Unmanned Aerial Vehicle conflict detection based on spatiotemporal data grid

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Abstract—The increasing number of unmanned aerial vehicles (UAVs) and the complexity of the low-altitude airspace operation environment have also increased. How to efficiently solve the pre-flight UAV conflict detection problem is an important link in the low altitude airspace operation environment. This paper combines the global airspace grid coding system and the relational spatio-temporal data structure to propose a method based on spatio-temporal data grid, establishes the grid size applicable to conflict detection, and verifies the feasibility and effectiveness of the proposed UAV conflict detection type in different environments through simulation experiments. The results also show that the seventh level grid of the global airspace grid is the most suitable basic grid size, and the time consumption is reduced by about 50-75% compared with the traditional method in different scenarios.

1. Introduction
With the continuous development of Unmanned Aerial Vehicle(UAV) technology, which makes the operation of UAVs easier and more flexible, the cost continues to reduce, and the popularity rate is increasing, the number of UAVs will continue to increase in the future and has a huge potential for development. From 2016 to 2018, China's UAV scale growth rate of more than 45%, and the total amount from 4.9 billion to nearly 10 billion. And, it is predicted that the growth rate will further accelerate in the next two years [1]. Therefore, in view of the continuous growth trend of the scale of low-altitude UAV operations, how to efficiently detect UAV conflicts and maintain the safety of low-altitude airspace operations is one of the key objectives and important challenges for the structural transformation and development of low-altitude airspace. The installation of airborne surveillance equipment (e.g., sensors, radar, etc.) [2-3], global or relative positioning [4-6], and airspace lattice [7-8] are effective ways to detect UAV conflicts. Among them, the airspace lattice method is a common method in recent years in air traffic management and low altitude airspace system management. The core idea is that the airspace is discretized by grids and map the physical flight space into the data information space, which provides a new spatio-temporal architecture for air traffic pre-flight conflict detection.

The current research focus on lattice of airspace to detect UAV conflicts mainly focuses on rasterization to reduce the computational complexity of local detection, and many airspace lattice methods have been proposed at the strategic and pre-tactical stages, but there is less research based on grid coding methods to integrate data information from spatial grids and build spatio-temporal data grid structures, which have not yet been able to support low-altitude airspace operations. In view of this, this paper focuses on the problem of UAV conflict detection at the strategic stage, proposes a UAV conflict detection method based on spatio-temporal data grid, discusses the appropriate grid size
and the calculation efficiency under different scenarios, provides a method basis for fast and accurate UAV conflict detection, and supports the perfection of China's low-altitude airspace operation system.

2. Problem Description
In addition to being affected by its own configuration and meteorological conditions, the operation of UAVs is significantly sensitive to navigation system errors, flight technology errors, minimum separation distances, and other related parameters. The conflict detection of UAVs, like traditional air traffic management, needs to consider not only the type of UAVs and the realistic low-altitude operation environment, but also the perturbation of external factors such as the risk of conflict in operation. How to achieve an efficient UAV conflict detection process and reduce the computational complexity and computation time under different low altitude airspace operating environments is the main problem addressed in this paper, and is also the main difficulty faced in the low altitude airspace management system.

In this study, in the process of UAV conflict detection, each UAV is considered as a sphere with a certain radius $R$, as shown in the figure 1 and the layers shown in equation (1)(2), including the total UAV body radius, UAV Navigation System Error (NSE), Flight Technical Error (FTE) and Separation Minimum as UTM airspace constraint. (UAV Flight Technical Error, FTE) and Separation Minimum as UTM airspace constraint.

\[ Constructor = Bodyradius + NSE + FTE \]
\[ r = Constructor + 0.5 \cdot SeparationMinimum \]

In this paper although the model is not modeled considering an accurate UAV kinematic model, the reliability of the error parameters in it has been verified in real flight tests [9]. Usually, different types of UAVs have different cumulative radius values.

Before performing UAV conflict detection, the definitions related to UAV trajectory and UAV conflict should be clarified. The UAV trajectory used in this paper is a collection of a series of trajectory points, where the trajectory points include spatial location coordinates and the time corresponding to the trajectory points.

