Cooperative Path Planning Based on Pattern Genetic Algorithm

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Abstract: In order to solve the problem of low “population” effectiveness of genetic algorithm in multi-vehicle route planning, this paper proposes a pattern-based genetic algorithm. The algorithm uses the limited way of "route pattern", which can greatly improve the effectiveness of population generation, crossover and mutation, thus reducing the iteration times of the algorithm and improving the convergence efficiency. The pattern-based genetic algorithm is applied to the cooperative path planning of multiple aircraft. The algorithm flow of cooperative path planning is designed. An example is given to prove its effectiveness and efficiency.

1. Introduction
Cooperative path planning for multiple aircraft is an important and difficult problem in the fields of mission planning, aviation control and conflict resolution. In order to solve kinds of problems, not only the optimal track should be found, but also the diversity of suitable tracks should be ensured so as to complete cooperative operation. Therefore, genetic algorithm is usually used to realize this. The coding methods of the route planning genetic algorithm can be divided into: one is continuous route coding method [1], such as Fourier transform route coding method. This method can ensure that the coded route must pass through the initial point and the target point, but it is difficult to adapt to the grid division of airspace. The route of each aircraft needs to readjust the coordinate system, making cooperative planning difficult. The second is discrete route coding method [2], such as Voronoi diagram-based route geometric coding method [3], grid coding method based on course change, etc. This method can be adapted to spatial grid division and is convenient for collaborative planning. However, the route coding length is uncertain and cannot guarantee that the coded route must pass through the initial point and the target point, thus the effectiveness is low. The core of antiaircraft route planning is to realize the coordination between routes, so it is very important to ensure the coordination between different aircraft routes. On the basis of grid coding method based on course change [4], the concept of "route pattern" is proposed in this paper. Through "route pattern" control, the coded route must pass through the starting point and the target point to improve the coding effectiveness.
2. Pattern-based genetic algorithm

2.1. Route pattern
An air route is a grid chain that connects from the initial point to the target point end to end. Each grid in the route has multiple choices when connecting the next grid. Considering each step of the route as a choice, the sequence of all choices from the initial point to the target point will be a good route coding method. In the discretion airspace grid, for a left-to-right route planning problem, the choice of each step of the aircraft is divided into five situations: right, right up, right down, up and down, as shown in Fig. 1.

If the five choices of right, right up, right down, up and down are respectively represented by "1", "2", "3", "4" and "5" codes, as shown in Table 1. A complete route can be represented by a series of "code strings" that select directions from the initial point to the target point.

![Fig. 1 Route Node Selection Direction](image)

For any "code string", although it can completely represent a route, the route does not necessarily have validity, that is, the route represented by the "code string" can ensure that it must start from the initial point, but not necessarily can finally reach the target point.

Assume that the coordinates of the initial point and the target point are \( (X_0, Y_0) \) and \( (X_D, Y_D) \); For an effective route "code string", the number of occurrences of codes "1", "2", "3", "4" and "5" are \( N_1, N_2, N_3, N_4, N_5 \), respectively. The coordinate change modes corresponding to different codes in Table 1 are necessarily satisfied:

\[
\begin{align*}
X_D - X_0 &= N_1 + N_2 + N_3 \\
Y_D - Y_0 &= N_2 - N_3 + N_4 - N_5
\end{align*}
\]

That is, from the initial point to the target point, the coordinate change value caused by the turning mode of each waypoint is equal to the difference between the abscissa of the target point and the initial point; The coordinate change is equal to the difference between the ordinate of the target point and the initial point.

Number of times to make route selection:

\[ n = N_1 + N_2 + N_3 + N_4 + N_5 \]
As the length of the code. If \( n \) is known, the solution of the vertical type (1) and the formula (2) is \((N_1, N_2, N_3, N_4, N_5)\) called \(n-(N_1, N_2, N_3, N_4, N_5)\) a code mode of an air route, which is simply called an air route pattern.

