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Collision avoidance strategies for advanced air mobility using UAS-to-UAS communications

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Abstract

Advanced air mobility (AAM) has introduced a new mode of air transportation that can be integrated, providing services including air taxis, which can quickly transport people and cargo from one place to another. However, urban airspace is already congested with commercial air traffic, so there is a need for an efficient and autonomous airspace management system. Establishing structured air corridors and enabling UAS-to-UAS (U2U) communications are essential to achieve autonomy. Air corridors are designated airspace primarily reserved for AAM traffic, which will streamline the movement of unmanned aircraft systems (UAS). Meanwhile, U2U communications facilitate efficient collision avoidance strategies (CAS). A key aspect of this system is the development of CAS, which requires advanced communication protocols to monitor traffic patterns and detect potential collisions. This paper explores designing and implementing CAS using U2U communications. Use cases for U2U communications include merging, minimum separation, information relay, collaborative sensing, and rerouting. All these use cases demand real-time solutions for managing traffic conflicts involving multiple UAS. The CAS discussed in this paper utilizes U2U communications to mitigate the risk of collisions in the airspace and demonstrates how U2U communications can assist in efficient AAM traffic management through simulations.

Key words: vehicle-to-vehicle communications, collision avoidance, advanced air mobility, structured airspace, unstructured airspace, cooperative vehicles

1. Introduction

Advanced air mobility (AAM) services, such as air taxis, promise swift transportation of individuals and goods across short distances. AAM has gained global interest within the industry and is poised to materialize in the coming years (FAA 2023). Within this evolving technology, this paper delves into innovative collision avoidance strategies leveraging vehicle-to-vehicle (V2V) communication protocols for unmanned aircraft systems (UAS) called UAS-to-UAS (U2U) communications (Namuduri et al. 2022). After successfully completing Phase 1 of the National Aeronautics and Space Administration's (NASA) National Campaign (NC-1) in 2022, the AAM NC is now heading towards Phase 2, where airspace autonomy emerges as the key concept. This envisioned autonomy encompasses a triad: (1) the realization of autonomous aircraft, (2) the establishment of an automated Air Traffic Management (ATM) system, and (3) the seamless integration of human autonomy teaming. This paper focuses on autonomous ATM systems and emphasizes deconfliction in the airspace. Deconfliction is of two types: strategic and tactical deconfliction. This study primarily focuses on tactical deconfliction, elaborated on in later sections (Wing and Levitt 2020; Wing et al. 2022).

1.1. Significance/relevance of the research problem

Standard organizations such as the Institute of Electrical and Electronics Engineers (IEEE), Radio Technical Commission for Aeronautics (RTCA) (Radio Technical Commission for Aeronautics 2022), General Aviation Manufacturers Association (GAMA) (GAMA 2023; EPIC General Aviation Manufacturers Association 2021), and regulatory agencies such as the Federal Aviation Administration (FAA) and NASA are working towards developing standards for airspace management and U2U communications protocols such as IEEE P-1920.2 and P-1954. The current UAS Traffic Management (UTM) generation typically oversees small UAS flying below 400 ft. in uncontrolled airspace. AAM aims to establish a nationwide air transportation system for people and cargo at altitudes ranging from 500 to 3000 ft. The airspace is different and specific to the autonomous system. In the case that a manned aircraft system would enter into the operation of the automated flight system, the manned aircraft would conform to a new set of rules following the digital flight rules (McCorkendale et al. 2024*b*) and further regulations to be determined defined by the FAA and the AAM community. However, due to the probability of high-density UAS traffic in and around urban areas, effective collision avoidance systems are necessary.

1.1.1. Manned aircraft collision avoidance systems

The primary types of CA systems for manned aircraft are:

(1) Airborne Collision Avoidance System (ACAS): ACAS is a short-range CA system that prevents MAC independent of a centralized base station (Jaya Sravani et al. 2023).
(2) Airborne Separation Assurance System (ASAS): ASAS is a long-range CA system that aims to maintain a standard horizontal separation distance of 5 nautical miles (9.3 km) and a vertical distance of 1000 ft. (300 m) between aircrafts (Quan et al. 2022; Jaya Sravani et al. 2023).
(3) Traffic Collision Avoidance System (TCAS): TCAS is the FAA mandated CA system that actively monitors the altitude and distance of other aircraft equipped with Mode C and Mode S transponders. If there is a risk of MAC between aircrafts, this system will provide traffic resolution advice to the pilots by issuing alerts that inform them to either climb or descend (Jaya Sravani et al. 2023).
(4) Portable Collision Avoidance System (PCAS): PCAS is a CA system similar to TCAS, with the caveat being that it doesn't actively interrogate the transponders of other aircraft; rather, this system actively listens for nearby transponder-equipped aircraft and notifies pilots if any are detected (Jaya Sravani et al. 2023).

Unfortunately, manned aircraft CA systems cannot be integrated into AAM operations for various reasons. Initially, they have designed for pairwise collisions, which results in inefficient use in areas experiencing high-density traffic. Additionally, the size and weight of these systems make them difficult for small UAS, as they can take up to a sq. ft. of space and weigh up to 20 pounds. Finally, they cannot be directly integrated into AAM operations, as they are typically designed for human intervention to mitigate any potential hazards (Jaya Sravani et al. 2023; Namduuri et al. 2024).

Detect-and-Avoid (DAA) systems (Sabikan et al. n.d.; Cobankiat et al. 2016), which use sensors like stereo vision and LiDAR (Aldao et al. (2022), are also limited by data processing requirements that restrict aircraft speed. Existing literature survey on DAA are generally used to gather sensor data about the local environment to calculate safe trajectories in order to avoid collisions. Partially observable Markov decision process, Markov decision process, and Monte Carlo simulations are used to define state-space and action-space to generate trajectories that are collision-free (Feng et al. 2020; Zhao et al. 2020). These are most commonly referred to as Obstacle Avoidance (OA) systems.

Hybrid systems, such as Airborne Collision Avoidance System X (ACAS X) and U2U communication systems, offer a more promising solution for AAM, enabling aircraft to communicate and monitor each other's positions, velocities, and intentions. However, even hybrid systems face challenges in dealing with noncooperative aircraft, highlighting the need for further development and standardization in collision avoidance systems for AAM. To overcome all the aforementioned challenges, effective collision avoidance strategies are needed, which are proposed and elaborated in this paper.

1.2. Major contributions

This paper contributes to autonomy in the airspace by presenting novel strategies for AAM that can be implemented without any further delay. The proposed collision avoidance strategies offer solutions that are part of an autonomous airspace management system through the use of locally distributed systems. The significance of these strategies is to allow for individual flight correction or UAV in urban areas with major emphasis on the use of V2V communications and AAM protocols (Namduuri et al. 2024). The first contribution is the concept of structured airspaces. It presents fundamental and mathematically well-founded principles for air corridors. Concepts such as air cells introduced by our team have gained traction in the literature (Muna et al. 2021*a*). This paper builds on these concepts and defines structured airspaces. Second, this paper contributes to U2U communications by building upon the use cases developed by the industry. While the industry listed the five use cases for collision avoidance strategies for U2U communications, this paper takes this list towards realistic implementation. In particular, U2U communications have been used to develop collision avoidance strategies.

