

# Ship Route Planning Using Historical Trajectories Derived from AIS Data

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**ABSTRACT:** Ship route planning is one of the key issues in enhancing traffic safety and efficiency. Many route planning methods have been developed, but most of them are based on the information from charts. This paper proposes a method to generate shipping routes based on historical ship tracks. The ship's historical route information was obtained by processing the AIS data. From which the ship turning point was extracted and clustered as nodes. The ant colony algorithm was used to generate the optimize route. The ship AIS data of the Three Gorges dam area was selected as a case study. The ships' optimized route was generated, and further compared with the actual ship's navigation trajectory. The results indicate that there is space of improvement for some of the trajectories, especially near the turning areas.

## 1 INTRODUCTION

Maritime transportation plays an important role in the global economy and nearly 90% of trade is realized by maritime transportation. Route design is one of the main tasks faced by navigators. The quality of route is related to the navigation safety and economic benefits of ships. Generally, the route should be able to satisfy two main objectives, which are avoiding dangerous areas and ensuring economic benefits, respectively. For maritime transport, it is important to design safe routes quickly and easily.

Ship route design is usually completed by the captain and chief officer. Although this approach will not cause problems in most cases, the manually designed route is still affected by the professional quality, sailing experience and personal emotion of the crew. Therefore, is not necessarily the optimal route.

With the development of computer technology, mapping technology and information technology, the

current marine data can accurately and completely describe the navigation environmental information. In this case, the researchers began to use heuristic algorithms to automatically generate ship route and many methods and procedures have been developed to determine the best route available (Dijkstra 1959, E. Kobayashi 2011, Choi et al. 2015). However, in complex situations, it is difficult to realize in the actual navigation environment, and it is difficult to accurately and completely represent the obstacles in the complex environment with many obstacles. The crew still rely more on sailing experience and reference routes to complete the route design.

In this paper, a path optimization method based on historical information generation is proposed, which can be a planned route in a certain area of a ship of different types, sizes and headings. The maritime department or the shipping company can use this method to obtain an optimized route and provide reference for the route planning of the ship. A path optimization method based on historical

information generation is proposed, which can be a planned route in a certain area of a ship of different types, sizes and headings.

The paper is organized as follows: section one mainly introduces the research on route planning, and section two introduces the route generation method. In the third section, the AIS data of the three gorges region of China were used to generate air routes and discuss. Finally, the fourth part is the conclusion of this paper.

## 2 RELATED STUDIES

### 2.1 AIS data in maritime transportation

The ship AIS equipment transmits information at different frequencies according to the equipment level and the navigation status of the ship in accordance with the regulations of the local maritime administration. The format of the information is strictly defined, including the actual position, speed, heading, and the direction of the ship, as well as the static or semi-static information such as ship's name, call sign, draught, ship size (Tetreault 2005).

At present, all the ships above a certain tonnage are forced to install the AIS system. And a lot of small ships also installed the AIS system. A large amount of AIS data has been used in many studies in maritime transport, such as risk assessment analysis (Montewka and Kujala 2014, Hänninen and Kujala 2014), ship collision avoidance (Wang et al. 2013, Zhang et al. 2015), traffic flow analysis (Xiao et al. 2015), etc.

AIS data can be used to generate ship historical routes. Zhang et al. deleted the abnormal AIS data by determining the state of the ship and used the regression model to smooth the route generated by the AIS data (Zhang et al. 2018). Wang et al. proposed a modified clustering algorithm to extract and analyze ship routes (Wang Gao and Yang 2017). To solve the problem of missing AIS data, Sang et al. proposed a curve fitting method to restore the vessel trajectory (Sang et al. 2015). Although there are some problems in AIS data, such as noise and absence, it can still generate the ship's historical route with a satisfactory accuracy.

### 2.2 Ship route planning

There are many ship route design methods based on heuristic algorithm, such as Dijkstra algorithm, genetic algorithm, ant colony algorithm, A\* algorithm. In order to avoid problems such as local optimal solution and long calculation time, many researchers have proposed improved methods combining other relevant algorithms (Lee et al. 2018, Vettor and Guedes Soares 2016, Roh 2013).

A lot of the above methods are cell-based, which means that obstacles need to be gridded. Therefore, it is difficult to accurately and completely express obstacles in the complex environment of obstacles such as bridges, shallow waterways, ship anchorage, reefs and navigation marks.