Based on the established UAV protected area volume model, we define the UAV conflict as the predicted process before UAV collision, i.e., the Euclidean distance between UAVs is less than the minimum separation distance between two UAVs, i.e., the sum of the respective radii of the two UAVs. Therefore, we define the following constraint to ensure the absence of conflict:

\[ \forall t, dist(p_i(t), p_j(t)) > r_i + r_j \]

where \( p_i(t) \) and \( p_j(t) \) denote the spatial position coordinates of the flight track of the i-th UAV and the flight track of the j-th UAV at the moment, \( r_i \) and \( r_j \) denote the UAV sphere radius of the i-th UAV and the j-th UAV tracks, respectively. When the Euclidean distance between the two UAVs is less than the sum of the radii of the respective UAV protection volumes, the two UAVs are considered to be in conflict risk requiring corresponding operations.
3. UAV conflict detection based on spatio-temporal data grid

The traditional pairwise conflict detection method can be used for UAV conflict detection in low-altitude airspace structures by calculating the distance between the positions of each track point to determine whether there is a conflict[10]. For N UAVs, the pairwise conflict detection method requires a pairwise comparison process. However, if the number of UAVs increases and the airspace involved is large, the pairwise conflict detection method has a high computational complexity, which reduces the efficiency of conflict detection and causes the algorithm computing time to be too long to meet the requirements of the initial strategic stage UAV trajectory planning. The traditional method of computing UAV conflicts in pairs is as follows:

| ALGORITHM 1: Pairwaise CD Algorithm |
|-------------------------------------|
| for \( i < N \) \[
| \quad j = i + 1 \|
| for \( j < N \) \[
| \quad \text{while } t < \text{trajectories} \|
| \quad \quad \text{Duration} \|
| \quad \quad P1 = \text{PositionAircraft}[i].\text{PositionTrajectory}[t] \|
| \quad \quad P2 = \text{PositionAircraft}[j].\text{PositionTrajectory}[t] \|
| \quad \quad \text{distance3D} = \text{calculate3DDistance}(P1, P2) \|
| \quad \quad \text{if } \text{distance3D} > (r1 + r2) \|
| \quad \quad \quad \text{A Conflict has been detected} \|
| \quad \quad \quad t++ \|
| \quad \quad \text{end while} \|
| \quad \text{end for} \|
| \] |

In the actual UAV operation scenario, there is a relatively large interval between the UAV and most of the UAVs in time and space dimensions, and there is no possibility of potential conflict, however, the process of pairwise conflict detection requires comparison of all UAV trajectories, resulting in a waste of computational resources. In order to improve the efficiency of conflict detection for a large-scale number of UAVs and reduce unnecessary computational processes, a conflict detection algorithm based on a four-dimensional spatio-temporal data grid is used. The spatio-temporal data grid, i.e., the mapping relationship between physical space and data space is constructed by combining the airspace grid coding with the related spatio-temporal data structure, which accurately reflects the spatio-temporal information in the airspace and provides a new thinking perspective.

3.1 Global Airspace Spatial Grid Code

The global airspace spatial grid coding method used in this study is to construct a global grid system with the reference position datum as the South Pole of the Earth[11]. On the basis of the spatial grid dissection of airspace, grid coding rules can be established. The method adopts an ellipsoidal dissection method of the Earth based on the integer rule of latitude and longitude, that is, the spatial partitioning of the ellipsoidal plane in the form of degrees-minutes-seconds integers of latitude and longitude, and this division is essentially a method of discrete description of the metric parameters of the geodetic coordinate system.

The airspace is treated separately by spherical and altitude, and the grid is defined in geographic latitude and longitude space and altitude space, respectively. Among them, spherical division is based on geographic space latitude and longitude, recursive spherical grid division, according to different research problem needs, can be recursively divided in again, to achieve the required grid accuracy requirements; which defines the grid coordinate origin, as the lower left position point of the grid; In addition, the height is divided independently from the sphere, according to the different height datum,
the height expression, according to different research problem needs for Different granularity of the division.

The space is divided into eight levels of recursive grid by the method of primary, secondary and final grid dissection, as shown in the figure 2 below; the grid size of each level is shown in the table 1 below.