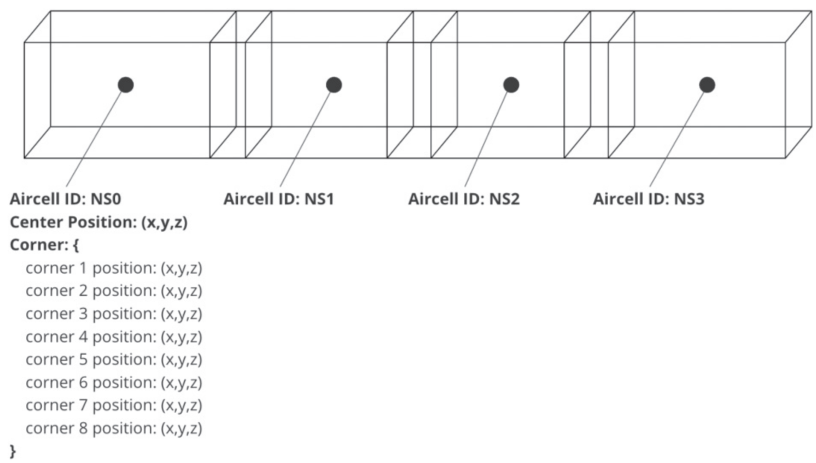
1.3. Organization of the paper

The rest of the paper is organized as follows: Section 2 presents the necessary concepts such as airspace, type of vehicles, use cases, and U2U communications to better understand the proposed methodology. Section 3 elaborates on the five use cases proposed by RTCA, GAMA, and IEEE. Later in the paper, Section 4 explains the four proposed strategies and mathematical models and simulations for the collision avoidance strategies. Finally, Section 5 concludes the paper with a summary of findings and details regarding upcoming future works.

2. Background and relevant concepts

With the rise in both manned and unmanned vehicles occupying airspace, the potential for high traffic density increases, necessitating the implementation of collision avoidance strategies to ensure safe travel. In general, deconfliction can be of two types: strategic and tactical. Strategic deconfliction is avoiding potential airspace hazards or collisions by adjusting the flight plan before takeoff (Causa et al. 2022). On the other hand, if these collisions are avoided while the UAS is in flight, the deconfliction type is categorized as tactical (Causa et al. 2022). This paper primarily focuses on tactical deconfliction. Current collision avoidance systems for UAS rely on onboard sensors, which can limit the scope of airspace. To overcome these challenges and address every scenario, this paper is divided into two different types of airspace and vehicles, which offers a creative approach to developing and implementing collision avoidance strategies in which UAS can intelligently collaborate and coordinate to ensure safe travel.

Fig. 1. Skylane diagram.



2.1. Airspace

The airspace can be divided into two categories which are:

- Structured airspace: Structured airspace is the airspace where the UAS travel in designated pathways called air corridors. In this framework, an air corridor is a well-defined structure to ensure safe and organized traffic flow (Muna et al. 2021*a*). An air corridor is envisioned as a virtual highway system similar to highways on the ground commonly found in urban areas. Skylanes are formed by an interconnected system of air cells interlinked within an air corridor. Figure 1 shows an example of a skylane comprised of multiple air cells, each defined by an air cell ID, center position, and eight corner positions. The structure incorporates an overlap of cells that allows for two cells to be occupied in order to track the progression of UAV in the skylane that will allow for minimum separation.
- Unstructured airspace: Unstructured airspace is airspace where there is no specified path or track designed for flights to travel. Unstructured airspace are commonly observed in rural settings.

2.2. UAS-to-UAS communications

Two or more UAS can exchange packets of data that contain information about the UAS and its intentions. The UAS can then process and leverage this data to collaborate with other UAS, avoiding potential collisions or airspace hazards by enhancing situational awareness. The IEEE 1920.2 (Bandelier et al. 2023; Hernandez et al. 2023) defines a standard message format for these data packets, which are divided into two classes of messages: a discovery message and a direct message. A discovery message is a message that is broadcast at a frequency of 1 Hz to all vehicles in the area. This message provides constant information on the current position and general state of the UAS. In the life cycle of a mission, all other message exchanges are event-triggered, but regardless of the scenario, the discovery message is always broadcast by the UAS. Whether a UAS is considered cooperative or noncooperative depends on two factors. The first factor is whether the messages are being transmitted and received regularly. The second factor is whether the UAS is following its intended flight plan. If a UAS is traveling too slowly, too quickly, or deviating from its intended route, it will be classified as a noncooperative vehicle, and surrounding vehicles will be notified to exercise caution and avoid that specific UAS. The cooperative and noncooperative identification of a UAS can be more directly defined as:

- Cooperative vehicle: A cooperative vehicle is a UAS that properly traverses its flight path and participates in constant radio communication using discovery or direct messages.
- Noncooperative vehicle: A noncooperative vehicle is a UAS that cannot transmit or receive any data from other vehicles, i.e., the vehicle does not broadcast a discovery message or is not flying its assigned flight plan.

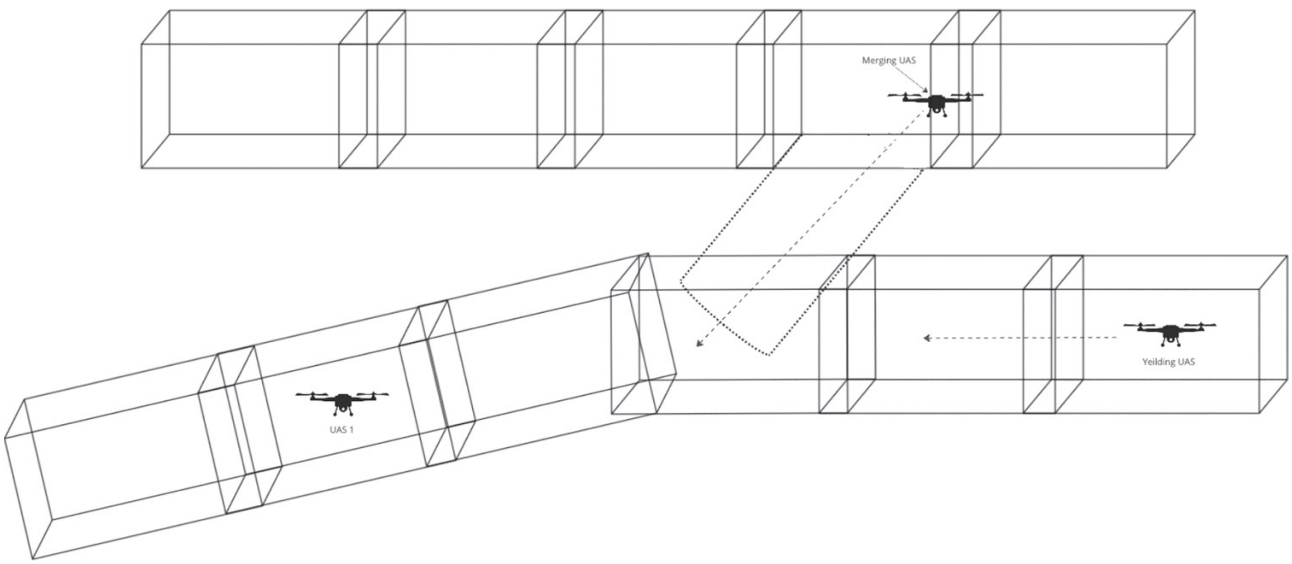
2.3. Use cases

The use cases are a set of scenarios proposed by the RTCA, GAMA, and IEEE for U2U communications and its applications. These use cases include merging, airborne rerouting, information relay, collaborative sensing, and minimum separation. The proposed use cases were developed and used to create the IEEE 1920.2 (Bandelier et al. 2023; Hernandez et al. 2023), which defines a standard message format for U2U communications. These use case scenarios are explained in the sections below.

2.4. Collision avoidance strategies

The collision avoidance strategies can be organized into two categories: strategic and tactical deconfliction. This paper primarily focuses on tactical deconfliction in structured and unstructured airspace. Four subcategories of collision avoidance exist based on whether the UAS is cooperative or noncooperative. For each subcategory, there exists U2U-based strategies and protocols for UAS to avoid collisions. The four different subcategories are (a) cooperative vehicles in structured airspace, (b) noncooperative vehicles in

Fig. 2. Use case of merging.



structured airspace, (c) cooperative vehicles in unstructured airspace, and (d) noncooperative vehicles in unstructured airspace.