Xiao et al.'s study on the traffic flow pattern of ships shows that different types and sizes of ships have different route positions, which is especially obvious in waterways with traffic separation management (Xiao et al. 2015). Most existing methods do not take into account the route differences of different ships.

The method proposed in this paper avoids the grid description of obstacles and can design different routes according to ship type, size or other special requirements, which overcomes the limitations of existing methods.

## 3 METHOD FOR THE ROUTE PLANNING

In this section, the route design method proposed is introduced. This method obtains the ship's historical route through AIS data, and then clusters the optimization to design the route.

### 3.1 Extraction of historical routes

This section describes how to get historical routes from AIS data. The time interval at which the AIS device sends the message is short, and the message contains the location information of the ship. Therefore, the historical route of the ship can be obtained by processing the AIS data. The AIS data includes the ship's MMSI and time. It can classify historical routes and select different historical route information according to actual needs.

#### 3.1.1 AIS data selection and classification

This paper mainly uses dynamic and static AIS data. Dynamic data provides the latitude and longitude of the ship at each moment and can be used to map the ship's historical routes. Static data is mainly used to classify ships. It should be noted that since the ship's static data only divides the ship into passenger ships, cargo ships, oil tankers, tugs and official ships, it is necessary to use the MMSI number to inquire about the specific ship type.

The purpose of classifying AIS data is to obtain different types of historical routes. The AIS data includes the ship's MMSI. The ship can be classified by the unique MMSI to obtain ship route information of different types, sizes and draughts. At the same time, according to the special requirements of the local maritime administration, the route information of special ships or dangerous goods ships can be selected. Further, considering the hydrological environment of the waters, the route information of the dry season, the flat-water period and the flood season can be obtained by selecting the AIS data of different seasons.

#### 3.1.2 Outliers removal

The outliers handled in this article is "particularly egregious" error data. Since the turning points will be clustered, the influence of random errors can be ignored. The processing of the abnormal data is

divided into two steps, which are removal and replacement.

For the abnormal data of the velocity, the confidence range is set by determining its maximum and minimum values. The scope of credibility is determined based on actual conditions. The speed range of ships in different navigation areas is inconsistent, different types of ships have different speed ranges as well. The choice of speed range should be determined by reference to the ship's performance of the same type and size and the regulations of the local maritime administration. Figure 1 shows the speed in the AIS data of a bulk carrier in an inland area, and the confidence range is set to be between 1 and 20 knots.



Figure 1. Analysis of abnormal velocity data

The position abnormal data, that is, the longitude or latitude, is abnormal, and the position deviates from the route. In this paper, a confidence range is established, and it is considered that the abnormal data is outside the current trusted range. The confidence range is determined by the position of the previous moment, the position of the latter moment, and the speed.

Depending on the speed, the maximum distance the ship can navigate in a fixed time span can be calculated, during which time the ship will not move to a further position. Since the starting and ending points of the movement of the ship during this time are certain (i.e. the position at the previous moment and the position at the next moment), the credible range should be the ellipse with the starting point and the end point as the focus. The sum of the distance from any point on the ellipse to the focus is the maximum distance the ship can move.

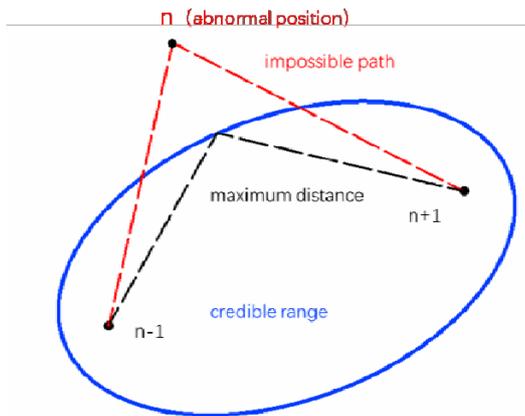


Figure 2. Analysis of abnormal position data

The long axis  $a$  and the short axis  $b$  of this ellipse are:

$$a = \frac{v_n \cdot (t_{n+1} - t_{n-1})}{2} \quad (1)$$

$$b = \sqrt{\left[ \frac{v_n \cdot (t_{n+1} - t_{n-1})}{2} \right]^2 - \left( \frac{l}{2} \right)^2} \quad (2)$$

where:  $t_{n-1}$  is the time at the previous moment;  $t_{n+1}$  is the time at the later moment;  $l$  is the distance between the position of the ship at the previous moment and later moment;  $v$  is the speed of the ship.

