Application of SAS Algorithm in Responsive Submarine-searching Path Planning

Qiang Han, Lin Li *, Xinyi Lv, Dongsheng Hao
Qingdao campus, Naval Aviation University, Qingdao, China

*Corresponding author e-mail: 2658880150@std.uestc.edu.cn

Abstract. Whether the planned path is optimal or not is an important condition for the completion of the responsive submarine-searching task, which depends on the applicability of the planning algorithm. According to the requirements of responsive submarine-searching mission of the anti-submarine aircraft, SAS algorithm used in responsive submarine-searching path planning is analysed in this paper, the relevant constraints are given, and the simulation calculation is carried out by using SAS algorithm. The results show that SAS algorithm has excellent performance in operation speed and planning effect, and it can better meet the training requirements.

Key words: SAS algorithm; Responsive submarine-searching; Path planning.

1. Introduction
According to the task requirements, anti-submarine aircraft conducts various missions mainly including responsive search and patrolling search. Responsive search is the most commonly used tactical method in anti-submarine warfare and training. Responsive search refers to the process in which the anti-submarine aircraft flies to the target sea area after receiving the task and searches and locates the target again on the premise of obtaining the general position, heading, speed and other information of the target submarine at a certain moment [1]. How to overcome the randomness and blindness of flight path and reach the target sea area in the shortest time is the key problem. In this paper, The SAS algorithm is used to carry out simulation calculation and planning efficiency evaluation for the submarine-searching path of anti-submarine aircraft, which can provide reference for the planning submarine-searching path in anti-submarine training and help to improve the efficiency of submarine searching.

2. Algorithm Analysis
Algorithms applied to aircraft path planning mainly include Simple path planning, A* search algorithm, Genetic algorithm, Ant colony algorithm, SAS algorithm, Fish swarm algorithm, Simulated annealing algorithm and some other new path planning algorithms [2], but not all algorithms are suitable for responsive submarine-searching path planning. After preliminary screening, the algorithms that can be used for path planning of anti-submarine aircraft mainly include Simple path planning, Genetic algorithm, Ant colony algorithm, and A* search algorithm.

Simple path planning algorithm is suitable for simple situations such as few obstacles, low threat degree and slowly moving speed of threat source on flight path. It has the advantages of simple path and
fast speed, and it is usually used in offshore anti-submarine warfare. Therefore, it is not the main research object here.

As a bionic technology, Genetic algorithm (GA) has been widely concerned since it was proposed because of its unique organizational learning adaptability. It has excellent performance in many fields, but it is not as effective as other heuristic path optimization algorithms in path planning. In the case of high environmental complexity, its convergence speed is slower than the sparse A* algorithm, and the search results are prone to local optimal phenomenon. In the case of low environment complexity, its search speed is not as good as the simple path planning algorithm, and the optimal path obtained is not very ideal. Considering the characteristics and practical application of the algorithm, it is not the research object of this paper.

Ant colony algorithm, also known as Ant algorithm, is an algorithm to find the optimal path, which is widely used to find the optimal path. The performance of the algorithm in finding the optimal path is very excellent. As a bionic algorithm, this algorithm has been widely used as soon as it appeared, and it has achieved considerable results in many fields. In addition to the field of path optimization, it also has high application value in the field of PID controller parameter optimization design. Considered the advantages and disadvantages of the algorithm and its application characteristics, this algorithm can be used for simulation verification.

A* search algorithm is one of the heuristic search algorithms and one of the excellent shortest path search algorithms [3]. Due to the complexity of A* algorithm and the infinite possible searching types of its search, its solution process would take up a lot of time and space to conduct the solution process. In order to facilitate practical application, it was compressed and optimized and improved to SAS algorithm, that is, Sparse A* search algorithm (SAS) [4]. This algorithm is an extremely powerful path index algorithm, applicable to submarine-searching path planning for anti-submarine aircraft, which can be better accomplish the task to find the optimal path with high efficiency on the higher complicated environment such integrated conditions as geographical barriers, the no-fly zone, threat sources. Therefore, this algorithm will be adopted to conduct computing analysis.

3. SAS algorithm

3.1. Algorithm Description
SAS algorithm is a new algorithm which compresses and optimizes A* algorithm in order to speed up convergence rate and save operation space. The function expression of A* algorithm is \( f^*(x) = p^*g^*(x) + q^*h^*(x) \), while the SAS algorithm sets the coefficient in this function as a constant, which is simplified to \( f^*(x) = g^*(x) + h^*(x) \) [5]. The core of this algorithm is the design of evaluation function. The evaluation function is introduced when selecting the next investigation contact “i” of the current node. \( f^*(x) \) represents the sum of the actual cost of an optimal path from node \( S_0 \) to node \( x \) plus the cost of an optimal path from node \( x \) to the target node. \( g^*(x) \) is the actual cost on the minimum cost path from node \( S_0 \) to node \( x \), and \( h^*(x) \) is the cost on the minimum cost path from node \( x \) to the target node.