![Global airspace gridding method](image)

Fig.2 Global airspace gridding method

### Tab.1 Grid Levels

| Level | Grid size | Actual size  |
|-------|-----------|--------------|
| 1     | 15° ×15°  | 1669km       |
| 2     | 1° ×1°    | 111km        |
| 3     | 30'×30'   | 56km         |
| 4     | 15′×10′   | 9km          |
| 5     | 5′×5′     | 5nmi         |
| 6     | 100′×100′ | 3km          |
| 7     | 10°×10°   | 0.3km        |
| 8     | 1°×1°     | 0.03km       |

The spatial height grid is set based on the generated unit grid of different granularities by setting height codes for individual granularity grids, including height upper and height lower limits. Depending on the reference altitude datum, the altitude can be divided into geometric altitude and barometric altitude. Different datums can be selected as the reference for measuring altitude according to the flight requirements of different regions in real situations. In this paper, the lowest altitude of the simulated airspace is used as the reference plane of altitude in meters (m), and the granularity of the altitude grid is coded with 30m for upward expansion. Since this paper studies a four-dimensional UAV trajectory, a temporal encoding is added to the spatial encoding and altitude encoding.

### 3.2 Relational spatio-temporal data structure based on grid encoding

Time-Space Date Structure (TSDS), represents each four-dimensional spatio-temporal grid cell of a spatial domain by a separate memory location[12]. For a given grid cell, the relevant information stored
in the TSDS, both spatial and non-spatial, can be accessed through its grid code as described above using the mapping relationship formula. In the conflict detection process, the TSDS can be considered as a network composed of individual grid cells in the spatial domain, and the granularity of the TSDS is obtained by grid hierarchy division according to the actual requirements, indicating the distance of each grid cell. The granularity is too precise, which affects the computational performance and requires a lot of memory, while the granularity is too sparse, which causes some targets in the airspace to be ignored. Therefore, it is necessary to determine the appropriate grid division level to determine the appropriate TSDS granularity.

The figure 3 illustrates the contents of a TSDS for conflict detection, which can be considered as a data table with each row recording a 4-D grid cell in the airspace under study with the same number of rows as the total number of grid cells in the airspace, and each column representing the UAV flight path to be processed with the same number of columns as the total number of UAVs operating in the airspace. The four-dimensional grid cells are accessed by the corresponding individual grid codes.

![Fig.3 TSDS structure diagram](image)

In the TSDS-based conflict detection process, when the algorithm wants to process a certain track, it first calculates the grid cells occupied by each track sampling point of the track and the index of the neighboring grid cells.

One obvious drawback of the above TSDS-based conflict detection algorithm is the increase in the memory required by the algorithm as the number of traces to be processed increases. In the structure of TSDS, the same amount of storage space as the number of traces needs to be reserved for each four-dimensional spatio-temporal grid cell. This drawback of TSDS greatly limits the size of the airspace and the number of traces that can be studied, and is limited when the airspace under study is wide and the number of traces to be processed is large. Therefore, there is a need to find methods for conflict detection that make more efficient use of memory for a given computer memory limit.

As shown in the figure 3, since the total number of grid cells in the studied airspace is much larger than the number of coordinates used by all aircraft, most of the storage locations in the TSDS are null and are not used to store information about aircraft. Based on this situation, in order to reduce the memory required by TSDS during the process of performing conflict detection, the Relational Time-Space Data Structure (RTSDS) is proposed by creating two different linear storage tables for managing the information\[13\]. As shown in the figure 4, one of the storage tables is used to store the basic structure of the TSDS, i.e., the information of the four-dimensional space-time grid cells of the studied airspace; the other storage table is used to store the non-space-time information of the trajectory, and the information between the two storage tables is related to each other by pointers.
RTSDS achieves the same functions as TSDS through two different storage tables, the first of which is the Base Time-Space Data Structure with the same number of records as TSDS, i.e., each row corresponds to the grid code and information of each grid in the airspace, but each record exists in only one column instead of n traces corresponding to n columns. This column is used to store the pointer associated with the second storage table.

The second storage table, called Stacked Trajectory Information (STI), is used to store the four-dimensional coordinates used for all trajectories. The structure of the STI can be designed according to the needs of the conflict detection and resolution algorithm, but a column is always needed to store a pointer to another STI location.

For coordinates in BTSDS, if the pointer associated with its STI is not zero, it indicates that at least one track occupies that coordinate point. The value of this pointer indicates the position in the STI of the last track information occupying this grid. The first three columns in the STI are used for non-temporal information about the track, and the fourth column stores a pointer to another STI location, indicating the position in the STI corresponding to the last track occupying that grid. If the pointer is not zero, the information about the track at the corresponding STI location is accessed according to the pointer, and the conflict between the track and the current track is judged by calculating the distance between the track points. After finishing the conflict judgment with other UAVs, continue to check the fourth column of the current STI position, if the pointer is 0, it means that no trajectory has occupied the grid before, if it is not 0 then repeat the above process.