2.2. Mode-Based Coding

Set the route pattern of \(n-(N_1, N_2, N_3, N_4, N_5)\) "code string" as " \(l: \{q_1, q_2, \ldots, q_{n-1}, q_n \mid q_i \in \{1, 2, 3, 4, 5\}\} \) " and satisfy formula (1) to be valid. Its composition is shown in Table 2.

| Code number | 1 | 2 | \ldots | n-1 | n |
|-------------|---|---|---------|-----|---|
| Corresponding code | \(q_1\) | \(q_2\) | \ldots | \(q_{n-1}\) | \(q_n\) |

\(l\) is called "basic code string". Changing the position of each code in its "code string" can produce "serial code string". Obviously, the "series code string" must satisfy formula (1), that is, the new route formed is effective.

For \(l\) is the basic "serial code string", the decimal random number sequence \(\{\alpha_1, \alpha_2, \ldots, \alpha_{n-1}, \alpha_n\}\) can be used as chromosome to encode, where \(0 < \alpha_i < 1 \ (i=1, 2, \ldots, n), \alpha_1 = 0, \alpha_n = 1\). The sequence of coding random numbers from small to large corresponds to the "code number" column in Table 2. The code at the coding position is the code corresponding to the "code number". Then any random number sequence corresponds to a specific "series code string" and must also correspond to the route corresponding to the specific "series code string", thus completing the encoding of the route with route pattern " \(n-(N_1, N_2, N_3, N_4, N_5)\) ".

Obviously, the route pattern \(n-(N_1, N_2, N_3, N_4, N_5)\) is only a solution of equation (1); The code (chromosome) of the "serial code string" derived from the "basic code string" \(l\) is only the secondary population of the whole population of length \(n\). The population with length \(n\) is only a part of the whole population (satisfying formula (1) is the whole population. The population length is \(n\) not necessarily). The relationship between them is shown in Fig. 2.

In conjunction with equations (1) and (2), all route patterns " \(n-(N_1, N_2, N_3, N_4, N_5)\) " are obtained, thus obtaining all populations of routes with length \(n\). The whole population can be obtained by discussing the sizes \(n\) in turn.

This genetic algorithm based on the encoding method of route pattern " \(n-(N_1, N_2, N_3, N_4, N_5)\) " is called pattern-based genetic algorithm. The mode-based coding method, through the transformation of "route-code-random coding", can not only realize the coding of the route, but also ensure that the route corresponding to the coding is effective. At the same time, the code length (the same as the code length) reflects the advantages and disadvantages of the population in the route length to a certain extent, which will provide a powerful reference for the selection of the initial population.
3. Cooperative Route Planning Pattern-based genetic algorithm

The multi-combat aircraft route cooperative planning based on genetic algorithm is divided into eight steps [1], as shown in Fig. 3.

The first step is to form an expanded threat field \( \text{field}(X,Y) \).

The so-called expansion of threat field is to transform the positions of no-fly zone, obstacle zone and danger zone into airspace that cannot be used (evaded), namely threat field. The penalty function cost in the threat field is relatively high (inf infinitely for the mode that cannot penetrate walls). The aircraft will avoid these areas when selecting the route. From the perspective of genetic algorithm, these restricted areas provide the most basic living conditions for the evolution of the population.

The second step is to code the route. The route is coded by mode-based coding.

The third step is to establish an initial population.

(1) Shortest route population

Determine the coding length of the shortest route population \( n_0 \). First, the A* algorithm is used to solve the optimal route of a single aircraft. Then, take \( n_0 \) as the code length of the solution route of A* algorithm, namely:

\[
N_1 + N_2 + N_3 + N_4 + N_5 = n_0 \tag{3}
\]

In combination with the vertical type (3) and the formula (1), all lengths are obtained as \( n_0 \) the coding mode \( n_0 = (N_1, N_2, N_3, N_4, N_5) \). The route lengths obtained by coding are all populations \( n_0 \).

(2) Other length route populations

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**Fig. 3 flow chart of route cooperative planning based on mode genetic algorithm**
Route population with other lengths refers to the effective population formed by routes with greater \( n_0 \) coding length. From the point of view of single route planning, routes in route population with other lengths are not optimal solutions, but optimal solutions or suitable solutions, and with the increase of length, the "optima" of solutions decreases. The steps for generating populations of other lengths are:

- **Step1**: Set the upper limit of population length \( n_{\text{max}} \);
- **Step2**: Order that \( n_0 = n_0 + 1 \) if \( n_0 \leq n_{\text{max}} \) the formula (3) is brought in, the vertical type (3) and the formula (1) are linked;
  - (1) if there is a solution, all the population with route length \( n_0 + 1 \) is obtained, and step 2 is turned;
  - (2) if there is no solution, turn to STEP 2;
- If \( n_0 > n_{\text{max}} \), turn to STEP 3;
- **Step3**: End.