3. Scenarios

In this section, scenarios in which there is a potential for collision are presented. These scenarios represent typical situations in which the safe operation of vehicles must be ensured in the airspace. These scenarios involve UAS in structured and unstructured airspaces equipped with onboard sensors and adherence to traffic regulations to facilitate safe flight operations. Some of the most prevalent communication usage would be collision avoidance or the DAA scenario (Bandelier et al. 2023). This necessitates leveraging onboard sensors and establishing communication between UAS. Below are the five specific use cases for collision avoidance using U2U communications including merging, information relay, collaborative sensing, minimum separation distance, and rerouting.

3.1. Merging

Merging is the use case scenario of structured airspace. Merging focuses on a UAS *changing lanes* traveling from one direction to another. This *changing lanes* process allows a UAS to be in one air corridor system and transition to another. The concept is similar to the rules of engagement for entering a new corridor system, as defined in Muna et al. (2021*b*). For a successful merge, the UAS within the target air corridor must be aware that another UAS is attempting to merge. This is facilitated through U2U communication, ensuring the UAS can join the air corridor without causing a collision. The merging use case is illustrated in Fig. 2, which shows two different air corridors with air cells and multiple UAS traversing their routes. When a UAS in the upper air corridor intends to merge with the lower corridor (as oriented in the image), merging protocols are initiated. These corridors can exist in any direction or orientation within the airspace.

3.2. Information relay

Information relay is a use case developed to allow two UAS to communicate beyond the Radio Line of Sight (RLOS). In this use case, a UAS can fall into three categories: a source node, a relay node, or a target node. Information relay can be achieved by placing an intermediary UAS—acting as a message relay node—between the source and target UAS attempting to communicate.

An example of this scenario can be seen in Fig. 3, where the role of each UAS and communication range is included. To send a message to the target through the relay, the source must create a direct message specifying that it is a relay message type and include the nodes through which the message will be routed to reach the target. Once that information, the payload, and other metadata are filled into the message, it can be sent to the first UAS in the routing list. When a relay node receives a message and determines it is a relay message, the UAS checks to see if it is the target node or a relay for that specific message. If its role is a relay, it will remove its ID from the routing list and send the message to the next UAS on the list. If it is the intended target of the message, it will process the message accordingly. Any direct message can be sent as a relay, and there is no required number of relay nodes for an individual message.

3.3. Minimum separation

Minimum separation distance is a use case for air corridor systems that allow for spacing between UAS within air cells, as seen in Fig. 1. In this scenario, UAS need to maintain specific distances away from each other to operate safely in the air cells. With this distance, the minimum separation between any two UAS in the corridor system is one air cell. Depending on the distances between each vehicle, the speed of the UAS can be increased or decreased, allowing for efficient

Fig. 3. Relay scenario.

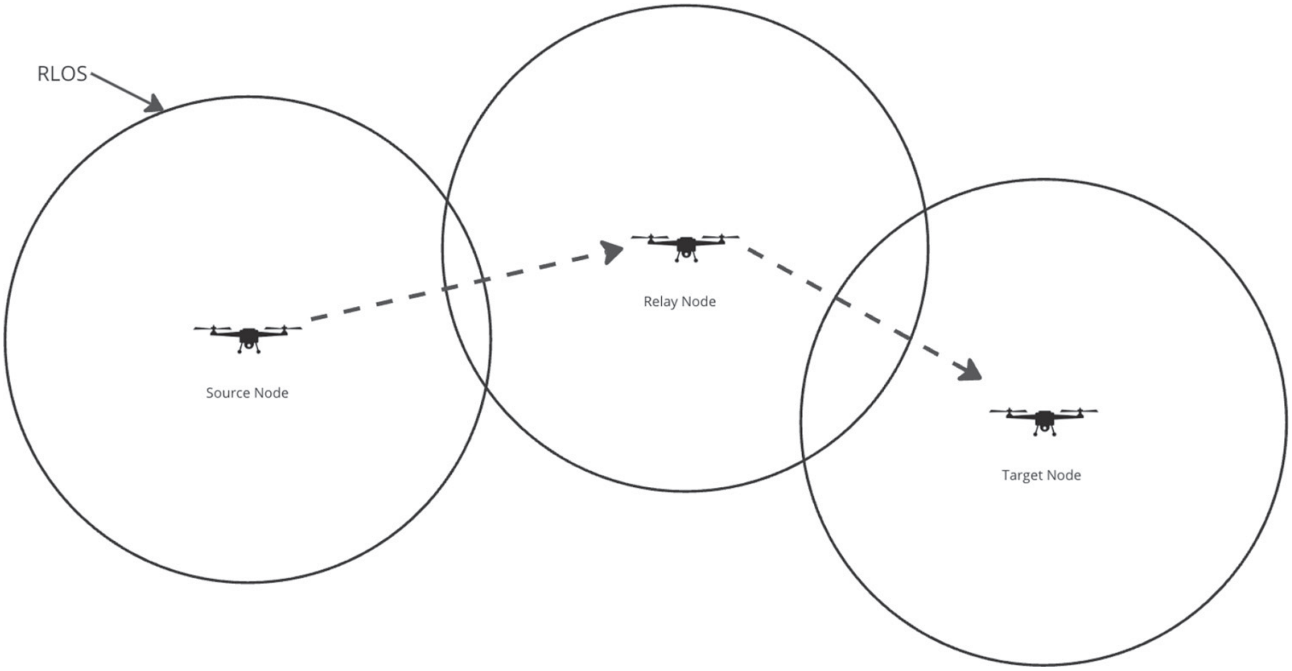
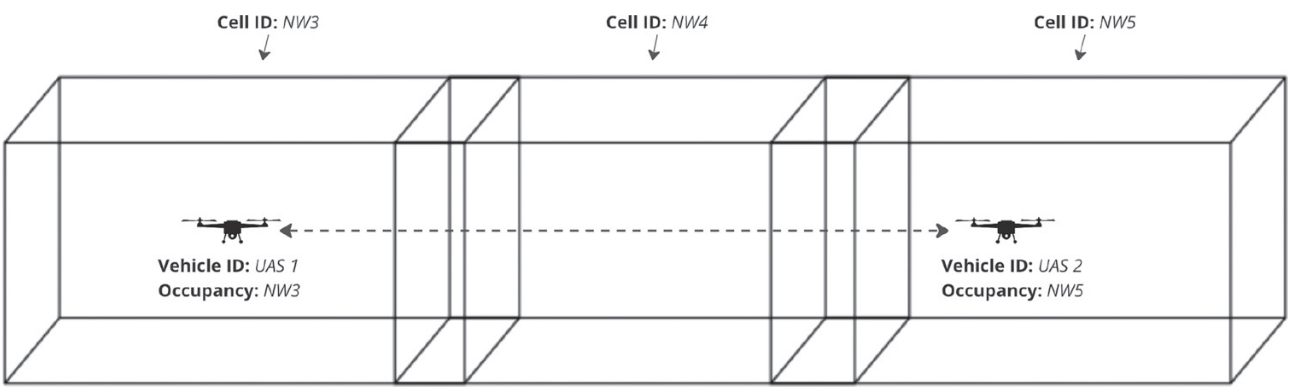


Fig. 4. Minimum separation.



flight operations. In Fig. 4, the concept of minimum separation for air corridor structures can be seen.

The concept of minimum distance has been discussed for aircraft within both vertical and horizontal flight, as seen in Namuduri (2023). These discussions support the use of minimum separation distance for both small and large aircraft. In this case, minimum separation distance is applied to the corridor and air cell design infrastructure in order to allow for the safe navigation of vehicles in urban areas. This creates a set of traffic rules that aim to prevent congestion in structured and well-defined airspace. This is an important use case as the projected traffic congestion caused by an increasing number of UAS in the airspace will need to be mitigated by flight rules such as minimum distance.

