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Create a weather routing network in ocean navigation and verify it with a simple cost function

Mehriar Ali Mohammadi[1*], Ali Mohammadi[2], Mostafa Khalifehgholi[3]

[1*] *Assistant Professor, Atmospheric and Oceanic Sciences, Imam Khomeini Maritime University, Nowshahr, Iran, mhyar_alimohammadi@yahoo.com*

[2*] *Assistant Professor, Navigation and Nautical operations, Imam Khomeini Maritime University, Nowshahr, Iran*

[3] *Master's degree in Navigation and Nautical operations, Imam Khomeini Maritime University, Nowshahr, Iran*

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ABSTRACT

Meteorology in maritime, unlike in the past, which was evaluated qualitatively, has entered the digital arena. With the digitization of meteorological data, the idea of automating meteorological calculations on sea routes has been proposed and implemented. Due to the need of the maritime community to reduce meteorological calculations on maritime routes, ship weather routing has attracted a lot of attention in recent years, both in the university and in the maritime industry. The problems in this field are finding the optimal route and speed of navigation for a certain voyage, taking into account the environmental conditions of wind and waves. Goals are usually considered to minimize operating costs, fuel consumption, or safety. The main methods used to solve the weather routing problem are the Isochrone method, dynamic programming, calculus of variation, use of routing, and exploration algorithms, while in recent years, artificial intelligence and machine learning applications have also increased. Most of these methods are well established and have not changed significantly over the years, although programs with a combination of these methods have been used. In this research first, the great circle route is calculated for the vessel between the departure and the destination positions, and using the Rhumb line method, the network points around the great circle route are created. Next, it is necessary to number the network points and network connections, and finally, using Dijkstra's algorithm and defining a cost function, the network efficiency is proved. The results and innovations of this research, the use of up-to-date methods in calculating the great circle route and turning points on it, creating minimal connections between network points, innovation in numbering points to reduce the search time to find the optimal route, not using ready-made MATLAB codes that all these things increase the efficiency and reduce the execution time of the computer program compared to other similar cases.

1. Introduction

One of the important concerns in ocean navigation is safe and economical navigation, a vessel faces various marine hazards during a sea voyage. Before the start of any sailing voyage, the need to design the route by the ship's captain and officers is a necessity. The purpose of route design is to reach a pattern where the ship navigates on it, from the departure point to the destination point safely and with the least time and least fuel consumption. This type of route design is optimal route design.

Depending on the type of vessel and the distance between the point of departure and the destination, regardless of the land and navigation risks of traffic lines, adverse weather endangers both the safety of the vessel and increases fuel consumption, and on the other hand, choosing the wrong route increases the sailing time. Adverse weather, for example, typhoons Kyar, Ashoba, and Gono in the northern Indian Ocean, whose wind and waves can endanger the safety of navigation [2] [3] [4] [5] [13] [23] [24].

One of the first approaches for minimum-time route planning based on weather forecast data was proposed by James (1957) [25]. In this method, isochrons (lines of the same time reaching from one point to another) are defined, which are determined by a geometrical form and a return relationship. During the last decades from the seventies, based on the original isochron method, the first computer-aided weather routing tools were developed. However, in computer implementation, a problem arises with the term "isochrone loops". Several methods for improving isochrone loops were proposed since the early eighties [23] [24].

The evolutionary approach has become popular as a natural successor to the isochron method in the last two decades and has been successfully applied to ship motion modeling in collision scenarios of vessel units. Modern weather routing tools also use evolutionary algorithms instead of outdated isochrones. However, isochrones can still be used to generate initial conditions. In such cases, special care must be taken to ensure that the route calculated by the isochron method does not cross any land. Otherwise, crossing over land in evolutionary algorithms may lead to long and time-consuming computations or end up determining a dangerous route that passes over or near the shore.

In the evolutionary approach, determining the optimal route is generally done using graph theory, the most important algorithm of which is Dijkstra's algorithm [22]. In this algorithm, all possible routes from the departure to the destination are searched and the route that has the minimum cost function (arrival time, fuel consumption, etc.) is selected.

Maritime routing that uses Dijkstra's algorithm [22] to search for the optimal route includes the following steps:

1- Providing weather forecast data

2- Network generation based on the great circle route (any line that connects two points of the network is considered an edge and can be part of the main route)

3- Interpolation of weather forecast data on the network

4- Calculation of ship's speed in different routes taking into account the weather conditions (routes where waves and wind cause serious damage to the ship and routes that cross land are excluded from the calculations)

5- Finding the optimal route by considering the ship's speed obtained in step 5

In this method, network generation based on the great circle route plays a significant role in marine navigation. In marine navigation, there are two types of routes, the Rhumb line route and the other one is great circle route. The Rhumb line route is a route that cuts all meridians with a fixed angle, and it is relatively easy to calculate the distance` between two points of departure and destination, but it is not suitable for long distances; because a longer route is sailed than the great circle route. On the other hand, the great circle route is a real route on the surface of the earth parallel to the great circles and is considered the shortest route. The method of calculating the distance and the angle of the great circle route is proposed by the international training organization of seafarers by finding the vertex point and turning points [26]. Due to the many calculations and the uncertainty of obtaining the result in the vertex method [1], in this research to find the position of the middle points on the great circle route, the new formulas of combined spherical triangles of Hsieh et al. (2019) [6] have been used. By having the position of the middle points on the great circle route and by combining the Rhumb line method, a network of points around the great circle route can be created. To continue the voyage on the great circle, the ship faces many restrictions and risks, the most important of which are encountering bad weather, dealing with land and shallow water areas, areas marked on nautical charts with marine navigation restrictions, traffic lines, etc., which each of these factors It can divert the vessel from the great circle route. In order not to face unfavorable weather, we need to receive weather forecast information before and during the voyage in order to correct the sailing route. As it was said, by having the position of the middle points and creating an algorithm to design and find the network points, it is possible to create a space around the great circle route so that the vessel can be diverted towards those points in case of any danger. Assuming favorable conditions, the most optimal route is the great circle route, which is the shortest route.

