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Enhancing Trajectory-Based Operations for UAVs through Hexagonal Grid Indexing: A Step towards 4D Integration of UTM and ATM

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Unmanned Aerial Vehicles (UAVs) are gaining popularity for use in a wide range of tasks, such as mapping, surveying, delivering, and surveillance. However, given to safety issues and the need for coordination with manned aircraft, their integration into the existing airspace system is a significant challenge. 4D trajectory-based operations can enable safe and efficient integration of UAVs into the airspace system (Shenoy & Tyagi, 2022). The use of 4D trajectory-based operations in UAV operations can lead to improved safety and reduced fuel consumption (Ramasamy et al., 2014). 4D trajectory-based operations can increase the predictability and reliability of UAV operations, which could make them more acceptable to regulators and other stakeholders in the aviation industry (Ramasamy et al., 2014).

Trajectory-Based Operations (TBO) is a novel concept in the field of Air Traffic Management (ATM) for the next generation of air traffic control. Strategic conflict detection and resolution (CD&R) based on flight intent or flight plans is critical in 4D trajectory-based operations, given the potential benefits (Hao et al., 2018). TBO can benefit from the use of UAVs as they can operate in the same airspace as manned aircraft, with 4D trajectory-based operations enabling safe and efficient integration. TBO and Unmanned Aircraft System Traffic Management (UTM) share a common goal of ensuring the safe and efficient operation of UAVs in the airspace system. UAVs could be able to function with much more autonomy by using 4D trajectory-based operations in UTM, which also allows for greater operational efficiency and flexibility while upholding safety standards. As a result, the implementation of 4D trajectory-based operations can radically transform the way that UAVs are integrated into the airspace system, making them an essential element of the next generation of air traffic control (Ramasamy et al., 2014).

Furthermore, the aviation industry must brace itself for the introduction of a significant number of mass-market drones (Hecto et al., 2021). Now, most drone operations are restricted to a certain height, a specific line of sight, and the freedom to fly in a designated or segregated zone. However, in the near future, the integration of UTM in ATM environments and mixed operations will be critical, especially when the concepts of air taxing and drone deliveries become fully operational. In ATM-UTM integrated operations, strategic conflict detection on the ground is essential in three key elements (Hao et al., 2018). The first is identifying trajectory conflict and allocating conflict-free trajectories to manned aircraft before departure. The second is identifying and allocating conflict-free trajectories to both manned and unmanned flights prior to flight departure. Finally, the third element involves identifying UAV conflicts and allocating conflict-free paths to UAVs before departure. As a result, new concepts are in high demand to address the increased complexity of the situation.

Trajectory generation, validation, conflict detection, and resolution are the four primary processes involved in trajectory-based operations (Klooster et al., 2010). In ground-based conflict-free trajectory planning, the last three processes depend not only on the flight's 4D positions but also on the airspace in which it operates and the standard separation requirements of that airspace. The use of geo-spatial data has become prevalent in recent years, and the traditional Geographic Information System (GIS) paradigm is becoming impractical due to the ever-increasing influx of data. Discrete Global Grid Systems (DGGSs) are an emerging multi-resolution 3D model that uses hierarchically subdivided cells to integrate and analyse massive earth data (Amiri et al., 2015; Sahr et al., 2003; Wang et al., 2020). Hexagonal structures have gained considerable prominence among the three regular polygon shapes (triangles, quads, and hexagons) that can tile the plane. Hexagonal grids minimize sampling bias due to the edge effects of the grid shape, and their circularity facilitates the depiction of curves more naturally in the data patterns than square grids. Additionally, hexagonal grids offer the highest angular resolution, uniform adjacency, and each neighbour connects an edge with the hexagon, with centres equidistant from their own centre (Zhou et al., 2020).

The proposed research suggests the use of a hexagonal grid indexing based UAV trajectory representation and grid indexing based trajectory conflict detection in trajectory planning. The proposed hexagonal protected zone or hexagonal prism in 3D space surrounds each UAV, which can be extended horizontally by connecting adjacent hexagonal prisms, creating a protected area of a desired dimension along the intended flight path/trajectory. The framework proposed strategically addresses the 4-D trajectory strategic conflict detection problem (pre departure trajectory) for TBOs. In a set of predicted trajectories, the framework identifies conflicts if another aircraft or UAV infringes on a protected zone on its trajectory at a given interval of time in the future. This approach can enable better decision-making while planning trajectories in the strategic or tactical phase of TBO. Overall, the proposed framework can enhance the safety and efficiency of airspace operations by providing more accurate and reliable conflict detection and resolution for UAVs in the airspace system.

Problem

The existing literature highlights several research gaps in the field of trajectory-based operations. While the concept of Trajectory-Based Operations (TBOs) in Eurocontrol (SESAR) is evolving, there is a need for advanced planning possibilities to deal with dynamic multi-trajectory situations. Several studies have proposed conflict detection and resolution methods, such as probabilistic conflict detection, trajectory specification, flight trajectory clustering, and intersection-based conflict prediction. However, these methods

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have their limitations, such as complicated probability calculations, subjective thresholds, and assumptions of steady velocity and zero sensitivity to environmental changes. In contrast to conventional manned aircraft air traffic management, which typically relies on predefined routes and fixes limited to airport-to-airport operations, UAV operations require a segregated area bounded operation without conflict, as they are often conducted away from airports and lack a traditional route structure and fixes. This practical difference distinguishes UAV operations from their conventional counterparts. Additionally, the current trajectory representation methods, such as the use of square or cubic tiles, have shortcomings such as difficulties in following curvature and approximation of protected airspace. Therefore, there is a need for advanced and computationally efficient methods, such as the use of hexagonal tiles and hierarchical indexing, to accurately represent trajectories and enhance conflict detection and resolution in the context of UAVs and Unmanned Traffic Management (UTM).