The fourth step is single route fitness.

In order to implement the principle of "survival of the fittest", the adaptability of a single route must be objectively evaluated. The fitness of a single route consists of two parts: one is the actual length of the route; The second is the cost of environmental threats.

1. **Actual route length**
   Since there is a difference between the length of the curb in the positive direction (0, 45, and -45) and the diagonal direction (90°, -90°), as shown in equation (4).
   \[
   L = \begin{cases} 
   L_0 & \text{positive: 0°, 90°, -90°} \\
   \sqrt{2}L_0 & \text{bidirectional: 45°, -45°}
   \end{cases}
   \]
   \[\text{(4)}\]
   Where, \( L_0 \) is the grid scale. The total length of the route represented by the route code is:
   \[S = (N_1 + N_4 + N_7)L_0 + \sqrt{2}(N_2 + N_3)L_0\]
   \[\text{(5)}\]
   Therefore, even if the codes (codes) are equal in length, the actual lengths of the routes are different.

2. **The cost of environmental threats**
   By decoding the chromosome in the inverse process of "coding-code-route", the grid set \( G \) through which the route passes can be obtained. Combined with the expanded threat field \( \text{field}(X, Y) \) formed, the route threat cost \( R \) can be obtained.
   \[R = \sum_{(X_i, Y_j) \in G} \text{field}(X_i, Y_j)\]
   \[\text{(6)}\]

3. **Adaptability**
   The linear combination of actual route length and environmental threat cost is taken as its fitness function, namely:
   \[J = kS + (1 - k)R\]
   \[\text{(7)}\]
   Among them, \( k \in [0,1] \) for the trade-off efficient, a trade-off is taken between route length and threat risk. Its size depends on the comprehensive index of the importance and feasibility of the weight items. Obviously, the shorter the actual length of the route, the less the cost of environmental threat and the higher the adaptability.

The fifth step is evolutionary operation.

Following the principle of biological evolution, the initialization route is subjected to evolutionary operations, including crossing, mutation and selection of routes.

1. **Cross**
   Single point crossover technique is used to realize the crossover of different genes between chromosomes. The specific design is as follows: for the selected length \( n \) of two parent individuals:
Randomly selecting the position of the \( t \in [1, n] \) gene as the crossing point, then the sub code obtained after the crossing operation are \( s_1 \) and \( s_2 \) sum; The gene of \( s_1 \) is composed of the \( t \) gene of \( f_1 \) and the \( n-t \) gene of \( f_2 \). The gene of \( s_2 \) consists of the \( t \) gene of \( f_2 \) and the second \( n-t \) gene of \( f_1 \), namely:

\[
f_1 : \{o_1, o_2, \ldots, o_t, o_{n-t+1}, o_n\} \quad f_2 : \{o_1', o_2', \ldots, o_t', o_{n-t+1}', o_n'\}
\]

Obviously, the crossover operation here also contains mutation operation.

(2) Mutation

Mutation is an important way to realize population diversity. It is also a guarantee for global optimization. According to the given mutation rate \( p_m \), for the selected mutation individuals, randomly take three integers \( u, v, w \) to satisfy \( 1 < u < v < w < n \). Insert the gene segment between (including \( u \) and \( v \)) to the back.

(3) Choice

Adopt a deterministic selection strategy. In other words, the individual with the smallest fitness \( M \) (objective function) is selected to evolve to the next generation, which can ensure that the excellent characteristics of the parent generation are preserved.

The sixth step is time-space cooperation.

Time-space cooperation refers to obtaining multiple routes of each combat aircraft through pattern-based genetic algorithm, quantifying the time-space conflict between a certain route of an aircraft and routes of other air crafts. Incorporating the value into the fitness function of the solution, which serves as the fitness of the route to guide co-evolution. There are two steps for the time-space cooperative operation:

One is to find a grid set of airspace conflicts \( C_{ajk} \) between the \( i \) -th route of one aircraft \( a \) and the \( k \) -th (generally about 3) route of other aircrafts \( j \).