Although there are many studies about Maritime navigation abroad. (E.g. Zhao et al., 2022 [22]; Wang et al., 2022 [15]; Dupuy et al., 2021 [9]; Tilling et al., 2020 [11]; Penino et al., 2020 [14]; Wang et al., 2018 [13]; Kim et al., 2017 [12]; Fang and Lin, 2015 [8]; Paddy et al., 2008 [10] and...) But most of those who used Dijkstra's algorithm in network design did not consider the great circle route as a basis or did not pay attention to its details.

Within the country, these studies are limited only to the research of Malekpour Gholsfidi et al. (2014) [16], who for the first time presented a timed routing method for safe and time-optimized marine navigation using environmental data. In designing the network, he did not consider the great circle route as a basis.

Also, one of the weaknesses of maritime routing using Dijkstra's algorithm is the volume of calculations performed to obtain the optimal route, which has not been addressed in other articles. In this research, after creating a network based on the great circle route, a method is presented that reduces the number of calculations performed to obtain the optimal route. The right test method is by searching for the shortest route without taking into account the meteorological information, and in other research that are being conducted in parallel with this research, the meteorological information is entered into the network and while investigating the effects of wind, wave and current on the ship's speed, maritime routing is carried out.

2. Methodology

First, a great circle route is determined from the departure point to the destination point. Then turning points on the great circle route are determined, which are known as midpoints. By having the position of the middle points on the great circle route and combining the Rhumb line method, a network of points around the great circle route is made. In the continuation of this section, the description of great circle routing, Rhumb line routing, how to create a network, and how to search the network to find the optimal route will be discussed. In this research, after creating the network based on the great circle route, the method of searching the edges of the network is such that each node of the network is determined by the number of nodes and interacts on the destination side. Therefore, the strength of this research is to determine the number of nodes along the route to search for the optimal route. Involving all network points to search for the optimal route will lead to a large computational cost, but this additional computational cost will not increase the accuracy of the problem. Therefore, the computer program for searching the cost function on the edges of the network does not take into account the connection of all the nodes to the desired point, which reduces the number of calculations performed to obtain the optimal route. The right test method is by searching for the shortest route without considering meteorological information.

In the continuation of this section, the theoretical foundations and mathematical relationships of the routing of vessels in the ocean are given.

2.1. Great circle routing

The first step in generating the network around the great circle route is to calculate the route from the departure point to the destination. First, it is necessary to define some terms. A ship can sail a route on the sphere through a Rhumb line route or a great circle route [25]. The Rhumb line route consists of straight lines on the Mercator chart, which will be the shortest route between two points if the earth is flat. According to the mathematical definition, the path of a Rhumb line route is a line or curve on the surface of a sphere that intersects all meridians at an angle. Therefore, the advantage of using a Rhumb line method for navigation is that the ship can have a fixed route. Due to the fact that the Rhumb line route is not the shortest route between the departure and the destination, The short route of the great circle route has always been the focus of seafarers. A great circle route is defined as the shortest line between two points on a sphere. For a ship in a calm sea, a great circle route will have minimum fuel consumption. However, when using a great circle route in navigation, the ship needs to constantly change course. Therefore, this route cannot be practically used for navigation purposes. The suitable route for navigation can be a combination of a Rhumb line method and a great circle method. By choosing several turning points on the great circle route, the ship can use the Rhumb line route between these turning points and change course only a few times during the voyage [18]. After calculating the maritime route, the network around the maritime route can be created by combining the great circle and Rhumb line. In this research, using the turning points on the great circle route (the main nodes of the route), the network nodes are defined using trigonometric relationships. In this research, using the combined triangle relations of Hsieh et al. (2019) [6], the middle nodes or turning nodes on the great circle route have been solved, and using the method described in Table 1, the nodes around the great circle route have been calculated and the network for each The route is drawn. By having the position of network nodes, the required data can be used to calculate the cost function and finally search the network and find the optimal route. Therefore, spherical trigonometry relationships are given to introduce the method [6].

2.1.1 Relations of combined spherical trigonometry [6]

Spherical trigonometry formulas are widely used to solve various spherical geometry problems in various fields such as navigation, aviation, geodesy, and astronomy. The main spherical trigonometry formulas include right-angled spherical triangle formulas, law of sines, law of cosines for sides, law of cosines for angles, half-angle formulas, half-side formulas, four-part formulas, five-part formulas, Dalembert's analogies, Napier's analogies, Connolly's formulas, etc. Assuming that the earth is spherical, spherical trigonometry relationships can be used to solve various navigation problems. These relationships express the relationship between the sides and angles of a spherical triangle. In this research, two relations are used to solve compound spherical triangles. The first relation is the divided spherical triangle and the second relation is the four part formula in the spherical triangle. By using the divided spherical triangle relations, it is possible to obtain the waypoints on the great circle route without finding the initial course angle on the great circle route. In fact, these spherical trigonometry formulas are all used to express the relationship between the six variables of a spherical triangle. The six variables include three sides a, b and c and three angles α, β and γ as shown in Figure 1. For example, the cosine law variable relationships for sides are the opposite relationships between three sides and an angle. Variable relations of four part formulas are adjacent relations between two sides and two angles. The advantage of these formulas is that they are easy to use. If the given variables meet the precondition of a particular formula, the unknown variables can be obtained directly using that formula. For example, when two sides and the angle between them are given, the third side can be obtained directly by applying the law of cosines to sides.