Purpose

The goal of this research is to investigate the possibility of applying hexagonal tiles for UAV trajectory representation and hexagonal hierarchical indexing for computationally efficient trajectory conflict detection in the context of UAVs and UTM. As research progresses in the field of trajectory-based operations for ATM and UTM, there is an increasing demand for novel, practically reliable and computationally efficient methods to represent trajectories accurately. The integration of 4D trajectory-based operations and UTM/ATM systems can lead to new planning possibilities for dealing with dynamic multi-trajectory situations, ultimately improving the safety and efficiency of the airspace system. When compared to ATM operation from airport to airport using set route structure with performance based navigational system, UAV operation in UTM airspace has certain limitations, including surveillance constraint. This research aims to address the shortcomings of existing trajectory representation techniques, such as the use of square or cubic tiles, by offering better angular resolution, uniform adjacency, reduced sampling bias, and more natural depiction of curves in data patterns. By proposing an innovative approach to trajectory representation and conflict detection, this research can contribute to the development of more effective UTM and ATM systems.

Research Questions

1. How can hexagonal tiles be used to represent trajectories and their protected airspace more accurately in UAVs and Unmanned Traffic Management (UTM) systems?
2. What are the benefits of using hexagonal tiles over square or cubic tiles for trajectory representation in UAVs and UTM?

3. How can the use of hexagonal hierarchical indexing enhance the efficiency and accuracy of strategic trajectory conflict detection (pre departure trajectory planning) in the context of UAVs and UTM?
4. How can the proposed approach of using hexagonal tiles and hexagonal hierarchical indexing improve the overall safety and reliability of UTM in the airspace system?

Literature Review

As the ATM concept based on TBOs in Euro control (SESAR) (Undertaking, 2016) evolves, in the strategic phase, TBOs introduce new planning possibilities with the aim of dealing with more dynamic multi-trajectory situations. When potential conflicts between aircraft trajectories can be resolved spontaneously at the planning stage, the workload of the controllers can be significantly reduced (Vela et al., 2010). This planning stage which occurs before the planned trajectory becomes a reference business trajectory (RBT), which comprises of the strategic as well as pre-tactical phases (Calvo-Fernandez et al., 2017).

Schuster and Ochieng (2014) carried out a detailed analysis of performance requirements of future Trajectory Prediction and CD & R tools within SESAR and NextGen. A strategic deconfliction method for European Air Traffic Flow Management was proposed by Jan Berling et al. (2015). To enable strategic deconfliction, a proposed flight path is evaluated against points of other flight paths for breaches in the separation minima. Probabilistic conflict detection (Guan et al., 2014; Jardin, 2005; Prandini et al., 2000) measures the probability of conflicts among aircraft utilising a genetic algorithm or a support vector machine (SVM) or other probabilistic methods (Weiyi Liu, 2011) or a combination of these methods. These approaches require complicated probability calculations, and the thresholds are subjectively chosen. This method is still prone to extensive misdetections due to extremely low thresholds or can contribute to missed detection due to excessively high thresholds. In short, conventional identification of flight conflicts is based on certain assumptions like specific flight angles, steady velocity, and zero sensitivity to environmental changes (Jiang et al., 2018; Paielli, 2016; Wang & Qiu, 2018).

A trajectory conflict detection and resolution based on bounding volume (trajectory specification; Paielli & Erzberger, 2017) proposed by Paielli and Erzberger (2019) for terminal airspace that uses rectangular bounding volume to represent protected airspace around the flight trajectory. Hao et al. (2018) proposed a method of conflict prediction conducted by examining whether aircraft STP (Space-Time Prisms) intersect or not, and conflict resolution is executed by planning a spacetime conflict-free trajectory that avoids intersection. Mio et al. (2019) proposed a low-altitude flight conflict detection method that consists of multi−level spatiotemporal grid map. This converts conventional trajectory- by-trajectory multivariate conflict detection calculations into a real time conflict state

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query of distributed databases, which in significantly lowers the underlying computational complexity and improve the speed of flight conflict detection.

As research progresses in the field of trajectory-based operations, there is an increasing demand for advanced and computationally efficient methods to represent trajectories accurately. The use of square or cubic tiles to discretize continuous trajectories into a cubic grid can lead to several shortcomings, including 0-adjacency, difficulties in tunnel-free approximation, poor quality of approximation of protected airspace and difficulties in following curvature. To address these limitations, Wang et al. (2020) proposed the use of hexagonal tiles. This research intends to address these issues by proposing the use of hexagonal tiles for trajectory representation and hexagonal hierarchical indexing for computationally efficient trajectory conflict detection in the context of UAVs and UTM. The proposed approach aims to resolve the drawbacks of square grid representation by providing higher angular resolution, uniform adjacency, minimized sampling bias, and more natural depiction of curves in the data patterns. The hexagonal hierarchical indexing can enable efficient conflict detection by assigning unique indices to each cell in a global grid system and retrieving or assigning datasets using these unique indices. This approach can enhance the accuracy and efficiency of trajectory-based operations for UAVs in the airspace system, improving the overall safety and reliability of UTM.