The second is to calculate whether the time interval \( T_0 \) for each route to reach the airspace collision grid is greater than the equal safety time interval. If the time interval \( T_0 \) is greater than or equal to, the cost function \( Pr \) takes 0; Take 1 for others.

Then the cost of the \( i \) -th route of aircraft \( a \) time-space cooperation is:

\[
J_{ai}' = \sum_{j=1, j \neq a}^{m} \sum_{k=1}^{3} \sum_{l \in C_{ajk}} Pr_{D_{aij}} \tag{8}
\]

Therefore, the total fitness of the \( i \) -th route of the aircraft \( a \) is:

\[
\min J_{cost} = k_1 J_{ai} + k_2 J_{ai}' \tag{9}
\]

Where, \( k_1, k_2 \) is the weight between single track fitness and time-space coordination cost.

The Seventh step, priority collaboration.

Due to the priority of flight tasks and the inevitability of airspace conflicts, priority design is needed for the route planning of aircraft in airspace to ensure the unity of important flights and eliminate conflicts. Mainly reflected in: according to the priority, expand the route code length in single route planning in reverse order. From the generation process of "other length route population" in the third step, it can be seen that the route length in each population increases from \( n_0 \) to \( n' \) ( \( n' > n_0 \) ), which is actually decreasing the "excellent" degree of single route planning, with local "degeneration" and co-evolution coexisting. Therefore, in the process of route cooperative planning, the higher the priority level of the route planning of the combat aircraft, the later expands its code and code length. The sequence of route adjustment according to priority mode is shown in Fig. 4.
4. Implementation of Multi-route Collaborative Planning

It is located in the airspace of 200km×140km and has three missions. According to the grid size of 10km×10km, the spatial domain is meshed into 20×14 spatial domain grids. Take-off airport 1, airport 2, and airport 3 are located in the grids of (3,11), (3,5), (9,3), respectively. The grid coordinates of respective target areas: target 1, target 2. Target 3 are (18,3), (18,9), (13,12), respectively. The task priorities are: task 1 > task 2 > task 3. The (5,5), (6,9), (6,10), (6,7), (7,7), (10,4), (10,5), (11,5), (11,9), (11,10) grids with threat areas distributed throughout the battlefield are in the form of “walls” and are not allowed to fly through, as shown in Fig. 5. To simplify the problem, assume that the three airports have the same type of aircraft and the same flight speed, 800 km/h.

4.1. Generation of Single Task Multi-route

4.1.1. Population Generation. Taking the route planning of task 1 (route 1) as an example, the generation process and significance of population are expounded. Route 1 refers to from grid (3,11)→(18,3). During this process, the aircraft has to go through at least 15 steps (calculated by A* algorithm) to reach the target point from the airport, namely. There are 4 code modes of “route 1” with length of 15, which are obtained by combining vertical type (1) and type (2), as shown in Table 3.
Table 3 Code Mode and Route Length of Route 1 with Length 15

| Mode   | Number of Right | Number of Right Up | Number of Right Down | Number of UP | Number of Down | Length |
|--------|-----------------|--------------------|----------------------|-------------|---------------|--------|
| Mode1  | 7               | 0                  | 8                    | 0           | 0             | 18.3   |
| Mode2  | 5               | 1                  | 9                    | 0           | 0             | 19.1   |
| Mode3  | 3               | 2                  | 10                   | 0           | 0             | 20.0   |
| Mode4  | 1               | 3                  | 11                   | 0           | 0             | 20.8   |

Obviously, using the above four route code modes can certainly ensure that the generated population passes through the target point, i.e. The code is valid. From the route lengths of the four modes, it can be seen that the "excellent" degree of each mode is satisfied: mode 1 > mode 2 > mode 3 > mode 4, so "mode 1" is preferred when generating population.

For mode 1 population, its trajectory is 7 times to the right (code "1") and 8 times to the right (code "3"). It is a typical "basic code string", as shown in Table 4.