3.4. Collaborative sensing

Collaborative sensing is a use case developed to allow a UAS to gain greater spatial awareness of possible threats like hazardous weather and objects in the airspace. These constraints can be anything that directly obstructs the path of the UAS in the air corridor. This is achieved by broadcasting a collaborative sensing message containing information on hazards to all neighboring UAS. The information inside the message can either be a fully formed 3D volume defining a constraint or raw sensor data. Peripheral information on the airspace hazard is also included within the message. Once neighboring UAS receive this message, it is up to them to process the information and reevaluate their current trajectory to avoid the constraint. Collaborative sensing can be seen in Fig. 5, where multiple UAS are traversing through the designated airspace while maintaining minimum separation distance in their own air cell. The UAS uses its onboard sensors to determine if something obstructs its flight plan and forms a constraint if necessary. If the obstacle intersects the UAS path, it reroutes the mission around the constraint. This information is also sent to the other UAS in the air corridor to ensure that all UAS are aware of the potential threat.

Fig. 5. Collaborative sensing.

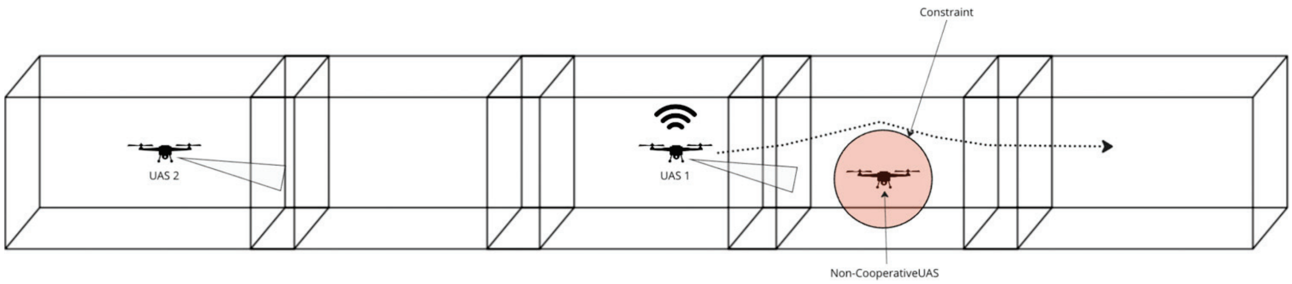
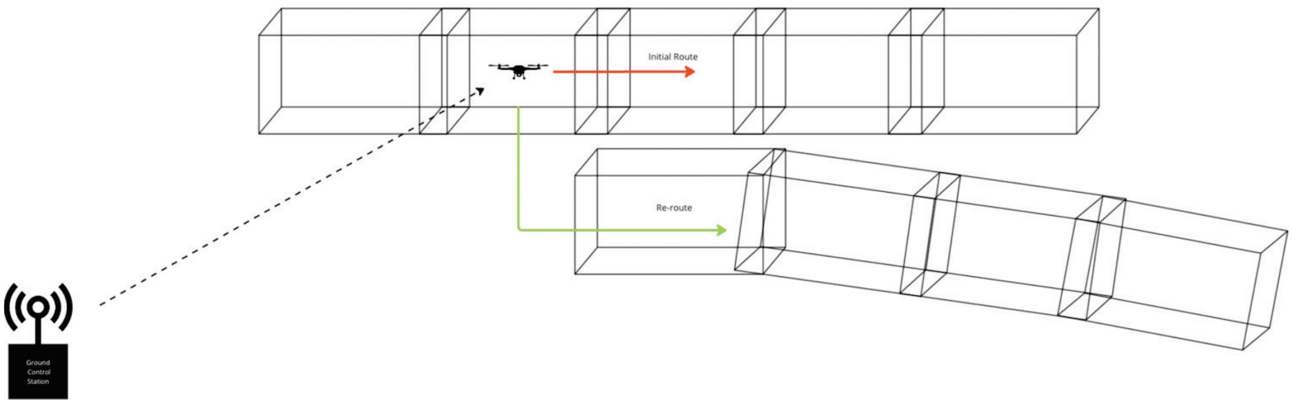


Fig. 6. Rerouting.



3.5. Rerouting

Rerouting is a use case for changing a UAS flight plan mid-mission. This may be required for no-fly zone such as weather constraints, birds, rogue UAV, buildings. The UAS would communicate with the Provider of Services (PSU) to obtain a new flight route. This allows for all operations in the airspace to be confirmed and ensures there are no potential risks or accidents. The rerouting process can be seen below in Fig. 6. The concept of rerouting uses air corridor structures and is applied to urban areas to ensure no congestion or collisions occur.

4. Collision avoidance strategies

In this paper, collision avoidance strategies are developed and implemented to address four different cases, which include (a) cooperative vehicles in structured airspace, (b) cooperative vehicles in unstructured airspace, (c) noncooperative vehicles in structured airspace, and (d) noncooperative vehicles in unstructured airspace. In the case of structured airspace, there is the use of air corridors in urban areas, whereas unstructured airspace allows collision avoidance strategies to take place in rural areas as there is no immediate threat of congestion. The class breakdown of collision avoidance can be seen below in Fig. 7.

4.1. Cooperative vehicles in structured airspace

4.1.1. Overview

Within the context of AAM, there is a constant investigation into developing methods to safely transport people and cargo, which includes applications involving air ambulances and air taxis. One technological innovation that can support this operation is replicating ground infrastructure such as roundabouts, highways, and intersections in the airspace. As demonstrated in Fig. 8, the roundabout is one use case of this airspace management that provides flight rules within air corridors to mitigate possible collisions. This roundabout system functions similarly to a standard roundabout used by cars on the road but is designed specifically for UAS. This is done using the rules of the roundabout system, which are enforced using U2U communications. An image of the roundabout intersection can be seen below in Fig. 8. In this image, the green corridors represent the ingress corridors that enter the roundabout system, the red corridors represent the egress corridors used to exit the roundabout, and the blue corridors represent the roundabout's circular roadway. The image shows a UAS entering the roundabout from the North side and a UAS leaving the roundabout via the South side. There are also two UAS communicating with each other to avoid potential collision.

4.1.2. Strategy

The roundabout system operates on three key concepts: U2U communications, subroutine protocol, and Designated Crossing Time (DCT). U2U communication ensures that information is continuously exchanged within the roundabout system. The subroutine protocol allows for the identification of routing conflicts in UAS flight plans. The DCT is used to compare and see if two vehicles will cross the same point, thereby determining if there is a potential collision (McCorkendale et al. 2024*a*).

Fig. 7. Collision avoidance classification.

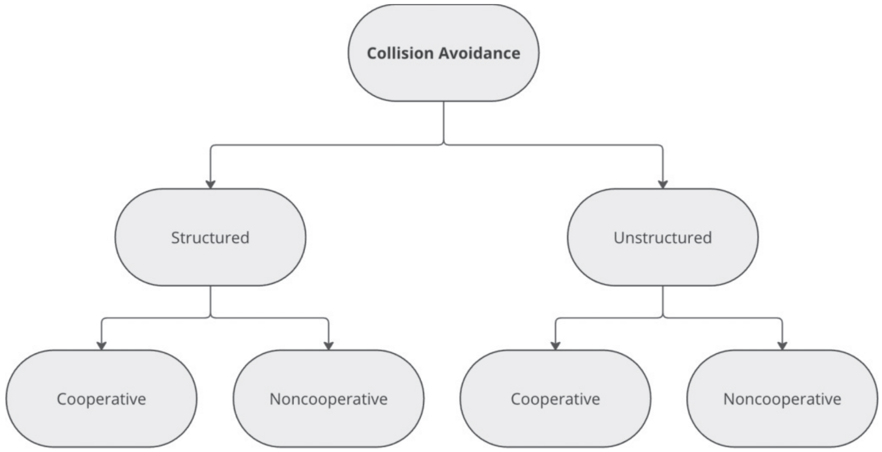
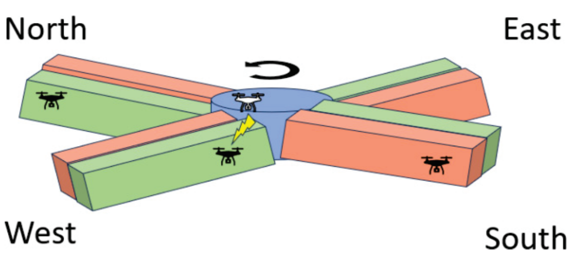


Fig. 8. Roundabout intersection for cooperative vehicles in structured airspace.