Methodology

The International Civil Aviation Organisation (ICAO) has defined trajectory as the description of the movement of an aircraft, both in the air and on the ground, including position, time, and at least via calculation, speed, and acceleration (International Civil Aviation Organization, 2016). Even though the flight and UAV movement are continuous, as no practical system is available for recording and storing the exact position of the actual trajectory of an aircraft, the available recorded and stored data are discrete samples which represent a near approximation of the original trajectory. In this section, we consider the trajectory predicted by the method described in the previous section, as well as any other available methods, and its representation. An aircraft/UAV trajectory ‘T’ can be represented as

$$T = [p_1, p_2, \ldots, p_n] \quad (1)$$

Where ‘p’ denotes the sampled positions and is defined by its 4D spatiotemporal parameters (longitude, latitude, altitude, and time). The position trajectories can be mathematically represented as $P_n = [x(n), y(n), a(n)]$, where x(n), y(n) and a(n) denote latitude, longitude, and altitude of the trajectory at time n. The discrete time value starts from the initial time to the final time. A discrete set of spatiotemporal measurements are collected as the UAV moves. Based on the sampling technique used, a time-driven (e.g., once every minute) sampling strategy is widely used over distance-driven (once every mile), and geometry-driven (e.g., once the aircraft deviates from its heading more than degrees). In our analysis, we use time-driven sampling techniques for the raw trajectory. Various methods are being tested to represent the flight trajectories and to minimise computational complexities. This work is inspired by the research provided by McClain et al.'s (2018) "Hexagonal airspace based capacity measurement" and Hao et al.'s (2018) "Conflict detection by verifying whether the Space Time Prisms (STPs) of aircraft intersect."

Selection of Hexagonal Grid Hexagonal Prism for UAV Trajectory

To effectively represent UAV trajectories, the use of homogeneous structures that can tessellate to create an evenly spaced grid is essential. Among the three polygon forms that can achieve this (i.e., equilateral triangles, squares, and hexagons), hexagons have been identified as the most appropriate option. Although triangular cells are commonly used to partition faces, their neighbouring association is complex, making them less suitable for representing UAV trajectories. While quads are compatible with many existing data sets, algorithms, and hardware, they are not as compact as hexagons. Hexagonal grids offer the highest angular resolution and uniform adjacency, with each hexagonal cell having six neighbours that share an edge with the hexagon and have centres equidistant from its centre (Girish & Richard Gordon, 2002). This results in a more regular and predictable pattern of connectivity, making them ideal for accurately representing UAV trajectories. Additionally, relevant research has shown that hexagons have the highest sampling efficiency and angular resolution (Wang et al., 2020). Therefore, in our framework for UAV trajectory representation, we propose selecting hexagons as the base cell.

A comprehensive comparative analysis was performed to evaluate the various structural and geometrical properties of square and hexagonal grids for trajectory representation. Table 1 provides a brief comparison of the relevant properties / features required for trajectory representation in square and hexagonal tiles. There are several virtues and features of the hexagonal tile that make it an appropriate choice for representing the flight trajectory and its protected zone.

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Table 1

Comparison of Square Tiles with Hexagonal Tiles

Property	Square Tiles	Hexagon Tiles
Tunnel freedom	0-connection possible, difficulty to make tunnel free approximation	Always 1-connected and tunnel-free approximation of continuous path is possible
Adjacency	0-adjacency is possible	0-adjacency is impossible.
Optimality-length of side for the same area ($1m^2$)	$\text{length of side} = \sqrt{(\text{area of cell})}$ $= \sqrt{(1\text{m}^2/\text{n})}$ where n is the number of cells required to cover the area. If we assume each cell is $1m^2$, then n = 1, so the length of side would be $\sqrt{1} = 1m$.	Side length is lower (s=0.62) $length\ o = 2\ x \frac{area\ of\ cell}{3\sqrt{3}}$, $= (2/3)\sqrt{(3/4)}m$ where we assume that each cell is $1m^2$.
Distance between farthest point	2=1.414	(13÷2) $*$ s=1.118
Regularity: For example, In contrast,	Less regular than hexagonal grids due to the non uniformity of neighbouring cells and the presence of right angles. eg: a square grid with cells that are 1 meter wide would have edges that are perpendicular to one another, resulting in 4 right angles per cell	more regular than square grids due to the uniformity of neighbouring cells and the absence of right angles. eg: a hexagonal grid with cells that are 1 meter wide would have edges that are at 120-degree angles to one another, resulting in no right angles.
Quality of Approximation	Less, As Maximum deviation of a discrete line approximation is more	Better, As Maximum deviation of a discrete line approximation is minimal.
Compactness	Less compact For example, if we want to cover a circular area with a radius of 10 meters using square cells that are 1 meter wide, we would need to use at least 41 cells.	more compact than square grids due to their more efficient use of space. to cover a circular area with a radius of 10 meters using hexagonal cells that are 1 meter wide, we would need only 20 cells to cover the same area.
Angular resolution	Lesser angular resolution eg: a square grid with cells that are 1 meter wide would have an angular resolution of 90 degrees per cell.	the highest angular resolution among regular polygons that tile the plane. eg: a hexagonal grid with cells that are 1 meter wide would have an angular resolution of 60 degrees per cell
Representation of curvature patterns	Unbroken, straight and parallel lines follow curvature with certain difficulties	The lines tend to split naturally, which permits curvature to be seen more clearly and effectively.
Representing large geographical area	Prone to more distortions due to curvature of earth	Suffer less distortion due to the curvature of the earth.
Subdivisions	Recursive subdivision is possible	Recursive subdivision is not possible.