SAS algorithm has two excellent characteristics. One is the adoptability, which can terminate and find the solution in the finite time in the solvable state space. The second is monotonicity. By appropriate monotonicity restriction to the heuristic function \( h^*(x) \), the evaluation value of the extended series of nodes will be monotonically increasing or non-decreasing [6], so as to ensure the efficient and optimal planning for anti-submarine aircraft to carry out responsive submarine-searching missions.

3.2. Algorithm Process
Path planning is a priority search issue that requires global optimum. SAS algorithm process is shown in Figure 1. Its search algorithm is as follows:
(1) Initializing and putting the initial node $S_0$ in the OPEN list;
(2) Looking for reachable points around the node, which will serve as the ancestor node of these points;
(3) Removing this point from the OPEN list and add it to the CLOSE list;
(4) Calculating the point: $F=G+H$ ($F=f(x)$; $G=g(x)$; $H=h(x)$);
(5) If $F$ is the smallest, the node would be found successfully, remove it from the OPEN list and add it to the CLOSE list. Otherwise, the point is not added to the CLOSE list;
(6) Whether the point is the target point, if yes, the end; Otherwise jump to step (2).

Figure 1. SAS algorithm flowchart

4. Constraints
During evaluating the responsive submarine-searching path, the evaluation index should be constructed first, which usually takes into account the range index, safety index, flight time index and comprehensive
weight index of anti-submarine aircraft. In addition, the performance characteristics and the battlefield environment of the anti-submarine aircraft should be taken into account, for instance the constraints of maneuvering performance, maximum range, threat and tactics [9].

4.1. Maximum Range Constraint
When responding the submarine searching mission, the anti-submarine aircraft would bring one or more submarine-searching equipment and weapons when necessary, which would limit the number of fuels. Moreover, anti-submarine warfare aircraft would often stay in target area for a period of time. Because of these factors, maximum range constraint should be considered during the path planning, namely each segment of the total distance should not be greater than the sum of maximum range.

For a path with “n” waypoints, the maximum range constraint can be expressed as:

\[ I_C \leq I_{\text{max}} \]

Where, \( I_C \) is the range index of a certain air path, \( I_{\text{max}} \) the maximum value allowed by the fuel consumption index.

For a path with “n” waypoints (including initial points and target points), the range constraint can be expressed as:

\[ J_C = \sum_{i=2}^{n} I_{i-1} \leq I_{\text{max}} \]

Where \( I_{i-1} \) represents the range between two adjacent waypoints.

4.2. Tactical Constraints
In the actual anti-submarine warfare, the time from the target being discovered to disappearing is usually relatively short, which requires the anti-submarine aircraft to search the target with the highest efficiency. Therefore, the tactical constraint condition is an important factor for the anti-submarine aircraft searching the submarine.

4.2.1. Direction and position constraints for entering the search area. For anti-submarine warfare aircraft search potential along different directions into the search area, the probability of target was found is different, which can make the corresponding target spreading probability model is also different. Therefore, anti-submarine aircraft are required to conduct the anti-submarine missions along different directions, according to the different search types. The entry direction and position should be constrained, that is:

\[ |H_S - H(X_f, Y_f, X_t, Y_t)| \leq D_H \]

Where, \( H_S \) is the predetermined entry direction; \((X_f, Y_f)\) and \((X_t, Y_t)\) are respectively the last waypoint of the anti-submarine aircraft and the longitude and latitude coordinates when the target submarine is found; \( D_H \) is the maximum deviation of the allowed direction of entry.

4.2.2. Time constraints. In the process of searching submarine, the time to reach the predetermined sea area is constrained in many cases, especially in the multi-aircraft, ship-aircraft cooperative operations. In this process, weather, environment, speed, path track and so on are all factors that affect time. If the time is too long, the target submarine will be given a more escape time and the difficulty of submarine search will be increased. Therefore, it is required to plan the path as reasonable as possible to ensure the efficiency of submarine search.

4.3. Maneuvering performance constraints
Maneuvering performance constraints mainly refer to such constraints as the minimum turning radius and maximum climbing speed that should be considered when the anti-submarine aircraft adjusts the flight direction and altitude when making a turn on the path due to the existence of the threat zone.
4.3.1. **Minimum turning radius.** It reflects the maneuvering ability of the anti-submarine aircraft to change course on the surface, which mainly considers the influence of the threat area and the maneuvering for tracking and searching in time when the target conducts circumvention at a large angle. The setting of key waypoints shall meet the following requirements:

\[
\begin{cases}
K_1, K_2 \leq 2r_{\text{min}} \cdot \sin \theta & \text{turning when go through the point} \\
K_1, K_2 \geq r_{\text{min}} \tan \theta & \text{no turning when go through the point}
\end{cases}
\]  

(2)

Where, \(|K_1K_2|\) is the distance between two key waypoints, which can be obtained by Bowring formula; \(\theta\) is the angle of turning; \(r_{\text{min}}\) is the minimum turning radius.

4.3.2. **Maximum climbing speed.** It reflects the maneuvering ability of the anti-submarine aircraft in the vertical direction under a certain horizontal initial speed. At a certain speed, when aircraft fly over a warship, an island and other obstacles of a certain height, it is necessary to consider them in order to avoid collision.