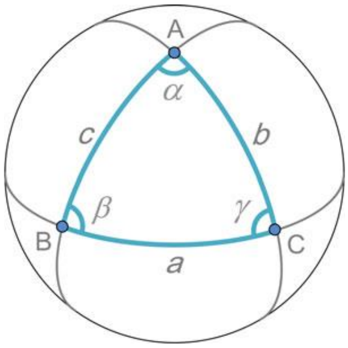

Figure 1 Image of single spherical triangle
Source: [6]

However, current spherical trigonometry formulas only express relationships between the sides and angles of a single spherical triangle. Many problems may involve different types of spherical shapes, such as spherical quadrilaterals and spherical polygons, which cannot be solved directly by adopting single spherical triangle formulas; Therefore, two types of formulas for combined spherical triangles have been proposed by Hsieh et al. (2019), which is a combination of the divided spherical triangle relationship and the four-part relationship [6].

A spherical triangle may be divided by an angle or a side as shown in Figure 2. In split angle conditions, the spherical triangle (ABC) is divided into two spherical triangles (ABX and AXC) from angle α. When two sides (c and b) and bisected angles (α, α1 and α2) are given, the other angles (β and γ) can be obtained using the four part formula, and side (a) can be obtained using the law of cosines for obtained sides. However, none of the spherical triangle formulas can directly find the side x (which we call the common side). Similarly, in the split-side condition, the spherical triangle (ABC) is split from side (a) into two spherical triangles (ABX and AXC). When two sides (c and b) and divided sides (a, a1 and a2) are given, none of the individual spherical triangle formulas can directly find the common side (x); Therefore, the formula of the divided spherical triangle is suggested as follows:

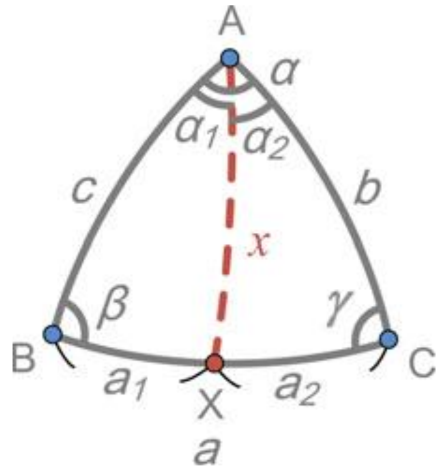

Figure 2. Image of the divided spherical triangle
Source: [6]

First, the four-part formulas of two spherical triangles (ABC and ABC) are written in Figure 2:

$$\tan\beta = \frac{\sin\alpha}{\sin c\cot x - \cos c\cos\alpha} \qquad (1)$$

$$\tan\beta = \frac{\sin\alpha_1}{\sin c\cot x - \cos c\cos\alpha_1} \qquad (2)$$

Substitute equation (1) in equation (2) and the formula is rewritten as follows:

$$\tan x = \frac{\sin\alpha}{\sin\alpha_1\cot b + \sin\alpha_2\cot c} \qquad (3)$$

Then we write the law of cosines for the sides of two spherical triangles (ABC and ABX) in Figure 2:

$$\cos\beta = \frac{\cos b - \cos c \cos a}{\sin c \sin a} \qquad (4)$$

$$\cos\beta = \frac{\cos x - \cos c \cos a_1}{\sin c \sin a_1} \qquad (5)$$

Substitute equation (4) in equation (5) and the formula is rewritten as follows:

$$\cos x = \frac{\sin a_1 \cos b + \sin a_2 \cos c}{\sin a} \qquad (6)$$

As a result, equation (3) is the formula of the common side (x) in terms of the given angle, and equation (6) is the formula of the common side (x) in terms of the given side.

2.2. Rhumb line routing

In this research, plane sailing has been used to calculate the position of nodes around the great circle route. In the following, plane sailing is introduced and the relationships used to determine nodes around the great circle route are given. Plane sailing is used to calculate the route and speed of a vessel from one latitude to another latitude. The reason why this type of navigation is known as plane sailing is that the earth is considered a flat surface, Therefore, this type of navigation over a long distance (distance of more than 600 miles) does not have the necessary accuracy and it is necessary to make corrections for the sphericity of the earth on the problem. A quarter course is used to solve plane sailing. The below figure is obtained from the quarter method.

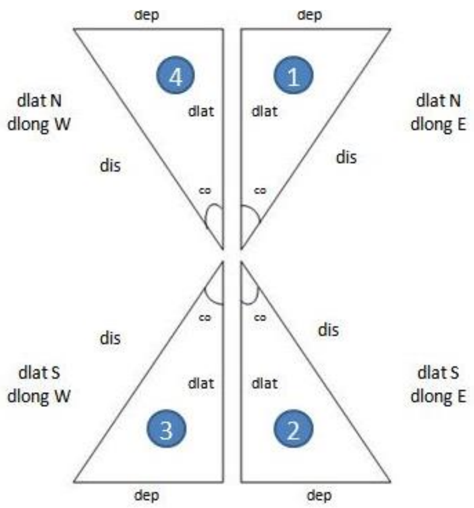

Figure 3. Shapes resulting from the quarter course
Source: Authors

" $dlat$ " and " $dlong$ " are calculated to obtain the necessary movement quarter and according to the sign of " $dlat$ " and " $dlong$ ", the movement quarter is determined. For example, if " $dlat$ " is north and " $dlong$ " is east, it means we are in the first quadrant.

We use trigonometric relations to solve course and distance in the plane sailing method.

$$\tan(co) = \frac{\text{dep}}{\text{dlat}} \Rightarrow$$
$$dep = dlong.cos\left(\frac{latA + latB}{2}\right) \qquad (7)$$

$$\cos(co) = \frac{dlat}{dis} \Rightarrow dis = dlat.\sec(co) \qquad (8)$$

Steps to solve the navigation problem on the flat surface:

1- Using the position of origin and destination, we determine the value of " $dlat$ " and " $dlong$ " and based on their signs, we determine the movement quarter.