In this paper, we intend to demonstrate that schematic models that use hexagonal grid tiles (called 2-hexels) to represent 2D trajectories, have some significant advantages over conventional cubic versions. Relatively less attention has been paid to the hexagonal grids and the graphic models based on them.

For the 3D space, where voxels (hexagonal prisms, also known as 3-hexels) may be used instead of cubes, similar results are present. Hexel-based graphical simulations are called honeycomb models. An attractive characteristic of such tiling's is that they are 1-adjacent to any two non-disjoint tiles. Unlike in the case of traditional rectangular grids, 0-adjacency is improbable here. It is, therefore, tunnel-free as the connected object is always 1-connected. The protected airspace around the aircraft is circular in shape (5/10 NM distance around the flight based on airspace it operates), which makes it possible for the hexagons to tessellate to form an equally spaced grid along the path, since it is the polygon in the most circular shape. The circularity of a hexagon grid allows it to reflect curves more easily in the patterns of the data than square grids, which makes the UAV flight path better represented. In addition, finding neighbours is more straightforward in a hexagon grid comparing to square grid. Since the edge or length of contact is the same on each side, the centroid of each neighbour is equidistant. In addition to the above benefits, while depicting airspace in a hexagonal grid, the calculation of the airspace capacity and air traffic congestion of a particular airspace sector can be made simpler.

Hexagonal Geospatial Indexing System and UAV Trajectory Indexing Technique

The repetitive subdivision of the parent grid to higher resolution is one of the obstacles to hexagonal tiling. To address this problem, different approaches are used for successful hierarchical indexing. H3 (Brodsky, 2018; Sahr et al., 2003) is a system of geospatial indexing that incorporates the benefits of a hexagonal grid with hierarchical subdivisions of S2, allowing for (approximately) subdivision using the hexagonal grid into finer and finer hexagonal grids. Sparse-space indexing converts n-dimensional space into a one-dimensional representation and provides improved representations for data analysis, visualisation, and queries. The Discrete Global Grid System (DGGS) commonly uses triangles, hexagons, and quadrilaterals shapes for indexing.

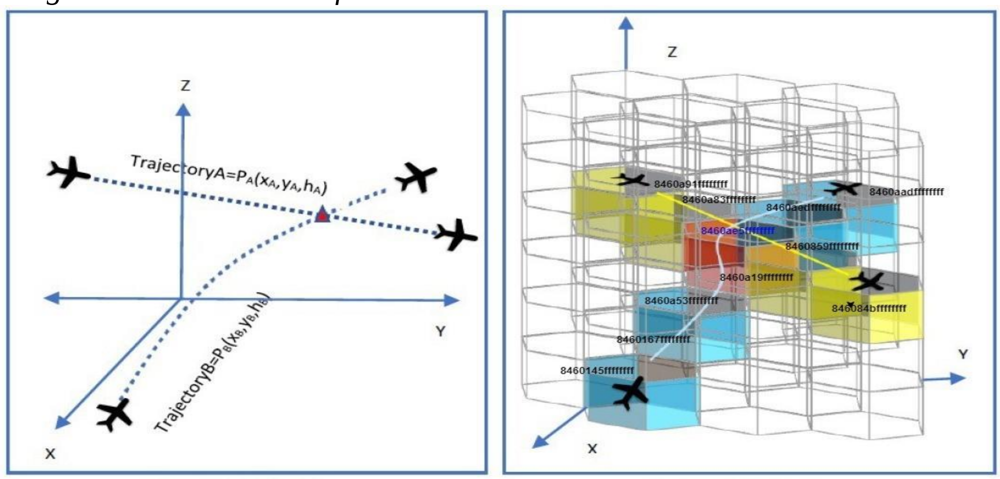
The geospatial indexing system H3 is a discrete global grid structure (Shar, 2019) composed of multi-resolution hexagonal tiling of spheres with hierarchical indexes. The trait of multi-resolution is typically realised through the use of such refinement by hierarchically subdividing cells throughout the sphere. The H3 grid is built on the icosahedron by recurrently creating hexagon grids of increasing precision until the intended resolution is attained. A table detailing the average cell area for each H3 resolution is available in Brodsky (2018).

Proposed Trajectory Conflict Detection Process Using Multilevel Spatio-temporal Indexing

When a new UAV flight plan is added, its 4D trajectory is created. Also, grid objects are created on a hexagonal grid with a hexagonal ID, time and altitude. The newly created trajectory is checked with the existing database to detect strategic conflicts. A conflict will occur when the same hexagonal grid is occupied by another aircraft at the same time. If the flights have the same trajectory, then a check will be carried out to find the time at which these flights would occupy the same hexagonal grid. If the time is not greater than or equal to the prescribed minima, suitable conflict resolution methods (time /distance based separation) can be applied.