The main advantage of RTSDS is that the memory required to construct BTSDS is related to the size of the airspace studied and the size of the grid cells, so that the memory required does not increase with the number of trajectories studied, and the total memory of BTSDS is.

\[
\text{totalMemory}_{\text{BTSDS}} = m \cdot t_{\text{max}} \cdot p 
\]

where \( p \) is the memory occupied by storing a pointer to a record, usually 4 bytes. The memory required for STI is calculated by the following equation.

\[
\text{totalMemory}_{\text{STI}} = n \cdot l \cdot (b + p) 
\]

\( n \) is the number of traces processed and \( l \) is the average number of time steps per trace. Therefore, the total memory space required for storing STI grows linearly with the number of traces \( n \), and the growth rate is lower than that of the TSDS structure. Due to the large number of UAV traces designed for the strategic phase of the trajectory planning, the limitation of computer memory on the operation

### Table: BTSDS

| Grid code   | STI pointer position |
|-------------|----------------------|
| FJHNZ6KX9EA, A, 1 | 0                    |
| FJHNZ6KX9EB, A, 1 | 0                    |
| FJHNZ6KX9EC, A, 1 | 0                    |
| FJHNZ6KX9ED, A, 1 | 120                  |
| FJHNZ6KX9EE, A, 1 | 0                    |
| ...          | ...                  |

### Table: STI

| Position | UAV ID | X     | Y     | Z     | STI pointer position |
|----------|--------|-------|-------|-------|----------------------|
| 1        | 4      | 4534  | 5467  | 300   | 0                    |
| 2        | 2      | 4678  | 5466  | 550   | 423                  |
| 3        | 2      | 4344  | 5751  | 300   | 54                   |
| 4        | 4      | 4913  | 5966  | 1200  | 120                  |
| 5        | 3      | 4537  | 4733  | 300   | 0                    |
| 6        | 3      | 3543  | 4646  | 2000  | 70                   |
| 7        | 67     | 7686  | 8768  | 1500  | 99                   |
| 8        | 8      | 4554  | 7866  | 400   | 5                    |
| 9        | 6      | 4551  | 5645  | 800   | 76                   |
| 10       | 4      | 6547  | 5464  | 960   | 8                    |
| 11       | 76     | 6773  | 5464  | 600   | 56                   |
| 12       | 7      | 5463  | 6713  | 450   | 8                    |
| ...      | ...    | ...   | ...   | ...   | ...                  |

Fig. 4 RTSDS structure diagram
of the conflict detection algorithm needs to be considered when using the data grid-based conflict detection method. The use of RTSDS can effectively reduce the running memory requirements of grid-based conflict detection, enabling conflict detection of large-scale UAV flight tracks in the strategic planning phase to provide a more efficient relief.

4. Experimental verification

4.1 Sensitivity Analysis

It is important to note that the conflict detection efficiency is significantly sensitive to the size of the grid granularity. If the grid size is too small, multiple grids are required to represent a UAV; if the grid size is too large, false warnings will be generated even if there is no conflict risk for UAVs within the same grid or adjacent grids, and the computational efficiency is low. Therefore, in order to explore the optimal grid size for conflict detection, this paper conducts sensitivity analysis with the number of UAVs in the airspace as 200, 400, 600, 800, 1000, and 1200, respectively. The relevant control parameters are as follows: Level 6 of the global airspace spatial grid code (100° × 10°), Level 7 (10° × 1°), Level 8 (1° × 1°), the simulation airspace is a cubic area of area 9 km × 9 km × 3 km, the time step for determining UAV conflict detection \( \Delta t = 1 \text{s} \), protection volume of UAV is a sphere of 12 m radius, average flight speed of the UAV is 300 km/h, the total conflict detection time is recorded as the calculation time from the detection of the first conflict to the calculation of the last conflict. The results are shown in figure 5. Overall, the conflict detection time showed an overall consistent increasing trend with the increasing number of UAVs. Meanwhile, the increasing trend of conflict detection time for the seventh level network is more obvious, and the conflict detection efficiency is significantly better than the remaining two networks. It should be noted that under the scenario, the conflict detection time shows a negative growth, which is due to the fact that the UAV trajectory generation is random in nature. In the airspace with low congestion and traffic patterns with low conflict probability, there is a certain degree of paradoxical relationship between conflict detection time and aircraft; however, with the increment of UAV sorties, the frequency of conflicts gradually increases, the complexity of traffic patterns significantly increases, and conflict detection time shows a consistent relationship with UAV sorties.

