraft and other larger aircraft when they pass through the SkyLink Express. In situations in which a commercial plane is landing across a SkyLink Express directional highway, UAVs must yield and stop until the plane has passed through. This communication is achieved through an air traffic control system that collects real-time data from both manned and unmanned aircraft to ensure coordinated and safe operations (See Section 3.3 for more information on this air traffic control system). Additionally, utilizing AI demand prediction will significantly decrease the chance of UAVs encountering other landing aircrafts.
§ 107.43 Operation in the vicinity of airports. [41] No person may operate a small unmanned aircraft in a manner that interferes with operations and traffic patterns at any airport, heliport, or seaplane base.	To ensure compliance with this regulation, UAVs will utilize the air traffic control system outlined in Section 3.3, which utilizes ADS-B In & Out transmissions to make decisions concerning flight paths amid commercial aircraft traffic.

Beyond regulatory considerations, Phase 1 involves enlisting the cooperation of firms and individuals to create a wide network of transportation on the SkyLink Express. Given the large-scale and innovative nature of this system, it is crucial to demonstrate the feasibility and value of UAV applications and their streamlined use within this infrastructure. The “network effect” has a vital role in this system; as more individuals and businesses use the system, its value increases, similar to how the rideshare app Uber [42] gained traction and value as more users joined the platform. Therefore, establishing the infrastructure alone is not enough; its success depends on active utilization by individuals and entities, including businesses, emergency responders, and government agencies. Therefore, by networking and establishing partnerships with key stakeholders such as emergency responders and large corporations like Amazon, Walmart, etc. UAVs can realize their full potential on the SkyLink Express. These partnerships will be crucial for demonstrating the system's benefits through projects and real-world applications, ultimately achieving widespread adoption and maximizing the system's value.

7.2 Phase 2

To eventually implement total autonomous navigation and collision avoidance, communication and collaboration with the FAA and the government is crucial to modify regulations; in addition, thorough testing on the reliability of the programs will ensure that the SkyLink Express can function autonomously as initially intended. Such examples of this testing will include test-flights in isolated locations, as well as gradual implementation of the program in specific regions/states.

7.3 Phase 3

In this final phase of implementation, all UAVs on the SkyLink Express will rely on the autonomous navigation and collision avoidance programs to navigate their flight paths. However, secondary safety measures exist in the form of remote flight controllers in the case of weather emergencies. Weather emergencies will be communicated through ADS transmissions to UAVs in a concentrated area where dangerous weather may affect their safe operation. An emergency landing protocol will be enacted, sending UAVs to the nearest air traffic control centers. This will be monitored by remote flight controllers, who can take necessary action to emergency land the UAVs. Additionally, if there is a program malfunction, the air traffic controllers as well as UAV operators will get a notification and intervene to take the necessary action to land the UAV. The camera modules will remain on the UAVs through Phases 2 & 3 as a backup to monitor travel on the system. With all UAVs on the system following the standardized protocols for weather emergencies and oncoming traffic in failure of the program, the safety of UAV operations can be ensured.

8. EVALUATION

8.1 Implications of System

The use of the autonomous navigation system allows for the operation of large UAV fleets, enabling complex tasks like search and rescue or large-area surveillance to be performed more effectively. With the proliferation of UAVs with many applications in everyday life, the system supports effective communication to enhance UAV efficiency. Additionally, the integration of advanced navigation, autonomous control, and collision avoidance systems significantly enhances the safety of UAV operations. These systems help prevent collisions with other aircraft, obstacles, and ensure compliance with air traffic control (ATC) instructions. Autonomous navigation and optimized path planning reduce flight times and energy consumption, improving the overall efficiency of UAV operations. This is particularly beneficial in logistics, surveillance, and other commercial applications. However, the implementation of advanced sensors, flight controllers, and autonomous navigation systems involves significant upfront investment. This can be a barrier for smaller companies or individual operators which risks UAVs not being supported by the system. The sophisticated technology requires regular maintenance and updates, increasing operational complexity and costs. Additionally, technical issues or system failures could lead to safety risks. Compliance with varying international regulations may also hinder global UAV operations, so it is crucial to implement this mission in phases with thorough safety checks.