Figure 1

Hexagonal Grid-based Conflict Detection



a.Conventional trajectory   b. Proposed trajectory

The Figure 1(b) is a pictorial representation of the proposed method of trajectory conflict detection in 3-dimensional hexagonal space. The conventional flight trajectories of two flights are indicated by Trajectory A (T_A) and Trajectory B (T_B) in Figure 1(a). In order to detect trajectory conflict in the airspace concerned, each trajectory point of one trajectory is compared with other trajectories in the conventional method using various approaches (Figure 1(a)). This process increases computation complexity as well as memory requirements. The proposed method of representing trajectories in the hexagonal dimensional prism is shown in Figure 1(b) and each hexagonal prism is indexed. In Figure 1(b) T_A and T_B are indicated by yellow hexagonal prism and blue coloured hexagonal prism, respectively. Trajectory A (T_A) and Trajectory B (T_B) can be represented using a hexagonal grid as below.

$$T_A = \{h_{A1}, h_{A2}. . . .h_{Am}\} \qquad (2)$$
$$T_B = \{h_{B1}, h_{B2}, ...h_{Bn}\} \qquad (3)$$

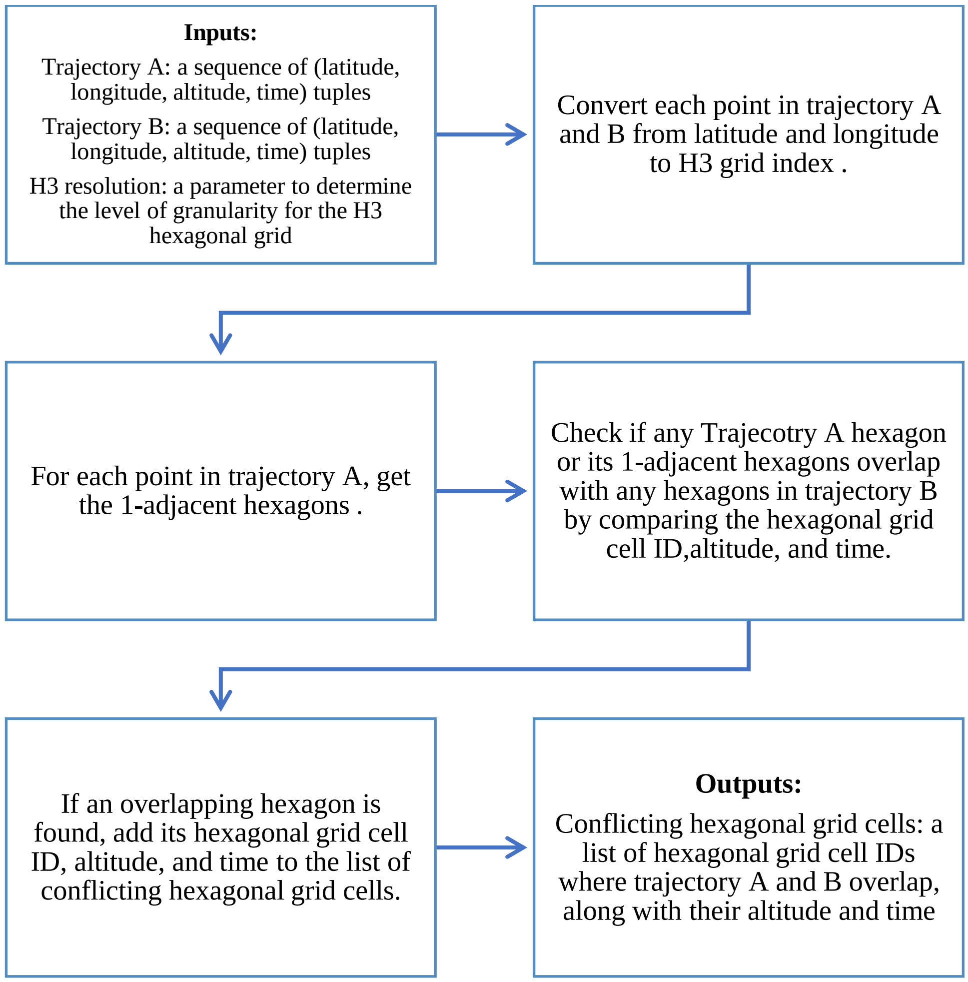
Where $h_{A1}, h_{A2}, . . ., h_{Am}$ are hexagonal grid objects with a hexagonal grid index (or hexagonal segment) and time for T_A, where 'm' denotes the length of the hexagonal grid object. Similarly, $h_{B1}, h_{B2}, \ldots, h_{Bn}$ denotes the hexagonal grid objects for T_B with length ‘n’.

Assume that both the UAVs are maintaining the same level at the enroute intersection point, and when T_B crosses T_A hexagonal prism at the same time, then it can be detected as a conflict. This can be easily found by comparing the hexagonal objects of the trajectories indexed in the database. The time difference for conflict free trajectory can be defined by separation minima (International Civil Aviation Organization, 2016) that are being applied or considered. Here it is assumed that the aircraft retains its average segment speed (Enroute/Terminal) under consideration, thereby making it possible to convert the minimum lateral distance separation into its equivalent time. As compared to the square grid approach, the adjacency and connection between the adjacent cells is well defined in the hexagonal grid, resulting in easier identification of neighbours (always 1-connected) and easier computation. The conflict detection process is summarised in Figure 2 (Algorithm 1).

The algorithm aims to identify overlapping areas between Trajectory A and its 1-adjacency grid with Trajectory B. The first step is to search for any common grid indices between the two trajectories, followed 1-adjacency check. If there are no overlapping indices, we can conclude that the trajectories are separated, and the output will indicate that there are no conflicting points. However, if there are overlapping indices, we proceed to the next step. In the second step, we check the altitude of both trajectories in the overlapping cell. If there is a difference of 1000 feet or more, it can be inferred that the trajectories are separated. Otherwise, we move to the final step, where we check the time interval that both trajectories occupy the overlapping cell.