4.4. **Threat constraints**

Threat constraint is an important element of many constraints, and it is dynamic. The common threat sources mainly include enemy air defense radars, air defense weapons and fighter jets. Considering that the threat must be avoided during the path planning, it can be attributed to the impassable obstacle area, which can be appropriately expanded in the simulation to prevent the aircraft from entering the threat area due to the accumulated errors during the submarine search mission.

Assuming that the set of the threat zone and no-fly zone in the process of the anti-submarine aircraft flying to the target sea area after receiving the submarine searching task, and the path function is \(f(x, y, t) = 0\) (\(x, y\) and \(t\) respectively represent the latitude and longitude coordinates of any point on the path and the flight time of the anti-submarine aircraft), the threat constraint can be described by the following formula:

\[
\forall x, y, t, f(x, y, t) = 0 \quad (x, y) \notin R_T
\]  

(3)

4.5. **Other constraints**

In addition to the above constraints, there are also aviation control zones, no-fly zones and third-country flight restriction zones that need to be considered [10], which are mainly involved in ocean-going training and combat missions. In order to facilitate the simulation calculation, it can be simplified to the threat zone qualitative obstacle model to conduct processing.

5. **Simulation Calculation**

When the anti-submarine aircraft carries out the submarine-searching task, it first needs to obtain the preliminary position of the target, then obtain the battlefield map information, enemy and enemy situation information and the obstacle area information such as no-fly zone, and finally selects the appropriate path planning algorithm to calculate the optimal path.

In order to adapt the SAS algorithm to find the optimal path, the relevant map information can be displayed in the form of grid, and the scope of the no-fly zone can be enlarged appropriately. Battlefield environment can be generated by loading txt file matrix data, and real-time battlefield situation information can also be loaded to carry out real-time path planning in the specific application process.

During path planning, the no-fly area information and relevant data are first loaded. After the pilot manually selects the starting point and target point, the search path can be displayed in animation (as shown in Figure 2). When the shortest path is found, it will be automatically displayed on the screen (as shown in Figure 3).

For the convenience of use, the North-East coordinate system can be used for display, and the starting point can be used as the reference point, and the position of the target relative to our side can be displayed. The pilot can control the flight to reach the target point according to the shortest path in the diagram (the
shortest path, that is, the optimal path, since other factors have been excluded), and can also plan the optimal path in real time according to the change of battlefield situation to assist the pilot to make decisions.

![Search path displayed in animation after entering start point and target point](image1)

**Figure 2.** Search path displayed in animation after entering start point and target point

The SAS algorithm is used to simulate and analyze the responsive submarine-searching path planning for anti-submarine aircraft to be called and searched, and the following results can be obtained:

(1) When the map information is not very large, the 32*32 matrix graph are employed to find the optimal path, and SAS is about 46.6 square distances (as shown in FIG. 4 (1)). In terms of planning speed, the entire simulation program takes about 8s, among which the SAS algorithm path planning takes about 0.2s.

![Shortest path found](image2)

![SAS Algorithm simulation diagram (1)](image3)

**Figure 3.** Shortest path found  **Figure 4.** SAS Algorithm simulation diagram (1)

(2) After the map information is enlarged appropriately, the 84*84 matrix graph is run to find the optimal path, and the optimal path planned is about 118.6 square distances (as shown in Figure 5.). In terms of planning speed, the whole simulation program takes 24.0s, among which the SAS algorithm path planning takes about 2.8s.
3) In order to further verify whether the algorithm meets the actual requirements, 168*168 geographic information matrix is used for simulation. Since the planned shortest path length is about 233.7 square distances (as shown in Figure 5), the simulated shortest path effect index is relatively ideal. In addition, the planning speed is also fast. The whole simulation program takes about 88.3s, among which the SAS algorithm path planning takes about 21.7s (as shown in Figure 7).

6. Basic Conclusions
By employing SAS algorithm to carry out simulation calculation for the responsive submarine-searching path planning of anti-submarine aircraft, the results show that:

(1) When the amount of map information is small and the effect of the optimal path obtained is similar, SAS algorithm is basically equivalent to other algorithms (such as Ant colony algorithm, Genetic algorithm, etc.) in terms of operation speed, and can better meet the requirements. That is to say, it is applicable to use SAS algorithm to plan the submarine search path when anti-submarine aircraft is called on in the non-belligerent environment or when the enemy's naval force is normal in the belligerent environment.
(2) When the amount of map is large, that is, sea conditions are complex, and enemy sea power is stronger. Compared with other algorithms such as Ant colony algorithm and Genetic algorithm, SAS algorithm has obvious advantages in computing speed and path planning effect. It can better meet the needs of combat and training.

Therefore, when performing responsive submarine-searching path planning, no matter how large or small map information is, SAS algorithm are better than other algorithms in terms of meeting the practical needs. Because the map operation speed will decline when information becomes large, it is suggested that the battle information should be filtered and simplified to improve the planning efficiency on condition that the submarine-searching efficiency is not affected.

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