Table 4 Structure of a Typical "Basic Code String" in Mode 1

| Position | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|----------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| Code     | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 3  | 3  | 3  | 3  | 3  | 3  |

A set of random number strings with length of 15 between 0 and 1 are randomly generated. Based on the "basic code string", the chromosome of "Mode 1" is encoded with the random number string. Its corresponding flight code and route are shown in Table 5.

Table 5 Chromosome Corresponding Flight Codes and Routes

| Position | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|----------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| Chromosome | 0.22 | 0.19 | 0.14 | 0.88 | 0.40 | 0.44 | 0.35 | 0.26 | 0.11 | 0.98 | 0.51 | 0.80 | 0.25 | 0.01 | 0.24 |
| Row      | 5 | 4 | 3 | 14 | 10 | 11 | 9 | 8 | 2 | 15 | 12 | 13 | 7 | 1 | 6 |
| Code     | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3  | 3  | 1  | 1  | 1  | 1  |
| Route    | 4,11 | 5,11 | 6,11 | 7,10 | 8,9 | 9,8 | 10,7 | 11,6 | 12,6 | 13,5 | 14,5 | 15,3 | 16,3 | 17,3 | 18,3 |

Obviously, for "mode 1", "mode 2", "mode 3" and "mode 4", the number of routes of each mode can be obtained according to the arrangement and combination as follows: \( C_{15}^1 \cdot C_8^8 = 6435 \), \( C_{15}^5 \cdot C_{10}^5 \cdot C_9^6 = 30030 \), \( C_{15}^1 \cdot C_{13}^2 \cdot C_{10}^{10} = 30030 \), \( C_{15}^1 \cdot C_{14}^6 \cdot C_{11}^{11} = 5460 \), i.e. The total number of routes with a length of 15 is 71955. They are all valid routes. It can be seen that coding according to "mode method" is much more efficient than random coding. As the length of the route code increases, the effective code will increase exponentially.

Still taking "mode 1" as an example, 500 chromosomes with a length of 15 are randomly generated, converted into corresponding codes. The same repeated codes are eliminated, thus obtaining a population composed of remaining chromosomes, from which 300 individuals are selected as initial populations according to fitness. At this point, the scale \( M = 300 \).

4.1.2. Selection and Evolution. The purpose of selection is to make the genes of the superior individuals have greater possibility of inheritance, thus maximizing the average fitness of the whole population. The "mode-code-coding" process based on the "mode method" already contains the selected operations:
(1) Determine the length of the code. The length of the code determines the length of the route to a great extent, thus directly affecting the quality of chromosomes. The process of determining the shortest code (code) in the "mode method" is a process of selecting a shorter route length.

(2) Generation of mode. The mode is obtained by solving equations (1) and (2). The length of the corresponding route of each mode can be directly determined through the mode. According to the sequence of route pattern length from small to large, the mode generation population is selected in order to ensure the route is effective and short.

For the randomly generated population, the first 300 optimal individuals are selected as the initial population (or the population before crossover) according to the size of fitness. The process is consistent with the normal genetic algorithm selection.

According to the method in step 5 of "2 cooperative path planning Pattern-based genetic algorithm", crossover and mutation operations are implemented. It is easy to find that this kind of crossover and mutation operation is similar to the random chromosome generation operation of "mode-code-code" in "mode method", i.e. There are certain "crossover" and "mutation" operations in the random chromosome generation process. Therefore, crossover and mutation operations can be carried out normally, or a new population can be generated. Then the top 300 optimal individuals in the two populations can be taken as the result of crossover and mutation. What needs to be determined is that only the crossing between chromosomes with the same coding length and pattern is meaningful. Therefore, the whole genetic algorithm process based on "mode" is similar to "inbreeding", which can maintain its optimal characteristics to the greatest extent and speed up convergence.

4.1.3. Single route fitness. The selected route is required to be short in length, not to pass through the "threat zone" and to make as few turns as possible. Since the measurement of route length has been optimized by the selection of coding length, a simplified fitness function is adopted:

\[
f = \begin{cases} 
0 & (R > 0) \\
 e^{-0.1Zw} & (R = 0) 
\end{cases}
\]  

(10)

In the formula, the threat level is expressed \( R \) by the number of times the threat grid passes. \( Zw \) indicates the number of turns on the route. The fitness indicates that the route is not allowed to pass through the "threat zone" and the number of turns on the route is guaranteed to be as small as possible. Obviously, \( f \in [0,1] \), the higher the value, the higher the adaptability, the better the route.