Figure 2

UAV Conflict Detection Using Hexagonal Grid Indexing Algorithm



If the time difference is less than the maximum cell occupancy time (2* apothem of hexagonal grid/ speed) of each trajectory, it can be considered that there is a conflict between the two trajectories. Once a conflict is detected, various conflict resolution methods can be applied to resolve it, such as delaying another trajectory or allotting alternate level or path/grid changes.

For example, consider Trajectory A with altitude 2000 feet and time occupancy of 5 minutes, and Trajectory B with altitude 1500 feet and time occupancy of 3 minutes. If the two trajectories have overlapping grid indices, we check the altitude difference of 500 feet, which is less than 1000 feet, indicating that there may be a conflict. We then check the time occupancy and find that there is a time difference of 2 minutes, which is less than the maximum time occupancy of 5 minutes for Trajectory A and 3 minutes for Trajectory B. Therefore, we can conclude that there is a conflict between the two trajectories. We can resolve this conflict using any conflict resolution method, such as adjusting the altitude or time occupancy of the trajectories. To ensure practical viability and maintain separation in all directions, the concept of "1-adjacency" is introduced, meaning that if two trajectories share at no common adjacent hexagonal cell of Trajectory A, the separation criteria will be ensured.

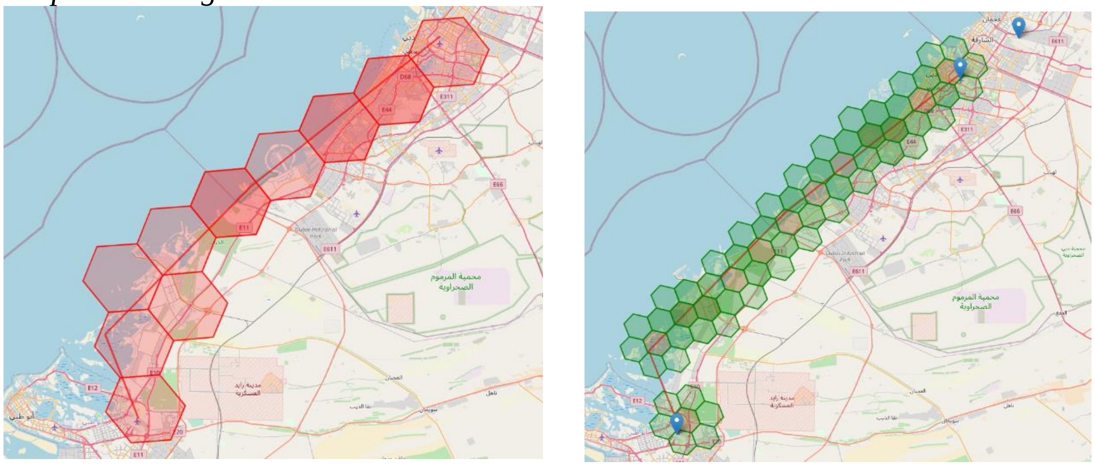
Results And Discussion

The 4D trajectories are developed from the flight plan using an in-house Python tool. The trajectory created from the flight plan includes latitude, longitude, altitude, and time. Here we used Uber 'H3' (Brodsky, 2018) DGGS hexagonal indexing in Python to develop the index for each coordinate (latitude and longitude). Initially, the data frame of hexagonal indices is created from the coordinates for a particular trajectory. This process reduces the number of memory locations required to represent the trajectory data since multiple locations are in the same hexagonal grid as per the grid resolution used. This can be considered as sampling in trajectory management, which reduces the storage requirements and computational complexity of trajectory data. Here we considered a simulated track between Dubai International Airport and Abu Dhabi International Airport as Trajectory A. We represented Trajectory A with 10-minute interval points (latitude, longitude) in a hexagonal grid. Figure 3 provides the trajectory representation with hexagonal grid resolution 5 (apothem = 9.854km = 5.32NM). The 12 points in geodetic coordinates were represented with 10 hexagonal grids.

Another representation of the same trajectory was done using resolution 6(apothem = 3.72 km) and its 1-adjacency. The significance of 1-adjacency is that it ensures the minimum required separation, especially in the planning phase of the trajectory, and reduces the computational complexity by checking if the grid index is occupied by another trajectory or not. This enables efficient trajectory conflict detection and resolution, reducing the risk of potential collisions. The use of 1-adjacency in hexagonal grid representation is particularly important for UAV operations, where the location of the UAV can be at any point within a hexagonal grid. The 1-adjacency separation ensures that no other UAV infringes the minimum separation requirement. Therefore, 1-adjacency representation in hexagonal grids is crucial for safe and efficient UAV operations.

Figure 3

Proposed Hexagonal Grid and Grid Index



(a) (b)

Note. (a) Proposed hexagonal grid (resolution 5) based trajectory; (b) Proposed hexagonal grid index (resolution 6) with 1-adjacency.

It can be observed that in low resolution, the geographical location of the trajectory lies in an adjacent hexagonal grid even though the high resolution (1/7th size of low resolution) lies in the connected hexagonal grid. In order to represent the trajectory, we use the H3 (Brodsky, 2018) hexagonal hierarchical indexed grid.

Conflict Detection Using Hexagonal Grid Indexing

Scenario 1: UAV to UAV Conflict Detection

We tested the model with different UAV trajectory points. A sample case study is presented in Table 2. We tested the model with different UAV trajectory points. In this scenario, we can use the same approach as explained earlier to detect conflicts based on hexagonal indexing and 1-adjacency (overlapping 1-adjacency indicated in red). We first need to create hexagonal grids and assign each data point of the trajectories to a particular hexagonal grid. Then, we can use 1-adjacency to check if there are any overlapping hexagons between the two trajectories.