The subroutine protocol is used to segment the roundabout into different routes that can be used in UAS flight plans. The specific route used by a UAS depends on its direction of approach as well as the turn it intends to take (left, right, etc.). To do this, the Trapezoidal Rule (Trapezoidal numerical integration—MATLAB n.d.) is used to generate Cartesian coordinates representing waypoints of the roundabout's ingress and egress corridors by numerically integrating the equation of the equilateral hyperbola (eq. 1). These points are then divided into separate routes based on the different combinations of UAS approach directions and possible turns. This allows UAS to identify potential collisions with other UAS by comparing their intended route with the routes of others. This information is transmitted to other UAS via U2U communication messages.

$$L = (b - a) * \frac{1}{2} * \left[\sqrt{1 + \left(\frac{-(r^2)}{2a^2} \right)^2} + \sqrt{1 + \left(\frac{-(r^2)}{2b^2} \right)^2} \right] \tag{1}$$

Once the roundabout's Cartesian coordinates are generated, they can then be rotated in order to orient the roundabout to any desired angle using the equations in 2, where p_x and p_y are the Cartesian (x, y) coordinates to be rotated and θ is the angle they are to be rotated by

$$\begin{aligned} q_x &= p_x * \cos\left(\theta\left(\frac{\pi}{180}\right)\right) - p_y * \sin\left(\theta\left(\frac{\pi}{180}\right)\right) \\ q_y &= p_x * \sin\left(\theta\left(\frac{\pi}{180}\right)\right) + p_y * \cos\left(\theta\left(\frac{\pi}{180}\right)\right) \end{aligned} \tag{2}$$

Furthermore, the scaling factors ϵ and μ, shown in eq. 3, are used to transform the generated Cartesian coordinates to WGS84 GPS coordinates (How big is a degree n.d.). Equation 4 shows how these scaling factors are used to scale the generated Cartesian (q_x, q_y) coordinates to GPS waypoints. Note that in eqs. 3 and 4, lat and lon are the latitude and longitude of the center of the roundabout system, which is used as a reference location to generate the GPS waypoints.

$$\varepsilon = \frac{1}{|111111 \cos(\text{lat})|}, \quad \mu = \frac{1}{111111} \tag{3}$$

$$\begin{aligned} \text{Latitude} &= (q_x * \mu) + \text{lat} \\ \text{Longitude} &= (q_y * \varepsilon) + \text{lon} \end{aligned} \tag{4}$$

The DCT is the window of time a UAS occupies a particular point in space (Mandapaka et al. 2023), which makes it possible to determine if two UAS will collide at a point. Combined, a working collision-free intersection is established by using structured airspace, with all vehicles in the airspace effectively cooperating. Below in Fig. 9, two vehicles can be seen flying in the roundabout system. The vehicle Niner is attempting to enter the roundabout corridor and is about to collide with the vehicle Rex. U2U communication is happening at all times, and the two UAS know where each one is going and when they will be there. This is done by using this subroutine protocol. This protocol will transmit the next segment of the roundabout system for each UAS, and if they are the same, a potential collision is detected. Lastly, the entrance point to each subroutine is compared, and a DCT is estimated. If a difference is below 5 s, then the UAS yields. The UAS yielding can be seen below in Fig. 10. After the collision is resolved, the UAS Niner resumes its mission, as seen in Fig. 11. By utilizing the roundabout infrastructure and the

Fig. 9. Two vehicles are about to collide.

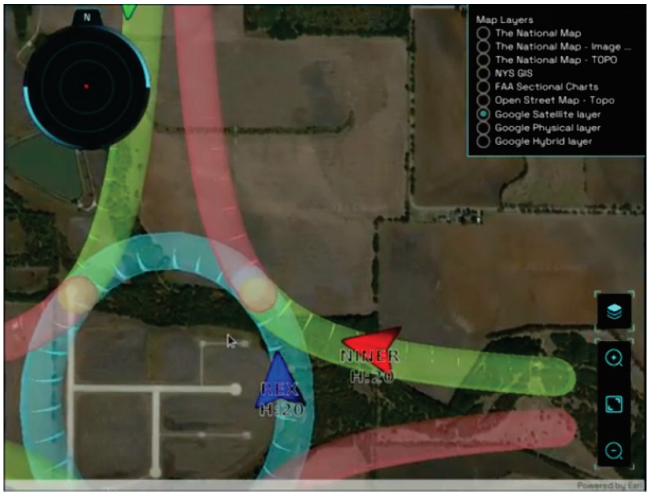


Fig. 10. The vehicle niner stops for Rex.

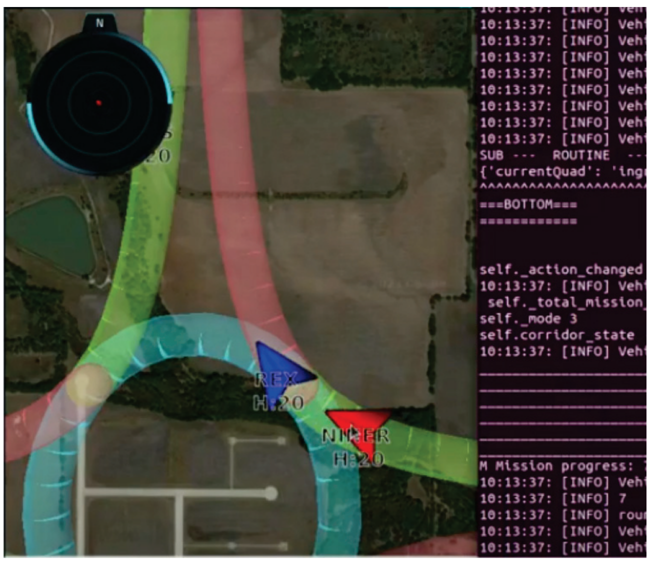


Fig. 11. Both vehicles continue their mission.