Through genetic algorithm based on "mode" and 67 generations of operation, three (or more) optimal routes from three airports to target points can be obtained. The three optimal routes from airport 1 to target point 1 are shown in Table 6.

| Position | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | Fitness |
|----------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|---------|
| Code1    | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3  | 1  | 1  | 1  | 1  | 1  | 0.81    |
| Route1   | 4,11 | 5,11 | 6,11 | 7,10 | 8,9 | 9,8 | 10,7 | 11,6 | 12,5 | 13,4 | 14,3 | 15,3 | 16,3 | 17,3 | 18,3    |
| Code2    | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3  | 1  | 1  | 1  | 1  | 1  | 0.74    |
| Route2   | 4,11 | 5,11 | 6,11 | 7,10 | 8,9 | 9,8 | 10,7 | 11,6 | 12,5 | 13,4 | 14,4 | 15,4 | 16,4 | 17,4 | 18,3    |
| Code3    | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | 3  | 3  | 1  | 1  | 1  | 1  | 0.74    |
| Route3   | 4,10 | 5,9 | 6,8 | 7,8 | 8,8 | 9,8 | 10,7 | 11,6 | 12,5 | 13,4 | 14,3 | 15,3 | 16,3 | 17,3 | 18,3    |
| Length   | 183.1 km |
The three optimal routes from airport 2 to target point 2 are shown in Table 7.

| Position | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | Fitness |
|----------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|--------|
| Code1    | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2  | 1  | 1  | 2  | 2  | 0.67   |
| Route1   | 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 | 166.7 km |
| Code2    | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2  | 1  | 1  | 2  | 2  | 0.67   |
| Route2   | 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 | 166.7 km |
| Code3    | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2  | 1  | 1  | 2  | 2  | 0.61   |
| Route3   | 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 | 166.7 km |

The three optimal routes from airport 3 to target point 3 are shown in Table 8.

| Position | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Fitness |
|----------|---|---|---|---|---|---|---|---|---|----|---------|
| Code1    | 4 | 4 | 4 | 2 | 2 | 2 | 2 | 4 | 4  | 0.82    |
| Route1   | 9, 4, 9, 5, 9, 6, 10, 7, 11, 8, 12, 9, 13, 10, 13, 11, 13, 12 | 106.5 km, 112.4 km |
| Code2    | 4 | 4 | 4 | 2 | 2 | 2 | 2 | 4 | 4  | 0.67    |
| Route2   | 9, 4, 9, 5, 10, 6, 10, 7, 11, 8, 12, 9, 13, 10, 13, 11, 13, 12 | 106.5 km, 112.4 km |
| Code3    | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 1  | 0.82    |
| Route3   | 9, 4, 9, 5, 9, 6, 9, 7, 9, 8, 9, 9, 10, 11, 11, 12, 12, 13, 12 | 106.5 km, 112.4 km |

It can be seen from the Table that among the routes with route length of 9, 3 optimal routes (fitness is not 0) cannot be found, thus expanding the route length to 10 to obtain "route 3". Although the adaptability of "route 3" is 0.82 obviously greater than "route 1" and "route 2", its coding (route) length is greater than "route 1" and "route 2", so the "excellent" degree of "route 3" lags behind "route 1" and "route 2". In the whole process of route collaborative planning, the priority policy of "adjusting mode-adjusting code length-adjusting priority" is always adhered to. Through the genetic algorithm based on "mode", each mission can get many better routes.

4.2. Time-Space Cooperation.
Although each combat mission is assigned several alternative routes, there are potential airspace and time domain conflicts between these routes of each mission. Therefore, it is necessary to combine conflict measurement and priority resolution strategy to complete the determination of the final route.