2- Using the mean latitude " $lat.m = \frac{latA + latB}{2}$ ", we get the value of " dep ".

3- Using trigonometric relations, we calculate the value of quarter course and speed.

4- Using " $dlat$ " and " $dlong$ " signs, we sign the obtained course. For example, if the obtained course is 42^0 , the course will be sign as follows:

$$\frac{\text{sign of dlat}}{N} \quad \frac{\text{value of quarter course}}{42} \quad \frac{\text{sign of dlong}}{E} \qquad (9)$$

For distances greater than 600 miles, the "mean latitude" can no longer be used for the departure formula. Doing so will result in a large error in the route calculation. Therefore, in this case, the "corrected mean latitude" (L) (Equation 10) is used [22].

$$\sec L = \frac{7915.7045}{dlat}\left[\log_{10}\tan\left(45 + \frac{T^0}{2}\right) - \log_{10}\tan\left(45 + \frac{F^0}{2}\right)\right]$$
(10)

In the above relationship, T means the latitude of the destination waypoint, and F means the latitude of the departure waypoint. In the discussion and results section, how to use the plane sailing relationships and the formation of a network of nodes around the great circle route is given. By introducing two methods of routing in the sea, the method of networking around the route of the great circle is explained.

2.3. Create a network

For optimal routing from the departure to the destination, it is necessary to provide a number of regular nodes to change the direction of the ship from the original unfavorable route.

Table 1. Node design. Source: [18]

level	Type of Activity
1	Find the center node" X_C "along the great circle route.
2	Calculate the route" α " between the center node and the node before the center node (X_{C-1}) on the great circle route.
3	Define perpendicular to α.
4	Draw nodes ($C \pm i$) along the vertical with the selected distance (δ_i) between the nodes.
5	Calculate the Rhumb lines between the start and end nodes and each of the center nodes.
6	Define a set of nodes along each Rhumb line.

In this method, two turning nodes on the great circle route are calculated using the Rhumb line route connected together (Table 1) and the distance between these two nodes is calculated. Then 90 degrees are subtracted from the calculated route and added to it (Figure 4) to create network nodes on both sides of the route and perpendicularly. Using the default distance, which is 50 miles in this research, nodes are created in the perpendicular direction and on both sides of the route (the distance between nodes C+1 and C+2 on the network is 50 nautical miles). In the following, these nodes are numbered. How to number the nodes is given in section 4 of the discussion and results. Figure 4 shows the result of applying the algorithm introduced in Table 1, and the node on the great circle route (node C) along with the nodes perpendicular to the great circle route ($C \pm i$) are shown.

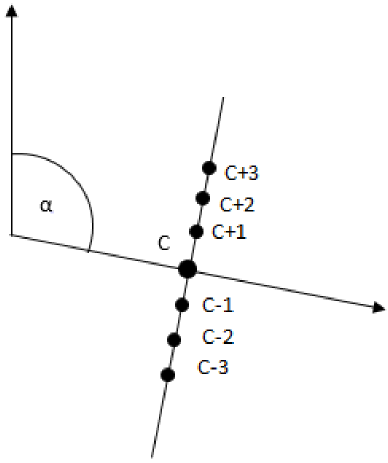

Figure 4. Definition of the nodes around the great circle route, the initial course angle, C, the position of the turning node on the great circle route.
Source: [18]

2.4. Search the network to find the optimal route:

By constructing a network of nodes around the great circle route, it is necessary to use the search algorithm to calculate the optimal route. To solve the optimization problem, the nodes around the great circle route should be converted into a graph. The act of converting into a graph is the concept of numbering the nodes and calculating the cost function between the graph nodes. By constructing a graph, a network of nodes and edges is created between the departure and the destination. The network defines the area of possible movement for the ship and includes all positions that the ship can sail through. Nodes are geographic coordinates and edges are defined as routes sailed between nodes. One of the shortest route-solving algorithms used in this research is Dijkstra's algorithm. The optimal route in a calm sea is almost the same as the great circle route. It is possible to find the shortest route on a sphere with a simple cost function using computer programming and graph definition. However, this computer program can be used to avoid future adverse weather (by introducing more complex cost functions such as speed drop between different nodes in the network). By defining the network, the discussion of how to search in the network is raised. Either all the network nodes should be searched to find the route of the vision or only a certain number of network nodes should be searched with an innovative strategy. The best node can be found by searching all the nodes of the network, but a lot of searches are definitely useless. But on the other hand, can you find the optimal route by limiting the searches? Won't limiting searches result in useful searches being removed? All of these are questions that are discussed in the next section and evaluated with a simple cost function of how to search network nodes.

3. Results and discussion

In the previous section, the basic principles of the work method in this research are given. In this section, each of the parts related to the working method is given in more detail. In this section, with the MATLAB program, the optimal network is created around a great circular route. Then, by calculating the cost function on the network nodes, we calculate the optimal navigation route. It should be noted that the main emphasis of this research is on creating a network around the great circle route and searching for the route by reducing the number of calculations, and for this reason, simple cost functions have been used to test the created network.

3.1. Calculation of the great circle route:

As stated in the research method section, Hsieh et al.'s (2019) method was used in this research to calculate the position of the middle nodes. The mathematical basis of this method was explained in the research method section. In this part, the practical application of the mathematical principles of combined trigonometry to calculate the position of mid-nodes is given.