### 3.1.3 Outliers restoration

After removing the outliers, the missing speed data and location data should be restored.

AIS devices send dynamic data at intervals ranging from 2 seconds to 3 minutes. The time interval of sending dynamic data is very short when the ship's navigation state are changing greatly, such as large angle steering and acceleration or deceleration. On the contrary, the time interval of sending dynamic data is longer when the change of navigation status is small. Therefore, the missing data can be obtained simply by linear interpolation.

Suppose that the point to be restored is  $n$ , the point at the previous moment is  $n-1$ , and the point at the latter moment is  $n+1$ , then the longitude, latitude and velocity of the point are:

$$v_n = v_{n-1} + \left( \frac{v_{n+1} - v_{n-1}}{t_{n+1} - t_{n-1}} \right) \times (t_n - t_{n-1}) \quad (3)$$

$$La_n = La_{n-1} + \left( \frac{La_{n+1} - La_{n-1}}{t_{n+1} - t_{n-1}} \right) \times (t_n - t_{n-1}) \quad (4)$$

$$Lo_n = Lo_{n-1} + \left( \frac{Lo_{n+1} - Lo_{n-1}}{t_{n+1} - t_{n-1}} \right) \times (t_n - t_{n-1}) \quad (5)$$

where:  $V$  is the velocity at this point,  $La$  is the latitude, and  $Lo$  is the longitude.

### 3.1.4 Generation and screening of historical routes

The processed AIS data contains more accurate longitude and latitude information at each moment of the ship and can be used to describe the ship's trajectory. Ship routes on short-haul flights lack reference value and should be deleted. In addition, due to the failure of AIS equipment or poor signal, the ship has too few AIS position points in the route. Such routes may lack key information and should be deleted as well. The route identification method with less AIS information is to calculate the frequency of the AIS message of the route. When the frequency is lower than a threshold, it is considered that the route lacks key information. The interval at which AIS

devices send packets varies from 2 seconds to 3 minutes. This is determined by the ship's heading status and is highly variable. Therefore, this paper selects a number of ships with different speeds and counts the time interval at which AIS equipment sends messages.

However, in the same waters with the same navigation environment, the time interval for the AIS device to send packets should converge in a range. Assuming that  $Xt$  is a specimen for the time interval of sending packets in a certain area, according to Chebyshev's theorem, the time interval for sending packets can be determined as:

$$(0, \bar{x}_t + 5 \cdot DX_t] \quad (6)$$

where:  $\bar{x}_t$  is the average value;  $DX_t$  is the standard deviation. Then, the minimum frequency of messages sent by the AIS device every hour is:

$$n = \frac{3600}{x_t + 5 \cdot DX_t} \quad (7)$$

When the number of AIS packets in the route is less than such threshold, it indicates that the route may lack key location information and needs to be deleted. It should be noted that the frequency of the AIS message calculated above refers to the dynamic data packet including the location information, and does not include other AIS messages such as static data and voyage data.

### 3.2 Determine the turning point of the ship

Turning point refers to the point at which the ship turns. The main method of route design is to determine the turning point of the ship, and the route between the turning points constitutes the route. After obtaining the historical route, the optimized route is generated by selecting the turning point of the ship therein. Due to the large amount of data, the route generated by using all the steering points of the ship is too complicated. The calculation amount is huge. The local optimal solution is easily generated, which is not in accordance with the actual situation. Therefore, the steering points need to be clustered before the route is generated.

In the database, the ship's historical route can be selected according to special requirements, and then their turning points are clustered. In this way, routes with different characteristics can be designed. For example, designing routes with different headings or routes in different seasons.

#### 3.2.1 Clustering method

Density Based Spatial Clustering of Applications with Noise (DBSCAN) is a spatial clustering algorithm that is widely used in many applications. It is capable of finding arbitrarily shaped clusters in the presence of noise data and performs well without the prior knowledge about the number of clusters. The characteristics of DBSCAN determine its suitability

for clustering spatial data. Therefore, the DBSCAN algorithm is selected to cluster the turning points.

The clustering effect of the DBSCAN algorithm is related to the Eps radius (Reps) and the neighborhood density threshold (MinPts). Start at any point (unvisited) and find all nearby points within the distance of Reps. If the number of nearby points is not less than MinPts, the current point forms a cluster with its nearby points. The starting point is marked as visited. If the number of nearby points is less than MinPts, the point is marked as a noise point. When no new points are added to any cluster, the clustering terminates.