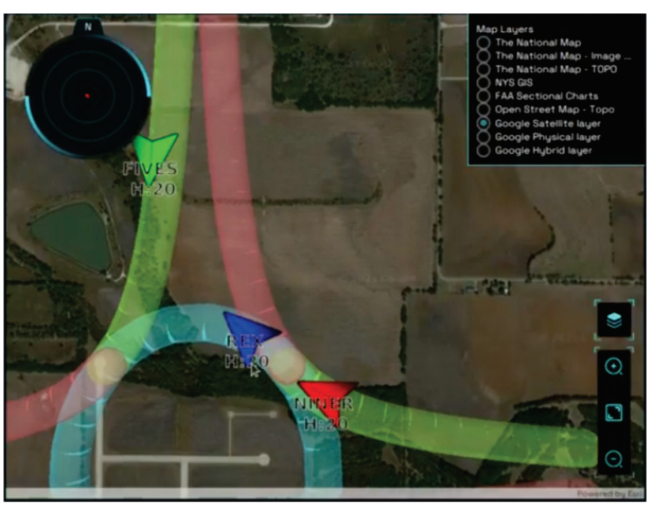
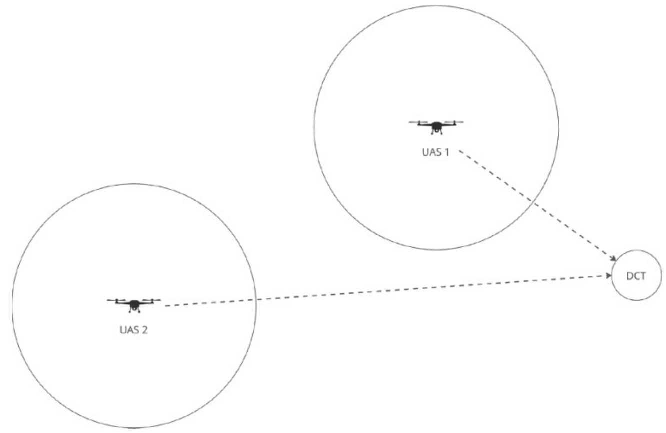


Fig. 12. Crossroads scenario.



three key principles—U2U communications, subroutine protocol, and DCTs—an effective collision avoidance strategy is established. This allows cooperative vehicles to traverse structured airspace, such as air corridor systems in urban areas.

4.2. Cooperative vehicles in unstructured airspace

4.2.1. Overview

The airspace in rural areas is not expected to be as congested as the airspace in urban areas. However, developing collision avoidance strategies in rural areas is necessary to ensure the UAS reaches its destination safely. Crossroads is a collision avoidance strategy for unstructured airspace with cooperative vehicles that works by establishing U2U communications between two or more vehicles to resolve any potential collisions (Mandapaka et al. 2023). This algorithm utilizes vehicle functions and parameters such as heartbeats, bump radius, parlance radius, and delta envelopes to perform collision avoidance strategies (Mandapaka et al. 2023). A visual as to how Crossroads works can be seen in Fig. 12. In this image, two UAS have a probability of colliding at the same point.

4.2.2. Strategy

When UAS detect each other within the parlance radius, they exchange information via U2U communications related to their current telemetry, heading, and velocity. This information allows the UAS to determine if there is a routing conflict between them and formulate a deconfliction solution. The calculations to determine if there is a risk of collision between two UAS require constructing *great circles* from the UAS headings and determining the closest point of intersection to each vehicle (Scripts 2021). If a potential collision is detected, then the DCTs of each UAS are compared to determine if there is any overlap. If there is an overlap in the DCTs, then there will be a process of determining which vehicle has right-of-way (ROW) at the projected point of intersection. ROW is determined based on UAS priority levels. DCT is calculated using the estimated time of arrival (ETA) to the detected intersection point and the value of the minimum safe radius (MSR) as shown in eq. 5 (Mandapaka et al. 2023). The ETA, shown in eq. 6, is the time it takes for a vehicle to reach the intersection point (Mandapaka et al. 2023).

$$(5)\qquad t_{\mathrm{DCT}} = \left(t_{\mathrm{ETA}} - \frac{r_{\mathrm{MSR}}}{v}, t_{\mathrm{ETA}} + \frac{r_{\mathrm{MSR}}}{v}\right)$$

$$(6)\qquad t_{\mathrm{ETA}} = \frac{d}{v}$$

The MSR is the distance between vehicles that must be maintained to be considered safe and is directly proportional to the vehicle's velocity (v) (Mandapaka et al. 2023) among other factors. These principles can be applied to resolve a conflict scenario detected between multiple UAS in unstructured airspace. A vehicle with a higher priority level gets to go first while the others yield to this crossing vehicle. After the vehicle crosses, the yielding vehicle will then continue its mission. The Crossroad intersection allows for cooperating vehicles in the unstructured airspace to operate without collisions. At this point, the nonprioritized vehicle receives the intersection message and analyzes its contents. Afterwards, the vehicles resolve the intersection conflict using one of the two following methods.

4.2.3. Altitude-yield intersection

The altitude-yield intersection allows two vehicles to avoid an intersection conflict using an altitude adjustment in one of the vehicles. Once the nonprioritized vehicle receives a heartbeat with an intersection message attached, it is prompted to resolve the intersection conflict by adjusting its altitude. To calculate this trajectory, an algorithm returns a list of position waypoints in the shape of a cosine wave, with the midpoint lying directly over or under the intersection point.

This algorithm uses a numerical approximation technique to determine points on the curve that are of equal arc length (L) away from one another. The drop distance (β) is the height at which the UAS will fly over or under the other UAS. The action distance (α) is the distance at which the UAS begins ascending/descending. The point b_n is the point on the curve that is L distance away from the starting point on the curve (a_n). The conditions for the algorithm are presented below in eq. 7:

$$(7)\qquad \text{while} a_n < \alpha : \begin{cases} n = 0 : a_0 = 0 \\ n \geq 1 : a_n = b_{n-1} \end{cases}$$

The following eq. 8 is used to solve for the series of b_n values that satisfy the conditions above.

$$(8)\qquad L = \frac{1}{2}(b_n - a_n)\left(\sqrt{1 + \left[\frac{-\beta\pi \sin\left(\frac{\pi a_n}{\alpha}\right)}{2\alpha}\right]^2} + \sqrt{1 + \left[\frac{-\beta\pi \sin\left(\frac{\pi b_n}{\alpha}\right)}{2\alpha}\right]^2}\right)$$

The list of generated (a_n, b_n) pairs is then converted from Cartesian coordinates into WGS-84 coordinates using a series of geometric transformations. First, the points are rotated around the z-axis by an angle equal to the UAS heading from North (θ).

$$(9)\qquad \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} a_n \\ 0 \\ b_n \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Afterward, a scaling factor based on the current location of the UAS is applied to the points that convert them into WGS-84 coordinates shown in eq. 9. Subsequently, the latitude, longitude, and altitude of the intersection point are superimposed on top of the scaled points and added together. Note that the longitude scaling factor uses the latitude point of the intersection (lat) during calculations as shown in eq. 3 (Snyder 2012; Veregin 2022). Once the list of position waypoints is generated, the nonprioritized vehicle follows the generated trajectory above the other vehicle. After crossing the intersection successfully, the UAS continues its original mission.

4.2.4. Velocity-yield intersection

The velocity-yield intersection is a simple way for two UAS to avoid an intersection conflict through a velocity adjustment in one of the UAS. Once the nonprioritized vehicle receives a heartbeat with an intersection message attached, it is prompted that action needs to be taken to resolve the intersection conflict by calculating a solution velocity.

The solution velocity is the velocity that a nonprioritized vehicle must yield to a velocity-yield intersection to avoid a collision. This velocity must satisfy certain constraints as dictated by the delta envelope of the yielding vehicle. The constraints imposed on the calculated solution are such that the final velocity must not exceed or fall below the yielding UAS maximum or minimum velocity; also, it must not require an acceleration for which the vehicle is incapable.

To calculate the solution velocity (v_{f}), the yielding UAS uses its distance from the intersection (d), initial velocity (v_{i}), and desired duration (t_{f}). The duration is chosen to be the same time as the prioritized vehicle's lower DCT since this allows the yielding vehicle to cross the intersection as soon as it has been cleared by the prioritized aircraft. The equations used for these calculations are derived from an ideal constant-jerk trajectory generator, which returns the solution velocity and the accompanying acceleration rate needed to achieve this velocity shown in eqs. 10 and 11(Jaya Sravani et al. 2023).