When the position of the departure point (F) and destination point (T) are given; The latitude of the departure point (φF), the longitude difference between the departure point and the destination point (λFT), and the latitude of the destination point (φT) will be specified. Navigation of intermediate nodes that are on the great circle route from the departure point to the destination point can make the distance less; Therefore, the main problem of the great circle route is to obtain the position of the intermediate nodes. There are two types of situations for calculating mid-nodes:

a) The difference in longitude between the departure point and the middle node (λFX) is given to calculate the latitude of the middle node (φX) (Figure 5-a). In this case, using a default value for the longitude difference, the latitude value can be calculated. Longitude is also calculated using the value. Because with algebraic addition (taking into account the positive sign for eastern longitudes and the negative sign for western longitudes), the longitude of the turning node can be calculated.

b) The great circle distance from the departure point to the waypoint (DFX) and the great circle distance from the waypoint to the destination point (DX T) are given to the latitude of the waypoint (φX) and the difference between the longitude between the departure point and Calculate the waypoint (λFX) as shown in Figure 5-b.

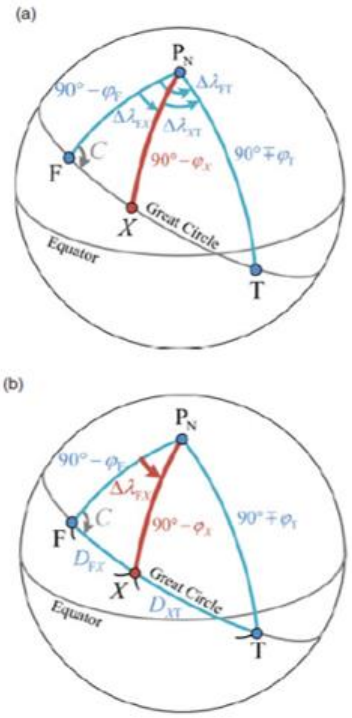

Figure 5. Finding the waypoints on the great circle track. Source: [6]

In the research method section, the use of combined triangle relationships was suggested in the following steps:

If the assumption of state A is true, we can directly obtain the latitude of the waypoint (φX) by using equation (3):

$$\tan\varphi X = \frac{\sin\Delta\lambda_{FX}\,\tan\varphi T + \sin\Delta\lambda_{XT}\,\tan\varphi F}{\sin\Delta\lambda_{FT}} \qquad (11)$$

Longitude will also be calculated based on the assumption of equality of longitude difference between rotation points. If condition b is established, we can directly obtain the latitude of the waypoint (φX) by using equation (6):

$$\sin\varphi X = \frac{\sin D_{FX}\,\sin\varphi T + \sin D_{XT}\,\sin\varphi F}{\sin D_{FT}} \qquad (12)$$

Then, by using the cosine law, the length difference between the departure point and the waypoint (λFX) can be obtained and converted to the longitude of the waypoint (λX).

$$\cos \Delta\lambda_{FX} = \frac{\cos D_{FX} - \sin \varphi F \sin \varphi X}{\cos \varphi F \cos \varphi X} \qquad (13)$$

In this research, using Hsieh et al.'s (2019) algorithm, a great circle route is divided into a number of mid-nodes that have equal distances from each other, assuming that state B is established. Figure 6 shows the division of a great circle route into 9 equal parts.

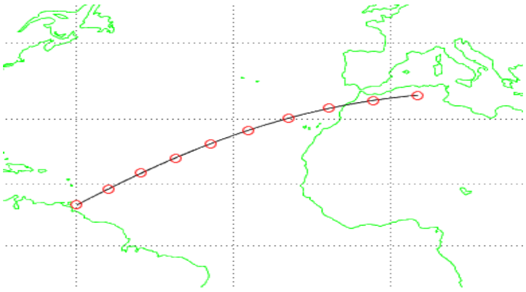

Figure 6. Dividing a great circle route with equal distances based on the algorithm of Hsuan Hsieh (2019). Source: Authors

3.2. Calculation of distance and course through the rhumb line route

When the departure and destination great circle route is drawn and the turning points on this route are calculated, then the route and distance between the turning points should be calculated. Here the relations of the great circle are no longer used, but the relations of the Rhumb line are used, which are navigable, and the purpose of the calculations in this part is to determine the course and distance of navigation between turning points.

After calculating the course and distance between the turning points, the algorithm of the table (1) is used. The perpendicular path is obtained by adding and subtracting 90 degrees from the true course. This step is given as step 3 and 4 in table (1). To calculate this part of this research, the calculator function is used for the course and distance between two points of departure and destination.

3.3. Calculation of the destination point with the course angle, distance and departure point

In this research, by calculating the course perpendicular to the great circle route, it is necessary to calculate the network nodes on these perpendicular courses. In this section, the position of network nodes is calculated using the destination point calculator function with course angle. In this function, the distance and the departure point are entered by the user as the input of the function, and then the destination point is requested. One of the requirements of this function is that the value of $dlat$ and should be calculated through the functions defined above.

$$\cos(Co) = \frac{\text{dlat}}{dis} \Rightarrow dlat = dis.\cos(Co) \qquad (14)$$

The main point is that the true course must be transformed into a quarter course, which is shown in Figure 3. By calculating the value of $dlat$ (the difference between the two latitudes of the departure and destination points) from equation (14) and having the latitude of the departure point, the latitude of the destination point can be obtained. Now, using the latitudes of the departure and destination, we calculate the value of the mean latitude.

$$mean\,lat = \frac{lat\,A + lat\,B}{2} \qquad (15)$$

Now we can calculate the value of dep using trigonometric relations.

$$\sin(Co) = \frac{\text{dep}}{\text{dis}} \Rightarrow dep = dis.\sin(Co) \qquad (16)$$

Now, by using dep and $mean\,lat$ value, we can calculate $dlong$, by having the length value of the departure point and $dlong$ value, the length of the destination point can be calculated, thus the latitude and longitude of the destination point are calculated. In this research, the set of relationships for calculating the destination point with the input values of the course angle, distance, and departure point in the form of a function, which is called the inverse function of the Rhumb line route, and the user can by providing the inputs of this function (departure point, course, and distance), calculate the geographic location of the destination point.