In Figure 3, when MinPts is 3, a, b, c, d are core points, and e, f are noise points.

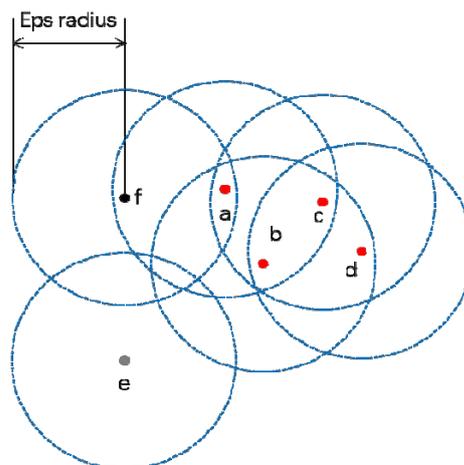


Figure 3. The schemes of DBSCAN cluster algorithm

#### 3.2.2 Algorithm parameters

When clustering the turning points, three parameters need to be considered: steering angle, Reps and MinPts in the DBSCAN algorithm. The steering angle and Reps are determined based on historical route conditions. MinPts is determined based on the generated turning point density. When the angle of the historical route changes small, the large ship steering angle and small Reps should be selected. When the historical route angle changes greatly, the small ship steering angle and the large Reps should be selected.

It should be noted that the historical routes generated in the previous section are connected by intermittent points, so the steering angle of each point cannot be obtained directly. The steering angle is calculated by the heading difference between the position point in the AIS data and the previous point position.

After turning to point clustering, a cluster containing multiple turning points is needed. The cluster needs to be converted into points with certain coordinates. The average longitude and average latitude of the turning points in the cluster should be calculated to determine the turning points represented by the cluster:

$$La = \sum_{i=1}^m La_i \quad (8)$$

$$L_o = \sum_{i=1}^m L_{o_i} \quad (9)$$

### 3.2.3 Clustering effect adjustment

In the clustering process described above, the clustering parameters selected for the entire route are consistent. However, the angle changes in various parts of the route may be inconsistent, or even vary greatly. Using the same parameters may cause the turning points in some areas to be too sparse, while the turning points in some areas are too dense. So for the area where the steering point density is small, the steering angle should be reduced. In the area where the turning point is dense, the steering angle should increase.

### 3.3 Route generation

After obtaining the turning point of the ship, treating it as a node, the Dijkstra algorithm and the ant colony algorithm are used to generate the route.

When there are too many data points, the traditional ant colony algorithm has the disadvantages of weak global search ability, slow convergence speed and low search efficiency. It is easy to generate local optimal solutions. If only the Dijkstra algorithm is used, the generated route will always be close to the outside and turn frequently, which is not in line with the actual situation. Therefore, this paper first uses the Dijkstra algorithm to plan the initial path and then uses the ant colony algorithm to optimize the path.

#### 3.3.1 Initial route generation

The Dijkstra algorithm is essentially a traversal algorithm that calculates the shortest path by calculating the length of many paths between two points (Dijkstra 1959). The Dijkstra algorithm starts from the starting point and selects the nearest node each time, until it reaches the end point.

When using the Dijkstra algorithm, the problem in the Figure-4 will appear. Due to no other restrictions, the route generated by the Dijkstra algorithm may pass through obstacles or beyond the deep water channel. When calculating the distance between two points, set the path length through the obstacle or beyond the deep water channel to infinity. In this way it is ensured that the designed route does not pass through obstacles or outside the deep water channel.

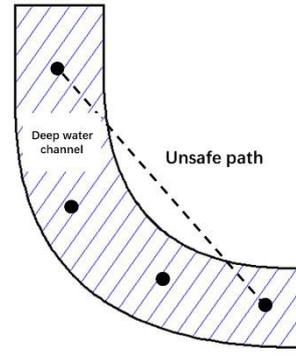


Figure 4. Unsafe path

The steps of Dijkstra algorithm are as follows:

**Step 1:** Create a point set  $S = \{v_0\}$ ,  $U = \{v_0, v_1, \dots, v_n\}$ .  $\langle v_i, v_j \rangle$  is recorded as the distance between any two points. When the two points are crossing the obstacle or exceed the deep water channel,  $\langle v_i, v_j \rangle$  is recorded as infinity.

**Step 2:** Select  $v_k$  from  $U$ , so that  $\langle v_0, v_k \rangle = \min\{\langle v_0, v_i \rangle\}$ , put  $v_i$  into  $S$ .