The first step is to find the constant (a_c) and maximum accelerations (a_{max}) that are required by the trajectory.

$$a_c = \frac{2d - 2v_i i t_f}{t_f^2} \text{ and } a_{max} = 2a_c \quad (10)$$

Next, the event's target velocity (v_f) is calculated.

$$v_f = \sqrt{v_i^2 + 2a_c d} \quad (11)$$

After finding these values, they must be compared to the yielding UAS delta envelope to ensure that none exceed or fall below the established minimums and maximums, respectively. If a valid solution is found, the nonprioritized vehicle uses velocity controls to yield this velocity at the calculated acceleration rate, allowing the prioritized vehicle to cross the intersection. Finally, the nonprioritized vehicle resumes the mission that it was previously executing.

4.3. Noncooperative vehicles in structured airspace

4.3.1. Overview

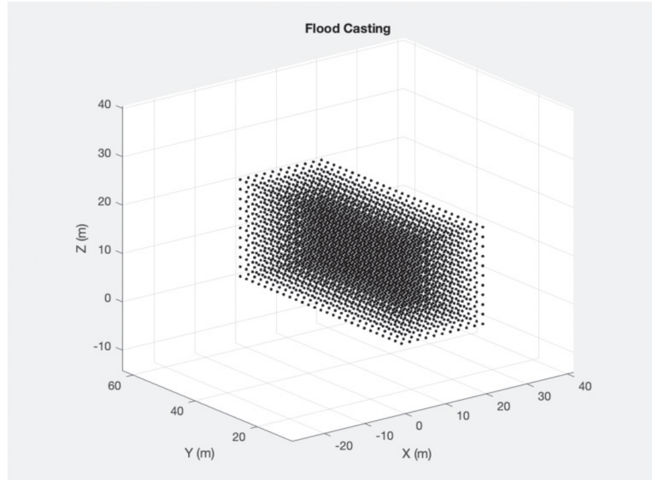
When a vehicle travels on time along its predetermined flight path, it is expected to broadcast a discovery message. When one or both of those requirements are unmet, the UAS is identified as a noncooperative vehicle. Due to its unpredictable nature, this status renders the UAS an airspace hazard, so all neighboring UAS must avoid noncooperative vehicles. It is assumed that a noncooperative vehicle is either incapable or unwilling to communicate, so the initial identification of a noncooperative UAS depends on onboard sensors. An onboard camera is the initial sensor used to identify a noncooperative vehicle. The UAS comes equipped with an object detection model trained on images of electric vertical take-off and landing (EVTOL) and other AAM vehicles. This model allows UAS to detect airspace hazards while in flight. This capability, combined with the rules of engagement in structured airspace and U2U communication protocols, provides a UAS with sufficient information to effectively deduce if a vehicle is noncooperative.

While a UAS executes its flight plan and detects another vehicle through the object detection model, two things are true: (a) this is the first instance of awareness of the detected vehicle, and no discovery messages have been received, thus indicating that the UAS is unable or unwilling to communicate, (b) since minimum separation is broken, the vehicle is not following its predefined flight plan. From those facts, the UAS can determine that the detected vehicle is noncooperative. Once the UAS detects the noncooperative vehicle, it creates a 3D constraint that encloses the noncooperative vehicle and broadcasts a collaborative sensing message to all neighboring vehicles, informing them of the presence of the airspace hazard.

The collaborative sensing message contains the hazard type, sensor type, constraint area, or sensor data. The message header, hazard type, sensor type, and message type are all indicator fields that clarify what the message truly contains. The hazard type specifies the nature of the hazard being addressed, which could be related to weather, a nonconforming vehicle, or a nonconforming object. The sensor type indicates the sensor used for detection, which may include LiDAR, camera, RF, temperature, wind, or RADAR sensors. The message type is the last indicator field that describes the payload's content.

The three message types are a constraint message, which is a list of coordinates that describe the 3D constraint; a sensor message, which contains sensor data; or a combination of both, in which a generated constraint is sent with the sensor data that was used in the constraint generation. Based on the message type, the actual payload of the collaborative sensing message will contain either a list of coordinates describing a constraint or an array of sensor data. Once the UAS broadcasts the collaborative sensing message, the recipient is responsible for processing the information and proceeding cautiously. In contrast, the sender of the message must take immediate action to avoid a collision.

Fig. 13. Flood casting within an air cell.



4.3.2. Strategy

To avoid a collision with a noncooperative vehicle within structured airspace, a new path must be generated around the constraint without exiting the air corridor. The characteristics of the corridor can be leveraged to create this new path by using a new technique called flood casting (FC). It is a method of populating one or more air cells with equidistant waypoints to generate an optimal route around a constraint shown in Fig. 13.

The FC generation depends on the bounds that define an air cell and the spacing between each waypoint. The UAS stores data locally on the locations of all air cells along its route. It retrieves the current air cell it occupies and the next cell in its route to establish the boundaries for the FC. The spacing variable in this context defines the distance between each waypoint given in meters (MATLAB 2023). Given the ranges:

$$\begin{aligned} \text{Lat} &= [\text{lat}_{\text{start}} : \text{spacing} : \text{lat}_{\text{end}}] \\ \text{Lon} &= [\text{lon}_{\text{start}} : \text{spacing} : \text{lon}_{\text{end}}] \\ \text{Alt} &= [\text{alt}_{\text{start}} : \text{spacing} : \text{alt}_{\text{end}}] \\ \\ \text{lat} &= [\text{lat}_0, \text{lat}_1, \ldots, \text{lat}_n] \\ \text{lon} &= [\text{lon}_0, \text{lon}_1, \ldots, \text{lon}_n] \\ \text{alt} &= [\text{alt}_0, \text{alt}_1, \ldots, \text{alt}_n] \end{aligned} \tag{12}$$

These vectors represent a set of points within given bounds and are equally spaced. From these vectors, matrices can be derived for lat, lon, and alt, which are defined by the dimensions:

$$n = \text{length}\,(\text{lat}) \;\; x \;\; m = \text{length}\,(\text{lon}) \;\; x \;\; p = \text{length}\,(\text{alt}) \tag{13}$$

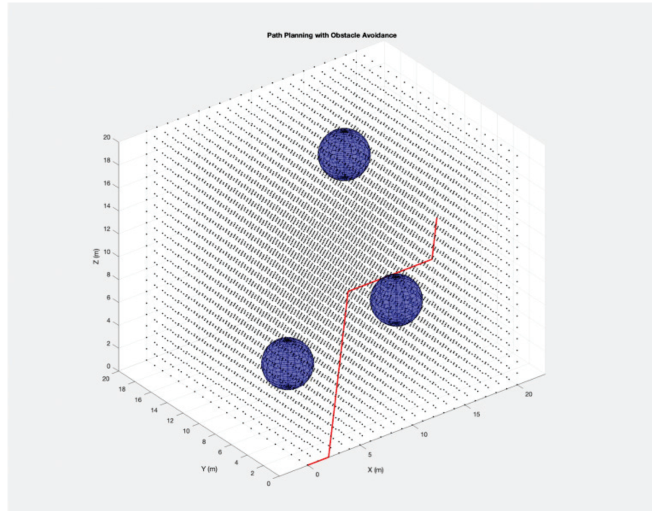
Each matrix holds the values of its respective vector while the other two dimensions are held constant. By iterating through each combination of elements in all three matrices.