Table 2

Conflict Detection Look Table for Trajectory A with 1-Adjacency and Trajectory B

Trajectory -A(UAV-1)				Trajectory B(UAV-2)		
Hexagonal Index	**Adjacent Hexagons**	**Altitude**	**Time**	**Hexagonal Index**	**Altitude**	**Time**
8443acdffffffff	{'8443a1bffffffff','8443ac5ffffffff', '8443ac1ffffffff', '8443ac9ffffffff', '8443127ffffffff','8443a13ffffffff'}	0	00:00	8443acdffffffff	0	00:15
8443acdffffffff	{'8443a1bffffffff','8443ac5ffffffff', '8443ac1ffffffff', '8443ac9ffffffff', '8443127ffffffff','8443a13ffffffff'}	1500	00:10	8443acdffffffff	1700	00:25
8443acdffffffff	{'8443a1bffffffff', '8443ac5ffffffff', '8443ac1ffffffff', '8443ac9ffffffff', '8443127ffffffff', '8443a13ffffffff'}	3400	00:20	8443a13ffffffff	3400	00:35
8443a13ffffffff	{'8443a1bffffffff', '8443a11ffffffff', '8443acdffffffff', '8443ac5ffffffff', '8443ae9ffffffff', '8443a17ffffffff'}	5500	00:30	8443a13ffffffff	5100	00:45
8443a13ffffffff	{'8443a1bffffffff', '8443a11ffffffff', '8443acdffffffff', '8443ac5ffffffff', '8443ae9ffffffff', '8443a17ffffffff'}	6800	00:40	8443a13ffffffff	6800	00:55
8443a13ffffffff	{'8443a1bffffffff', '8443a11ffffffff', '8443acdffffffff', '8443ac5ffffffff', '8443ae9ffffffff', '8443a17ffffffff'}	8500	00:50	8443a11ffffffff	8500	01:05
8443a13ffffffff	{'8443a1bffffffff', '8443a11ffffffff', '8443acdffffffff', '8443ac5ffffffff', '8443ae9ffffffff', '8443a17ffffffff'}	10000	01:00	8443a11ffffffff	10000	01:15
8443a11ffffffff	{'8443a1dffffffff', '8443a1bffffffff', '8443a19ffffffff', '8443a17ffffffff', '8443a15ffffffff', '8443a13ffffffff'}	8300	01:10	8443a11ffffffff	8300	01:25
8443a11ffffffff	{'8443a1dffffffff', '8443a1bffffffff', '8443a19ffffffff', '8443a17ffffffff', '8443a15ffffffff', '8443a13ffffffff'}	6600	01:20	8443a11ffffffff	6600	01:35

If there are any overlapping hexagons, we can calculate the time difference between the two trajectories at that point and compare it with the required separation distance. If the time difference is less than the required separation requirement, we can consider it as a conflict in trajectory planning.

First, we need to calculate the maximum occupancy time for each hexagonal index based on the speed and altitude of the UAVs. Let's assume that the maximum occupancy time for a hexagonal index is equal to the time it takes for a UAV to traverse the height of that index at its maximum speed. For example, if a UAV is flying at 1500 ft(feet) altitude, and its maximum speed is 10 ft/s, then the maximum

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occupancy time for a hexagonal index at 1500 ft altitude would be 150 seconds. Similar way we can calculate lateral cell occupancy time. If another aircraft occupies the same cell or 1-adjecency there possibility of conflict in trajectory planning and further minimum separation criteria can be checked point by point for those points. However, we are utilising this for trajectory strategic planning phase, where macroscopic level planning take place to identify the trajectories having conflict rather minimum separation breached.

Now, let's check for conflicts between Trajectory A and Trajectory B (Table 2) using the hexagonal indexing and adjacency approach. We'll start with the first-time step (00:00) and check if any UAVs from Trajectory A and Trajectory B are present in the same hexagonal index or in an adjacent hexagonal index. At time 00:00, the only UAV present in the airspace is in Hexagonal Index 8443acdffffffff at altitude 0ft. There are no other UAVs present in the same hexagonal index or in an adjacent hexagonal index, so we can mark this time step as separated. At time 00:10, both Trajectory A and Trajectory B have UAVs present in Hexagonal Index 8443acdffffffff, which means there is a potential conflict. Since the altitudes of the UAVs on Trajectory A and Trajectory B differ by more than 1000ft (1500ft for Trajectory A and 0ft for Trajectory B), there is no conflict in the current step.

We can continue this process for each time step, checking for conflicts between Trajectory A and Trajectory B based on their presence in the same hexagonal index or in an adjacent hexagonal index, their altitude, and the time they entered that hexagonal index. At time 00:15, there is a conflict between Trajectory A and Trajectory B, as both have UAVs in the same hexagonal index (8443acdffffffff) at the same altitude (0ft) and the time difference between their entry times is less than the minimum separation time. At time 00:25, there is no conflict between Trajectory A and Trajectory B, as the UAVs from Trajectory A and Trajectory B are in different hexagonal indices. We can continue checking for conflicts at each time step until the end of the trajectories. Hence, in the strategic conflict detection process during the flight planning phase, a database querying process is used to compare and analyse the trajectories of different UAVs based on their hexagonal indices, altitude, and time information, to identify potential conflicts and ensure safe and efficient trajectory-based operations.