**Step 3:** Add  $v_k$  to  $U$  and let  $\langle v_0, v_k \rangle = \min\{\langle v_0, v_i \rangle, \langle v_0, v_k \rangle + \langle v_k, v_i \rangle\}$ .

**Step 4:** Repeat Step 2 and 3 until  $U$  is an empty set.

#### 3.3.2 Route optimization

The ant colony algorithm regards the walking path of the ant as a feasible solution to the problem to be optimized. All the paths of the entire ant group constitute the solution space of the problem to be optimized. The ants with shorter paths release more pheromone. As time progresses, the concentration of pheromone accumulated on the shorter path gradually increases, and the number of ants that select the path increases. In the end, the whole ant will concentrate on the best path under the action of positive feedback, and the corresponding solution is the optimal solution to be optimized.

When selecting a path, the ant needs to be determined according to the transition probability  $p_{ij}$ . The state transition probability can be calculated by the following formula:

$$p_{ij}^k = \begin{cases} \frac{[\tau_{ij}(t)]^\alpha \cdot [\eta_{ij}(t)]^\beta}{\sum [\tau_{ij}(t)]^\alpha \cdot [\eta_{ij}(t)]^\beta}, & j \in allowed_k \\ 0, & others \end{cases} \quad (10)$$

where:  $allowed_k = \{0, 1, \dots, n-1\}$  represents the set of nodes allowed in the next step;  $\tau_{ij}(t)$  represents the pheromone left by ant  $k$  on path  $(i, j)$  at time  $t$ ;  $\eta_{ij}$  represents the distance heuristic function factor, usually expressed by the reciprocal of the distance between nodes;  $\alpha$  is the relative importance coefficient of the ant pheromone trajectory;  $\beta$  is the relative importance coefficient of the heuristic function.

The traditional ant colony algorithm pheromone update method is a simple accumulation. In order to avoid the local optimal problem and speed up the

algorithm efficiency, this paper uses a new pheromone update method.

Whenever an ant passes a path, the pheromone of the path is updated according to the following formula, which is a local pheromone update strategy.

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \rho\tau_0 \quad (11)$$

where  $\tau_0$  is the pheromone under the initial condition;  $\rho$  represents the pheromone volatilization coefficient, and the range of the value is  $[0, 1]$ .

When all the ants complete a hit path search, the shortest path in the iteration is selected and the pheromone on the path is updated. This is the global update strategy for pheromone. The update method is as follows:

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \rho\tau_{ij}(t, t+1) \quad (12)$$

where:  $\Delta\tau_{ij}$  is the pheromone increment left by the ant on the path  $(i, j)$  in the global update;  $\Delta\tau_{ij}(t, t+1)$  is the reciprocal of the optimal path length for this iteration.

By setting the local update strategy and the global update strategy of the pheromone, the quality of the optimal solution and the search efficiency of the algorithm can be effectively improved, but the algorithm will also prematurely converge. To avoid this problem, the upper and lower bounds of the pheromone threshold are set as:

$$\tau_{ij} = \begin{cases} \tau_{\min}, & \tau_{ij} \leq \tau_{\min} \\ \tau_{ij}, & \tau_{\min} < \tau_{ij} \leq \tau_{\max} \\ \tau_{\max}, & \tau_{ij} > \tau_{\max} \end{cases} \quad (13)$$

where:  $\tau_{\max}$  and  $\tau_{\min}$  represent the maximum and minimum values of pheromone concentration, respectively.

The optimization procedure for the initial path using the ant colony algorithm is:

**Step 1:** Plan the initial path using the Dijkstra algorithm;

**Step 2:** The ant colony algorithm starts searching, and the ant selects the next node  $j$  according to the current node position  $i$ ;

**Step 3:** After the next node  $j$  is determined, the ant needs to locally update the pheromone on the path  $(i, j)$  that has just passed until the ant reaches the endpoint;

**Step 4:** Count the optimal path searched by the current  $m$  ants, select the one with the shortest length, update the global pheromone, and repeat step 2 to iterate;

**Step 5:** The number of iterations satisfies the out-put result after  $iter \leq NC$ .

## 4 SIMULATION AND RESULTS

In this section, the route is generated in the Three Gorges Dam area of China for simulation and compared with the actual trajectory of a ship. The data used in this section is the ship AIS data for the Three Gorges Dam area from Dec. 18 2018 to Jan. 18 2019, collected by nearby AIS base stations.