8.2 Strengths

As identified in the literature review section, the most significant issues with current technology are limited autonomous functions, single-sensor systems, and coordination and collision avoidance in multi-UAV operations. The SkyLink Express solves these problems through improved autonomy, enhanced obstacle detection, and better coordination with the large number of UAVs. With the communication from UAV to UAV with the flight controller working hand in hand with the collision avoidance and autonomous navigation programs, the UAVs on the system overcome issues with coordination. The UAVs on the system utilize the most efficient flight controllers, making sure the computational power is sufficient to support all sensor operations. Additionally, with the standardization of the system, the sensors function together inputting data directly into the flight controller, and communicating this data seamlessly to other UAVs on the system. Additionally, with the limitations of current radar systems, the SkyLink Express’s strength is the ADS-B technology. ADS-B provides much better visibility regardless of the terrain, whereas radar signals cannot travel long distances or penetrate solid objects; this is because radio waves are limited to line of sight. UAVs and other aircraft transmit position data no matter where they are, and this position is then received by ground receiver or, better, by satellites, which helps the ADS-B system to be very effective even when flying over difficult terrain. Unlike ground-based radar towers, satellite-based ADS-B receivers are able to provide coverage across the globe without interruption, 24/7, regardless of the terrain. They can relay data in areas that would normally be hard to reach by radar, such as large bodies of water and mountainous terrain. The cost of implementing ADS-B globally is also much lower than traditional radars, as the combination of ground-based ADS-B receivers and nanosatellites are economical.

8.3 Limitations

Despite advances, sensor accuracy can still be compromised in certain conditions, such as low-light environments or with highly reflective surfaces. This will need to be addressed with advancing technology in machine learning to make sure UAVs optimize their routes. Additionally, high-traffic areas can experience delays in data processing and communication, potentially affecting the timely execution of collision avoidance maneuvers. Work with collision prediction algorithms will significantly reduce this risk before UAVs risk any collisions, which will require utilization of ATC data. Integrating new technologies with existing UAV systems and ATC infrastructure will also be complex and costly. There are still limitations with obstacle directions in the collision avoidance algorithm as they are restricted to the 6 directions, not including diagonal directions.

8.4 Metrics to Evaluate the System

Once implemented, the system will need metrics to evaluate how safe and successful the UAV missions are. Therefore, the metrics to evaluate will be safety, operational, and regulatory compliance metrics.

Table -8: Evaluation Metrics

Safety Metrics	**Operational Metrics**	**Compliance Metrics**
Collision Avoidance Rate: The frequency and success rate of collision avoidance maneuvers	**Efficiency Gains:** Reduction in flight times and energy consumption compared to current UAV operations	**Compliance Rate:** Adherence to local and national UAV operation regulations
Incident Reports: The number and severity of incidents involving UAVs in shared airspace	**System Uptime:** The operational reliability and downtime of the UAV systems	**Certification Achievements:** Obtaining necessary certifications for autonomous and collision avoidance systems through each implementation phase

9. CONCLUSION

UAVs have immense potential to transform human lives, offering significant benefits in terms of efficiency, safety, and accessibility. This research paper has introduced and evaluated the SkyLink Express, a UAV air highway system that leverages autonomous navigation and collision avoidance algorithms to streamline UAV operations and expand their current applications. By utilizing standardized sensor infrastructure, SkyLink Express ensures efficient operations and reliable communication between UAVs. Potential future expansions for SkyLink Express include the development of collision prediction algorithms and global expansion. Utilizing the full capabilities of machine learning, AI can be utilized along with ADS-B information to predict collisions based on UAVs' travel trajectories. Also, such adaptive machine-learning algorithms can improve UAVs' ability to avoid dynamic multi-obstacle collisions. This system has future potential to be expanded globally, currently facing feasibility challenges due to varying international air traffic control systems and the numerous stakeholders involved. Achieving worldwide implementation would necessitate broad collaboration among many nations and global leaders. In summary, the SkyLink Express represents a significant step forward in UAV technology, with the potential to revolutionize air transportation and various other sectors. Its success will depend on continuous technological advancements and cooperation, creating a future where UAVs are an integral part of our daily lives.

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