3.4. Network production

Generating a network around a great circle route is one of the main goals of this research. The network generation algorithm is given in table (1). Here is a scientifically programmed algorithm. For explanation, we consider the first four points of the route in Figure 6. These four points are connected by Rhumb line routes (black lines in Figure 6). The course and distance between points are calculated by the Rhumb line function. In the following, each Rhumb line route is considered separately. Next, to explain how to generate network points, for example, two points 2 and 3 in

Figure 6 are considered. The course angle between these two points is calculated, which is the black line between two points 2 and 3 (black line in Figure 7). According to the algorithm of Table 1, 90 degrees should be reduced and added from this course, and courses perpendicular to this route should be built, where the first, 90 degrees are reduced from the desired course, and the course with red color is created (Figure 7). Then, the inverse function of the Rhumb line route is used and two points on the red course route are calculated, each with a distance of 50 miles from the other; the same process can be continued for the desired number of points for the user. Then 90 degrees is added to the path between two points 2 and 3 (black line in Figure 7) and the blue path in Figure 7 is obtained. Using the inverse function of the rhumb line route, blue point number 1 is at a distance of 50 miles from black point number 2; in the same way, blue point number 2 is also calculated at a distance of 50 miles from the next point. The arrays holding the blue and red points are different, this means that the bottom and top half of the network are kept in two separate arrays. Therefore, in the following, it is necessary to place the lower and upper half of the network in a single array. The numbering method in the network unit array is such that the last point on the 90 degrees true course route (the same red route) is selected as the first point perpendicular to the route at each point. For example, in Figure 6, the red point number 2 is placed with number 1 in the unit array, then the red point number 1 is placed with number 2 in the unit array, then the middle point on the great circle route (black point number 2) is placed as point number 3. The unit array is selected and then the blue point number 1 is selected as point number 4 of the unit array. In the end, the blue point number 2 is selected as point number 5 of the unit array. In this way, all the lower and upper halves of the network are stored in a unit array.

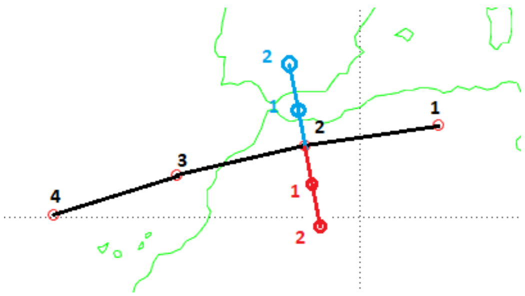

Figure 7. Generating the network around the great circle route. Source: Authors

3.5. Search in network nodes

After determining and calculating the network nodes, it is necessary to number the network nodes. Above is the numbering of the nodes in the upper and lower part of the track in a unit array. Therefore, in this section, a two-dimensional array has been obtained, one dimension of which is the number of each node on the great circle, and the other dimension is the number of the node perpendicular to that network node. In order to use search algorithms, it is necessary to convert the network around each great circle route into a graph. In each graph, all nodes must be numbered as a one-dimensional array. Therefore, the two-dimensional numbering method mentioned at the beginning of this paragraph should be converted into a one-dimensional numbering method. For this, the starting node as node number 1 and the rest of the nodes respectively from the departure to the destination and from the south of the route (the perpendicular route with the connecting course between the turning nodes minus 90 degrees) to the north of the route (perpendicular route with the connecting course between the turning nodes plus 90 degrees) degree) are numbered. In this process, an interface variable that relates the numbering index in the two-dimensional array to the numbering index in the one-dimensional array is also used.

For example, Figure 8 shows how to number points in a one-dimensional array. The starting point is number 1 and the first point on the routes perpendicular to the great circle is number 2, the endpoint of the first route perpendicular to the great circle is number 20, and the starting and ending points of the second route perpendicular to the great circle are numbers 21 and 39. The number of points perpendicular to the route of the great circle for the figure is 20 points; But in the numbering, it can be seen that numbers 2 to 20 are assigned to the vertical route. This is because the route point is shared with course minus 90 degrees (southern route) and course plus 90 degrees (northern route).

After numbering the network points, the connection matrix between the points must be created. This matrix has a value of 1 for connected points and a zero value **for points that are not connected. The dimensions of the** connection matrix are a square matrix with the same rows and columns and numbered by the total number of points. For example, if the total number of numbered points is 500 points, the connectivity matrix has dimensions of 500x500 (500 rows by 500 columns). The important point and optimization made in this article are related to the connection matrix. One of the easiest ways to connect between network points is to connect all points together and look for the optimal route among all these connections. Is it necessary to connect all the points of the network and create a matrix with the value of the unit entries? Or only considering the drawn route, the points that are along each other and can form a possible route are considered connection points. Definitely, the second solution is a better solution than connecting all the points together. It is natural that the higher the number of points connected to each other, the higher the calculation cost and the longer the program execution time. Considering the choice of the second solution to connect the points that are along each other to form the route, it is still possible to create optimizations for the performance of the program. For example, each point can be connected to" n "opposite points. Definitely, the smaller the value of " n ", the number of calculations will decrease. On the other hand, the decrease of " n " also causes the elimination of selectable routes by Dijkstra's algorithm. For this reason, the problem of optimization is not only limited to reducing calculations and also includes the correct result of calculations. In this research, a great circular route is divided into a number of points along the route and perpendicular to the route (Figure 8). Each row of points that is perpendicular to the great circle route has another row of points on the destination side. Therefore, it can be concluded that each vessel sails only between the points of these two rows. Here it is assumed that a ship in navigation can only sail from one row of vertical points to the next row of vertical points on the destination side and cannot sail to the row of rear points or two rows of points next to the destination. Applying this assumption will reduce the very large number of point connections in the connection matrix. It should be noted that this assumption is completely correct because a ship is sailing from the departure to the destination and there is no reason to bring displacement in the opposite direction of the route in the connection matrix, and a ship has to pass through the middle row to reach two rows after each row. Therefore, it can be seen that the assumption of sailing between two consecutive hypothetical rows is accurate and can cover all connection states in a shipping route.