$$\text{Flood Casted Waypoints} = \begin{bmatrix} (\text{lat}_0, \text{lon}_0, \text{alt}_0) & (\text{lat}_1, \text{lon}_0, \text{alt}_0) & \cdots & (\text{lat}_n, \text{lon}_0, \text{alt}_0) \\ (\text{lat}_0, \text{lon}_1, \text{alt}_0) & (\text{lat}_1, \text{lon}_1, \text{alt}_0) & \cdots & (\text{lat}_n, \text{lon}_1, \text{alt}_0) \\ \vdots & \vdots & \ddots & \vdots \\ (\text{lat}_0, \text{lon}_m, \text{alt}_0) & (\text{lat}_1, \text{lon}_m, \text{alt}_0) & \cdots & (\text{lat}_n, \text{lon}_m, \text{alt}_0) \end{bmatrix} \\ \vdots \\ \begin{bmatrix} (\text{lat}_0, \text{lon}_0, \text{alt}_p) & (\text{lat}_1, \text{lon}_0, \text{alt}_p) & \cdots & (\text{lat}_n, \text{lon}_0, \text{alt}_p) \\ (\text{lat}_0, \text{lon}_1, \text{alt}_p) & (\text{lat}_1, \text{lon}_1, \text{alt}_p) & \cdots & (\text{lat}_n, \text{lon}_1, \text{alt}_p) \\ \vdots & \vdots & \ddots & \vdots \\ (\text{lat}_0, \text{lon}_m, \text{alt}_p) & (\text{lat}_1, \text{lon}_m, \text{alt}_p) & \cdots & (\text{lat}_n, \text{lon}_m, \text{alt}_p) \end{bmatrix} \tag{14}$$

The matrix (eq. 14) represents the FC waypoints and their elements in all three dimensions. Once waypoints are generated, they must undergo a filtering process to remove the waypoints that exist within the constraints. The Euclidean distance is calculated between each waypoint and the center of the constraint. If this distance is less than the radius of the constraint, the waypoint is deemed to be within the constraint and is removed. All the remaining waypoints are then taken and used as nodes within a graph. Dijkstra's shortest path algorithm was applied to the graph object to generate a path around a constraint where the weights correlate to distance (MathWorks 2023). In this scenario, the source node is the current position of the UAS, and the target node is the center point of the next air cell.

Figure 14 illustrates this process. The three blue spheres are constraints that a UAS must traverse through. The UAS initial position is at the origin, and the final position is the center point of the following air cell defined as the target node. The red line represents the shortest path from the source to the target node.

Fig. 14. Obstacle avoidance and path planning using Dijkstra's algorithm.



4.4. Noncooperative vehicles in unstructured airspace

4.4.1. Overview

In unstructured airspace, noncooperative vehicles present a challenge for collision avoidance strategies because they operate against established communication protocols or flight plans, making them difficult to track and detect. Collision avoidance strategies in unstructured airspace must include a detection and tracking mechanism to identify noncooperative vehicles and take the necessary measures to avoid potential collisions. This involves sensor technologies with the use of machine learning algorithms or avoidance algorithms to ensure the safety of airspace operations in unstructured airspace. An image of how object detection and avoidance work can be seen below in Fig. 15. In this image, the UAS uses onboard sensors such as a camera, LiDAR, RADAR, or any onboard peripherals. Using these sensors, another vehicle is detected, and the UAS appropriately maneuvers around it, showing how noncooperative vehicles operate in unstructured airspaces.

4.4.2. Strategy

An artificial potential fields algorithm was used for a UAS to avoid collisions with noncooperative vehicles and objects in unstructured airspace. The potential fields can be divided into attractive and repulsive forces, where constraints or obstacles exert a repulsive force on a UAS, and the next waypoint of the UAS flight plan exerts an attractive force. The summation of the attractive and repulsive forces governs the motion of the UAS. Through the use of onboard LiDAR and RADAR sensors, a UAS is accurately able to derive the position and velocity of an object. These quantities allow the UAS to create constraints enclosing a noncooperative vehicle. The constraints are then used within the potential vector field

Fig. 15. Object detection and avoidance.

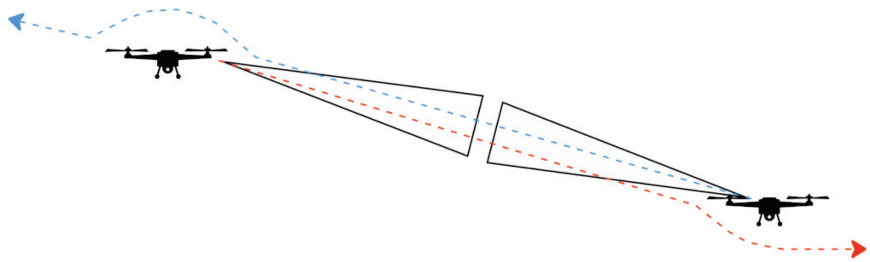
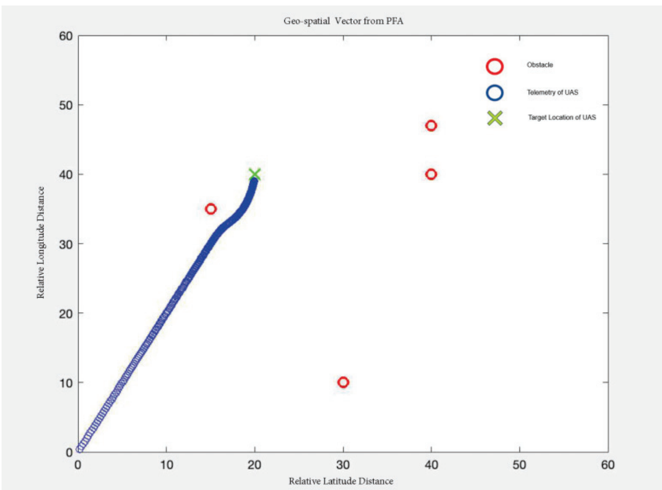


Fig. 16. Potential fields algorithm.



algorithm so the UAS can generate a new path to avoid a collision (Rostami et al. 2019).

(15) $$\text{AttractiveForce}: F_{\text{att}} = -k_{\text{att}}\left(\mathbf{p} - \mathbf{p}_{\text{goal}}\right)$$

(16) $$\text{RepulsiveForce}: \left(\mathbf{F}_{\text{rep}} = \sum_{i=1}^{n}\left(k_{\text{rep}}\left(\frac{1}{\rho_i} - \frac{1}{\rho_0}\right)\frac{1}{{\rho_i}^2}\frac{\mathbf{r}_i}{\rho_i}\right)\right) \text{ for } (\rho_i < \rho_0)$$

The use of the constraint with the algorithm is the generation of repulsive forces. Equation 15 shows the formula used to evaluate the attractive force of an object, while eq. 16 represents the formula used for repulsive forces. These two equations are then summed using eq. 17 to calculate the forces exerted on a UAS by the artificial potential fields at any given instance. Equation 18 is then used to calculate the new position of the UAS based on the force it feels from the potential field. Lastly, Fig. 16 demonstrates the functioning of the artificial potential fields algorithm to avoid obstacles.

(17) $$\text{TotalForce} = \left(F_{\text{att}} + F_{\text{rep}}\right)$$

(18) $$\text{NewPosition}: \left(\mathbf{p}_{\text{new}} = p + \alpha F_{\text{total}}\Delta t\right)$$

5. Conclusions and future work

With the developing efforts of AAM, an autonomous collision avoidance system will be required for the safe operation and mitigation of traffic. The density of the UAV is projected to increase in the near future, so it is important to operate these vehicles effectively in structured and unstructured airspaces. These vehicles will need to autonomously account for conforming and nonconforming conditions and vehicles. These can be birds, weather conditions, rogue vehicles, etc. that will require UAV to make fast and accurate decisions. Techniques such as the ones described in this paper will resolve real-time concerns such as traffic and collisions by using concepts like U2U communications as a means for UAV in the airspace to cooperate with each other. With the use of autonomous operations, more efficient means of transportation, logistics, and medical services can be achieved.

Future works include implementing the simulated solutions in real world setting. This is important to test the accuracy of the systems. Additionally, ongoing research looks to merge unmanned and manned vehicles in the airspace. Manned vehicles have defined flight rules that make integrating autonomous system difficult when introducing new flight rules. The effort is to converge the airspace allowing for both to operate and follow flight rules that will allow for a collaborative airspace.

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Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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Competing interests

The authors report that there are no competing interests to declare.

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