In summary, in the low-altitude airspace operation scenario, the UAV conflict detection method based on spatio-temporal data grid proposed in this paper can effectively solve the problem of conflict detection, and the conflict detection efficiency is significantly better when the grid size of the seventh level is large, with stable and efficient to cope with the demand of different traffic posture complexity.

Fig. 5 Total time for UAV conflict detection. The three selected grid levels are level 6, level 7, and level 8.
4.2 Scenario 1: Conflict detection under obstacle-free airspace

To investigate the conflict detection efficiency of the spatio-temporal data grid based on the seventh level grid, this paper sets up the number of UAVs in increments of 200/400/600/800/1000/1200, whose trajectories are composed of randomly generated four-dimensional track points. For this scenario, the conflict detection method by calculating the Euclidean distance between UAVs in pairs in the traditional 3D coordinate system is used to compare with the conflict detection method between UAVs based on the spatio-temporal data grid method. The growth of conflict detection time is shown in the figure 6.

Overall, the total conflict detection time shows a consistent growth trend as the number of UAVs grows. When the traditional pairwise calculation method is used for conflict detection, the conflict detection time tends to grow more obviously with the number of UAVs and becomes nearly exponential, while the spatio-temporal data grid-based method shows a more moderate increase in the conflict detection time with the number of UAVs, showing a certain stability and efficiency.

In summary, the spatio-temporal data grid-based method proposed in this paper can efficiently achieve conflict detection of UAVs in scenarios under obstacle-free airspace, reducing the computation time consumption by about 77% compared with the traditional method, and has the stability and efficiency to cope with the increase of congestion in traffic scenes.

![Figure 6](image)

Fig.6 Total time for UAV conflict detection with two methods in conflict-free airspace

4.3 Scenario 2: Conflict detection in an airspace with random obstacles

To explore the generalizability of the spatio-temporal data grid-based approach, scenarios based on generated random terrain obstacles are investigated. In this paper, 200/400/600/800/1000/1200 incremental numbers of UAVs are set, and their trajectories are composed of randomly generated four-dimensional track points. For this scenario, the conflict detection method by computing the Euclidean distance between UAVs in pairs in the traditional 3D coordinate system is used to compare with the conflict detection method between UAVs based on the spatio-temporal data grid method. The growth of conflict detection time is shown in the figure 7.

Overall, the total conflict detection time shows a consistent growth trend as the number of UAVs grows. In the traditional pairwise calculation method, the conflict detection time grows exponentially with the number of UAVs and increases significantly compared with the time in Scenario 1, while in the spatio-temporal data grid-based method, the conflict detection time grows more slowly with the number of UAVs and the difference with the conflict detection time in Scenario 1 is smaller, showing some universality. Shows a certain degree of universality and efficiency.
In summary, the proposed spatio-temporal data grid method can also effectively achieve UAV conflict detection in the airspace scenario with random terrain obstacles, and the method has a strong stability with the increase of airspace complexity.

![Fig.7 Total time for UAV conflict detection with two methods in an airspace with obstacles](image)

5. Conclusion
This paper studies the UAV conflict detection problem based on spatio-temporal data grid, based on the spatio-temporal data structure combined with the global airspace spatial grid coding, proposes the spatio-temporal data grid structure, determines the grid size applicable to the operation scenario through sensitivity analysis, and compares with the traditional method of calculating Euclidean distance based on 3D coordinates for different number of UAVs in different scenarios, and the results prove that the method of UAV conflict detection based on spatio-temporal data grid can effectively improve the efficiency of conflict detection, save a lot of computation time, and can effectively solve the problem of UAV conflict detection.

The paper did not address the problem of conflict resolution and failed to obtain realistic data by using simulation data as experimental analysis. In future research, the UAV conflict resolution problem, the low-altitude airspace situational monitoring problem and the low-altitude airspace complexity assessment problem can continue to be studied in depth based on the spatio-temporal data grid.

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