Accepting the assumption of connection only between two consecutive rows, the next issue is the number of connection points between each point and the points of the next row. For example, each point in a vertical row can be connected to 5 points or 10 points, or all points in the next row. Of course, the number of connecting points between two rows is unexpected because it is almost impossible that the route from point 2 to 39 with this long distance is an optimal route compared to other connecting routes from point 2 to the row of points 21 to 39.

The optimization method for connecting points in two consecutive rows in this research is to connect the symmetrical points of each row on the route to the ship with" n " points of the next row. For example, point number 16 in figure 8 is connected with 8 points from the next row along the route. These 8 points that connect with point number 16 are points numbers 38, 37, 36, 35, 34, 33, 32, and 31, if the number of 10 points is considered for connecting point number 16, points numbers 39 and 30 are also added to this connection. In border areas such as points numbers 2 and 20 in the first row of the network, the full connection of 8 points is not established because in the algorithm used, the symmetry of the connection between the points in each row with the next row is considered. For example, in Figure 8-b, point number 12 is connected to 8 points in front of it with 4 northern points (green connection with point number 12 in Figure 8) and 4 southern points (blue connection with point number 12 in Figure 8). In the border points like points numbers 2 and 20, the symmetrical connection is not applicable, and therefore the points on the southern border are connected with half of" n " northern points (point number 2 is connected with four northern points) and the points on the northern border are connected with half of n southern points. (point number 20 on the northern border of the first row is connected with its 4 southern points, Figure 8-b).

Next, for optimization, the network is created around a great circle route, and the execution time of the program is recorded based on " n " (the number of connections of each point with the points of the opposite row). For this purpose, various separations have been tested around the great circle route. The first test was tested with a resolution of 12x12 (12 points along the route and 12 points perpendicular to the route). The number of connection points for separation of 12x12 is selected as " n "equal to 8 and 16. Table 1 shows the execution time of the program for different separations for each value of " n ".

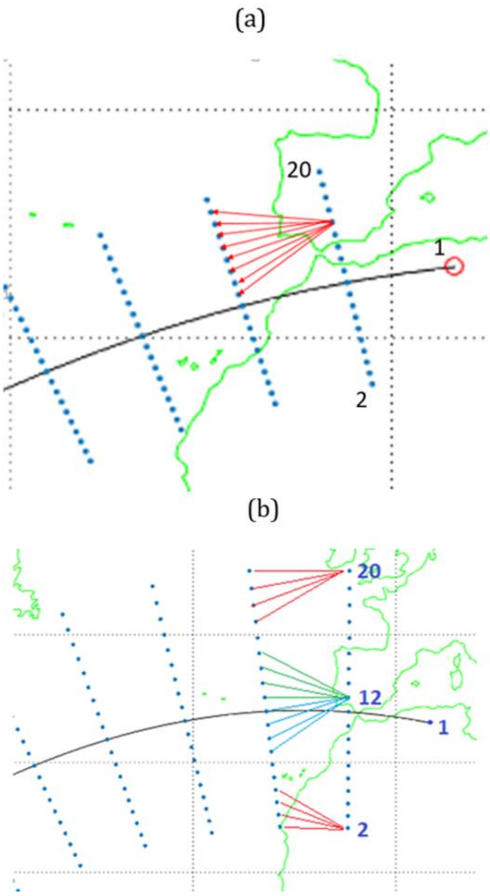

Figure 8. How to search for network points
Source: Authors

Table 1. The execution time of the program for the network with Different segregations on the great circle route for different connection values

Execution time (seconds)	Number of connections	n	Separation
0.574619	1693	8	12×12
0.674543	3133	16	12×12
0.601494	2902	8	15×15
0.796028	5542	16	15×15
1.111746	13807	8	30×30
1.119315	27847	16	30×30
1.133519	40537	8	30×30
3.716961	40947	16	50×50
3.817885	84187	8	50×50
3.849923	1255077	16	50×50

Source: Authors

3.6 Search through Dijkstra's algorithm with a cost function

Dijkstra's algorithm is used to find the shortest routes between vertices in a graph [16]. There are different types of algorithms. The original type finds the shortest paths between two nodes, but the more common type fixes a vertex as the source and finds the optimal route from the origin to all other vertices in the graph, generating the shortest path among all possible vertices. In this research, the simple cost function is used; Because in this research, the emphasis was on routing and network generation. The methods of optimizing the search on network points and calculating the great circle with up-to-date methods have been among the goals of this research. Therefore, in this research, the simple cost function, which is the distance between network points, has been used.

By implementing all the above algorithms and considering the simple cost function of the distance between points for two points of departure and destination in Figure 9, the optimal route (red circles in Figure 9) among network points (blue points in Figure 9) is calculated from departure to destination. The optimal route with the minimum distance cost function corresponds to the same great circle route (black line in Figure 9), which indicates the correctness of all the calculation algorithms in this research.

In Figure 10, the optimal route (red circles in Figure 10) is calculated between network points (blue points in Figure 10) from point 2 of the network to the destination, and in Figure 11, the optimal route (red circles in Figure 11) Among the network points (blue points in Figure 11), it is calculated from the 20th network point to the destination.