### 4.1 Simulations

In this paper, the route of the ship with a length of 85 meters to 120 meters and from the downstream to the upstream is selected to plan the route.



Figure 5. Outliers of AIS data

After extracting the ships that meet the requirements in the database, they process their AIS data, delete the abnormal data and complete the data by linear interpolation.

Then it is necessary to select the historical route. Short routes can be deleted directly in the database. For the routes lacking key information, the minimum frequency of messages sent by the AIS device every hour needs to be calculated. After statistics, the time interval for sending AIS messages in the Three Gorges Dam area is (2s, 38.04s). Calculate the minimum transmission frequency of AIS messages according to the formula (7) to delete the routes with low frequency.

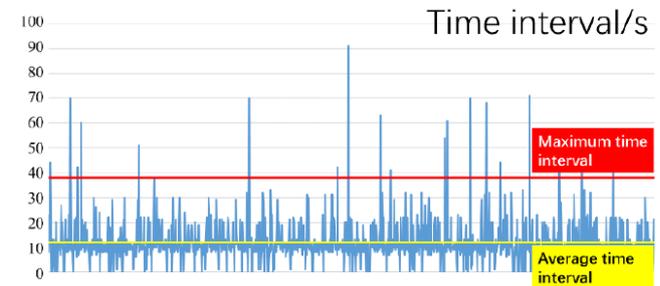


Figure 6. Sample of the time interval

After obtaining the historical route, the ship turning points are clustered. The most important influence on the clustering effect is the steering angle. After deleting all the turning points with a steering angle of  $0^\circ$ , the average steering angle of the ship in the Three Gorges Dam area is calculated to be  $4.2^\circ$ . It can be seen that the deflection angle of the ship route in the Three Gorges Dam area is small. The steering angle selected in this paper is  $4^\circ$ . The selected steering

angle is appropriately changed in some areas to obtain better clustering effect.



Figure 7. Partial area clustering effect

Finally, the route is generated according to the Dijkstra algorithm and the ant colony algorithm, the red line in the Figure 8 is the generated route. Among them, the red line is the ship route from west to east (from upstream to downstream), and the blue line is the ship route from east to west (from downstream to upstream). This is achieved by selecting different historical ship trajectories. Due to the Three Gorges ship lift equipment, there are large ship anchorages and port facilities in front of the Three Gorges Dam area, where the ships are anchored and waiting to pass the ship lift. No ship can pass the ship directly,

they all need to line up at the anchorage or port. Therefore, it is meaningless to generate routes in this area. This is also the reason why the generated route is incomplete.

#### 4.2 Results and discussion

In this section, two different course routes are planned by selecting different historical ship trajectories, which is presented in Figure 8. It can be seen from the figure that there are obvious differences between the two routes. The route from west to east is close to the south bank, and the route from east to west is close to the north bank, which is in line with the actual situation. This indicates that the proposed method can plan unique routes for ships of different types and different headings by selecting different types of historical ship trajectories.

At present, there is little research on the route design of the Three Gorges Dam area. Therefore, this paper selects the navigation trajectory of the actual ship and compares it with the generated route.

The black line in the Figure 9 is the real ship trajectory, and the red line is the generated route. After calculation, the length of the generated route is slightly smaller than the actual ship's trajectory. Obviously, the generated route has a small number of turns and a small amplitude. By comparing with the deep-water channel map, the generated routes are all in the deep water channel and remain basically in the middle position. Therefore, it can be considered that the generated route is safer than the actual ship trajectory, which also indicates that the existing trajectories of some ships have space of improvement.



Figure 8. Route planning results



Figure 9. Compared with the actual route

## 5 CONCLUSION

This paper proposes a method for route planning based on historical AIS data. This method obtains historical route information by analyzing AIS data, and seeks optimal path implementation using Dijkstra algorithm and ant colony algorithm. The results show that although this method cannot significantly reduce the length of the route, it can reduce the complexity and improve safety of the route. Compared with other route design methods, this method does not need to model obstacles, and can plan different routes for different requirements, such as designing routes of different types of ships, designing dry seasons, flat water periods, and wet season routes. The method proposed in this paper has some limitations. First of all, the processing of AIS data is not accurate enough. Secondly, the method selected in this paper is simple in the way of whether the route crosses obstacles and exceeds the deep water channel. In a complicated environment, some routes may cross obstacles or be in shallow waters. Nevertheless, the proposed method is feasible in most waters and can be used as a design reference for route planning.

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