Scenario 2: Manned Aircraft to UAV Conflict detection:

The strategic conflict detection technique between manned aircraft and UAVs follows a similar approach as described in the preceding scenario. Generally, manned flight operations cover longer distances compared to UAV operations, which are currently limited to short distances based on line-of-sight or beyond-line-of-sight operations. UAVs typically operate in airspace designated for unmanned aerial vehicles. However, in the future, they may be able to share the same airspace with manned aircraft.

We propose a UAV trajectory and manned trajectory representation based on a flight plan that utilizes hexagonal grid indexing. The protected airspace around a UAV is represented as a hexagonal grid, meaning that the UAV will be flying within the boundaries of the hexagonal grid. Due to the slower speed of UAVs compared to manned aircraft, the UAV's grid occupancy times are longer.

For example, let's assume that the protected airspace around a UAV is set to 5 nautical miles (NM). In this case, the 1-adjacent hexagonal grid of the UAV's flying location might also be considered a conflict zone. Conflicts may arise if a manned aircraft and a UAV share the same grid or are 1-adjacent in the hexagonal grid system. In such cases, the nearest point can be determined to meet the minimum separation criteria, or the UAV's trajectory profile can be altered to ensure separation. As long as the UAV's hexagonal grid ID and at least one adjacent grid do not match the profiles of manned aircraft, the flight paths can be considered free of conflict. This approach reduces the memory requirements and computing expenses, while considering multiple flights in the simulation environment.

Comparison with Conventional Pairwise Computation and Square/Cubic Grid

In point-by-point computation, for each point in Trajectory A, we need to compute the distance to each point in Trajectory B. This would require a total of 13 x 13 = 169 distance calculations. For each distance calculation, we need to compute the square root of the sum of the squared differences in latitude and longitude between the two points. This requires two subtractions, two squares, and one square root operation, which can be computationally expensive. On the other hand, in the hexagonal grid method, we only need to compute the hexagonal cell IDs for each point in Trajectory A and Trajectory B. This requires 13 hexagonal cell ID computations for each trajectory, or a total of 26 computations. We can then compare the adjacent hexagonal cells for each point in Trajectory A to the adjacent hexagonal cells for each point in Trajectory B using the check for conflict function. This requires a total of 13 x 6 = 78 adjacency comparisons. Overall, the hexagonal grid method requires fewer computations than the point-by-point method, especially as the number of points in the trajectories increases and number trajectories increases. The hexagonal ID conversion and conflict detection have a lower complexity and memory requirements, will be significant for large datasets.

Conclusions

A novel method of strategic trajectory conflict detection based on the spatiotemporal index of the multilevel grid is proposed. The concept contributes to the trajectory planning process to detect strategic conflicts and ensure a conflict-free trajectory by specifying a protected airspace using the spatio-temporal hexagonal conversion technique. This will not impair any applicable standard separation that affects operational safety, rather it effectively identifies possible conflicts and their position during the planning phase. The proposed method employs conflict state query of hexagonal index-based databases instead of conventional path-by-path by computation. The research assessed the applicability of ’h3’ hexagonal grid indexing approach for flight trajectory representation and presented computationally efficient grid indexing technique for detection of strategic conflict.

The proposed method introduces a hexagonal grid reference based 4D trajectory representation and hexagonal grid index-based conflict detection process for UAVs with reduced computational complexity for UAV trajectory planning. The use of a hexagonal grid overcomes the limitations of the traditional square grid in detecting 1-adjacent neighbours, providing a more accurate representation of both manned and UAV trajectories and their respective protected airspaces based on separation criteria. This approach enables the identification of trajectory conflicts between various UAVs and manned aircraft during strategic planning, while also facilitating the evaluation of demand capacity balancing of each sector and traffic density of UAV/manned aircraft in any sector. The spatiotemporal hexagonal conversion technique contributes to the trajectory planning process by detecting strategic conflicts and ensuring a conflict-free trajectory by specifying a protected airspace. This technique not only improves the overall performance of query-based grid conflict for large data sizes but also makes it suitable for practical implementation in Traffic Flow Management (TFM). By providing a computationally efficient method for UAV trajectory planning and conflict detection, the proposed method can contribute to the development of an efficient UTM system, which can enable safe and efficient integration of UAVs into the national airspace system.

The use of hexagonal grid indexing can not only improve UAV trajectory planning and conflict detection but also be extended to other applications such as UTM and manned aircraft to UAV strategic conflict detection. Furthermore, the proposed approach can be expanded to include sector capacity estimation, traffic density computation, and ATC workload measurement, allowing for more efficient traffic measurements and strategic conflict resolution in the ATM system.

Recommendations

UAV flight planning in UTM can be effectively implemented using the proposed spatiotemporal hexagonal conversion technique for trajectory planning and strategic conflict detection using hierarchical index search algorithm. This approach can contribute to the safe and efficient integration of UAVs into the national airspace system. The proposed strategic conflict detection process during the flight plan phase incorporates hexagonal indices in conjunction with a database querying process to compare and analyse UAV trajectories, providing suggestions for conflict-free trajectories for UAVs. This approach ensures safe and efficient trajectory-based operations in UTM-ATM integration.

Further research can be conducted to explore the potential of hexagonal grid indexing for other applications such as sector capacity estimation, traffic density calculation, and Air Traffic Control (ATC) workload measurement. These developments can lead to more efficient traffic measurements and conflict handling in ATM systems. The proposed method can be extended to include manned aircraft for strategic conflict detection with UAVs. This can lead to a more comprehensive approach for airspace management and conflict avoidance.

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