4.2.1. Potential airspace conflict. According to the route information in Tables 6, 7 and 8, the potential conflicts between each optimal alternative route are shown in Table 9.

| Task-Route | Task1 Route1 | Task1 Route2 | Task1 Route3 | Task2 Route1 | Task2 Route2 | Task2 Route3 | Task3 Route1 | Task3 Route2 | Task3 Route3 |
|-----------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Task1     | Route1       | -            | -            | (11,6)       | (11,6)       | (11,6)       | (10,7)       | (10,7)       | (9,8)        |
| Task2     | Route1       | -            | -            | (11,6)       | (11,6)       | (11,6)       | (10,7)       | (10,7)       | (9,8)        |
| Task3     | Route1       | -            | -            | (11,6)       | (11,6)       | (11,6)       | (10,7)       | (10,7)       | (9,8)        |
The time consumed from each task route to this type of collision point is calculated in turn to prepare for time domain conflict analysis.

4.2.2. Time Domain Conflict and Resolution. Due to the need of the flight mission, the flight time of the multi-task aircraft will have two requirements: one is to start on time, including starting at the same time or at different times; The second is to arrive at the same time. Under these two different time requirements, it is also guaranteed that each mission will have a short flight blank time, i.e. a short flight route, reduce fuel consumption, reduce the probability of being discovered by the enemy and have no potential conflict with the multi-task route.

Under the condition of "starting on time":

In order to meet the needs of the mission, the take-off time of each mission aircraft is \( T_i (i = 1,2,3) \) respectively. The safe time interval between aircraft is judged according to the following formula.

\[
\text{if } \left| (T_i + t_{i,(x,y)}) - (T_j + t_{j,(x,y)}) \right| > T_k
\]

no time-domain conflicts;
else, time-domain conflicts exist

where, \( t_{i,(x,y)} \) indicates the time consumed by the \( i \)-th task route when reaching the grid point \((x,y)\).

The time consumed by each route in this example is shown in Table 10.

| Task sequence | Route |  1  |  2  |  3  |  4  |  5  |  6  |  7  |  8  |  9  | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|---------------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Task1         | Route1| 4.11| 5.11| 6.11| 7.10| 8.9 | 9.8 | 10.7| 11.6| 12.5| 13.4| 14.3| 15.3| 16.3| 17.3| 18.3|
|               | Route2| 4.5  | 90  | 135 | 198.6| 262.2| 325.9| 389.5| 453.1| 516.8| 580.4| 644.1| 699.1| 734.1| 779.1| 824.1|
| Task2         | Route1| 4.11| 5.11| 6.11| 7.10| 8.9 | 9.8 | 10.7| 11.6| 12.5| 13.4| 14.4| 15.4| 16.4| 17.4| 18.3|
|               | Route2| 4.5  | 90  | 135 | 198.6| 262.2| 325.9| 389.5| 453.1| 516.8| 580.4| 625.4| 670.4| 715.4| 760.4| 824.1|
| Task3         | Route1| 4.10 | 5.9  | 6.8  | 7.8  | 8.8  | 9.8  | 10.7| 11.6| 12.5| 13.4| 14.3| 15.3| 16.3| 17.3| 18.3|
|               | Route2| 63.6 | 127.2| 190.9| 235.9| 280.9| 325.9| 389.5| 453.1| 516.8| 580.4| 644.1| 699.1| 734.1| 779.1| 824.1|
|               | Route3| 4.6  | 5.6  | 6.6  | 7.6  | 8.6  | 9.6  | 10.6| 11.6| 12.6| 13.7| 14.7| 15.7| 16.7| 17.8| 18.9|
|               | Route1| 63.6 | 108.6| 153.6| 198.6| 243.6| 288.6| 333.6| 378.6| 423.6| 482.6| 532.2| 577.2| 622.2| 685.9| 749.5|
|               | Route2| 4.5  | 5.6  | 6.6  | 7.6  | 8.6  | 9.6  | 10.6| 11.6| 12.7| 13.7| 14.7| 15.7| 16.7| 17.8| 18.9|
|               | Route3| 4.5  | 108.6| 153.6| 198.6| 243.6| 288.6| 333.6| 378.6| 423.6| 482.6| 532.2| 577.2| 622.2| 685.9| 749.5|
|               | Route1| 9.4  | 9.5  | 9.6  | 10.7 | 11.8 | 12.9 | 13.10| 13.11| 13.12| -   | -   | -   | -   | -   | -   | -   |
|               | Route2| 45   | 90   | 135  | 198.6| 262.2| 325.9| 389.5| 434.5| 479.5| -   | -   | -   | -   | -   | -   | -   |
|               | Route3| 9.4  | 9.5  | 10.6 | 10.7 | 11.8 | 12.9 | 13.10| 13.11| 13.12| -   | -   | -   | -   | -   | -   | -   |
|               | Route1| 9.4  | 9.5  | 9.6  | 9.7  | 9.8  | 9.9  | 10.10| 11.11| 12.12| 13.12| -   | -   | -   | -   | -   | -   | -   |
|               | Route2| 45   | 90   | 135  | 198.6| 262.2| 325.9| 389.5| 434.5| 479.5| -   | -   | -   | -   | -   | -   | -   | -   |
|               | Route3| 9.4  | 9.5  | 9.6  | 9.7  | 9.8  | 9.9  | 10.10| 11.11| 12.12| 13.12| -   | -   | -   | -   | -   | -   | -   | -   |
When set the take-off time of each mission aircraft as \( T_i = T_j = K \), \( T_j = K + 200s \). The time safety interval as \( T_\Delta = 45s \). Then the time domain conflict situation can be obtained, as shown in the following Table 11.

| Task | Task1 | Task2 | Task3 |
|------|-------|-------|-------|
| Route | Route1 | Route2 | Route3 | Route1 | Route2 | Route3 | Route1 | Route2 | Route3 |
| Task1 | Without Conflict | Conflict | Conflict | Without Conflict |
| Task2 | Route2 | Route3 | Conflict | Conflict | Without Conflict |

Therefore, through time-space cooperation, the optimal routes for time-space cooperation under the condition of "starting on time" are: task 1- route 1, task 2- route 1, Task 3- route 3, as shown in Fig. 6.

The arrival times of the mission aircraft at the target points are: \( K + 824.1s \), \( K + 749.5s \), \( K + 705.9s \).

Under the condition of "simultaneous arrival" (arriving on time):
If it is set to meet the needs of combat missions and the time when each mission aircraft arrives at the target point at the same time is set to, whether there is a time domain conflict in the potential conflict airspace is determined according to the following formula:

\[
\begin{align*}
\text{if } & \left( (K-t_i+t_{i,x,y}) - (K-t_j+t_{j,x,y}) \right) > T_\Delta \\
\text{no time-domain conflicts;} \\
\text{else, time-domain conflicts exist}
\end{align*}
\]

Where, \( t_i \) indicates the total time consumed by the \( i \)-th task route. Then the time domain conflict situation under this condition is shown in Table 12.

| Task | Task1 | Task2 | Task3 |
|------|-------|-------|-------|
| Route | Route1 | Route2 | Route3 | Route1 | Route2 | Route3 | Route1 | Route2 | Route3 |
| Task1 | Conflict | Without Conflict | | | | | | | |
| Task2 | Route2 | Route3 | Conflict | Conflict | Without Conflict | | | | |

![Fig. 6 optimal route for mission flight under the condition of "starting on time"](image-url)
Obviously, the three routes between Task 1 and Task 2 all have time domain conflicts. Since the priority is satisfied: task 1 > task 2, a new route for task 2 needs to be obtained according to the adjustment sequence in Fig. 4. For the adjusted route of task 2, the time-airspace cooperative operation is implemented until the optimal time-airspace cooperative route is obtained. The adjusted optimal time-space coordinated route is shown in Fig. 7 below.

![Fig. 7 optimal route for mission flight under the condition of "simultaneous arrival"](image)

In order to ensure "simultaneous arrival", the take-off time of the mission plane is $K - 824.1s, K - 786.8s, K - 479.5s$, respectively.

5. Conclusion
In this paper, a mode-based route coding method is proposed, and a multi-route planning method based on genetic algorithm is improved. The coding method, starting from the coding length and composition mode, can well solve the problem of low coding efficiency of traditional genetic algorithm and greatly improve the convergence rate of the algorithm. On this basis, the pattern-based genetic algorithm is applied to the multi-task route cooperative planning, and conflict resolution is realized through the multi-route solution of the mission and the time-space cooperation. An example is given to show that the algorithm can efficiently solve the multi-task route cooperative planning problem.

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