In all three cases, it can be seen from the experiment of the numerical scheme that calculates the optimal route that the correct result is obtained and the route with the minimum distance between two points is always calculated.

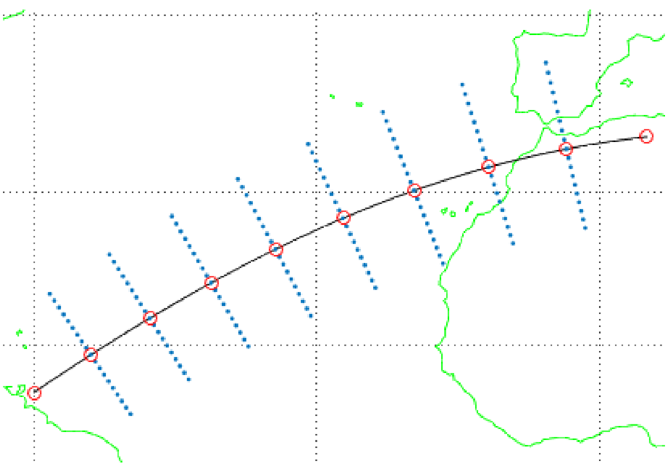

Figure 9. The optimal route between departure and destination points with a distance cost function
Source: Authors

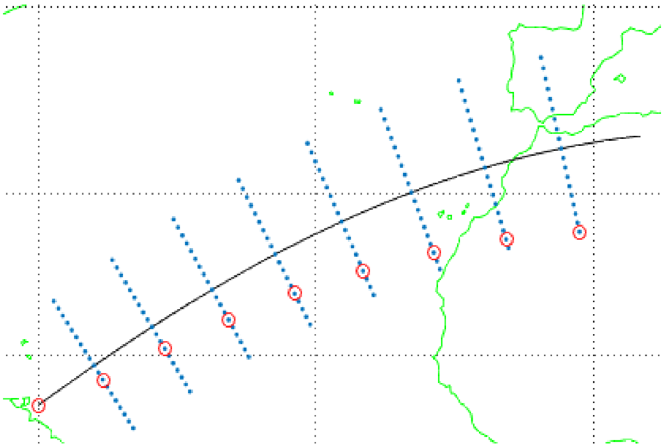

Figure 10. The optimal route between the 20th network point and the destination point with a simple cost function. Source: Authors

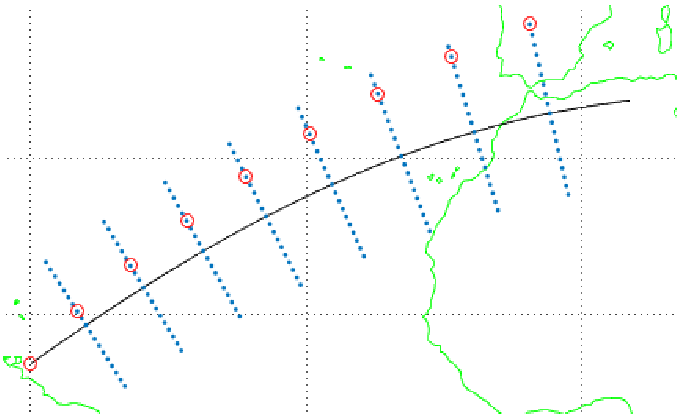

Figure 11. The optimal route between the second network point and the destination point with a distance cost function. Source: Authors

4. Conclusion

In this research, weather routing with a simple cost function is studied. This research is an applied research and is based on the operational aspects of weather routing. Weather routing includes several algorithms and functions, and each of these algorithms and functions have been collected and used from independent articles.

Weather routing consists of two major parts: routing and weather. Routing in this algorithm includes two types of routing: great circle and Rhumb line. The application of great circle routing includes the main route from the departure to the destination and the formation of intermediate points. In short distances below 600 miles, the two great circle and Rhumb line routes will end in the same result, but in longer distances, the great circle route will be shorter than the Rhumb line route.

The great circle method is used in routing even in distances less than 600 miles. One of the important points in the great circle method is that the route must be divided into an equal number of turning points. Of course, it is better that the distance between the turning points is equal to each other, in order for the distance between the turning points to be the same, a comprehensive search has been done in research articles in this field, and most of the methods use the same longitude differences as the criterion, which necessarily means the same longitude difference It does not mean that the distance is the same because the distance between the two rotation points is a function of the geographic latitude difference, which is not taken into account.

In one recent research, Hsieh et al. (2019) used the method of combined triangles, and the use of this method in routing a great circle will lead to the production of turning points with equal distances. Therefore, this method has been used in this research and the routing of the great circle has been converted into more triangles using combined triangles, and finally, the position of the turning points will be calculated.

The second component of routing is generating a network of points on the great circle route. To generate network points, it is necessary to use the Rhumb line method, because the distance between network points is often less than 100 miles, and using the Rhumb line method will produce favorable results. To generate network points, the route and distance between the turning points are calculated and the perpendicular route between two consecutive turning points is calculated, then network points are created at equal distances from each other on the route perpendicular to the turning points, in this research, 50 miles for Spacing between network points on the vertical route is used. After generating the network points around the great circle route, the numbering of these points should start from the departure point and under the route (the route less than 90 degrees to the course between the two turning points) and continue until the destination point. After numbering the points, it is necessary to create a graph and connect the network points. In this research, each point of the network is connected with 10 points from the front points towards the destination, the choice of 10 points is because the program does not search for more connections and to optimize the search in the network. Of course, there is a qualitative reason for this choice, and this qualitative reason is that the 10 destination points towards each network point are the closest network points to that point, and therefore, they are considered to have the highest probability of being optimal. This method will lead to a significant reduction in the number of calculations.

Dijkstra's method has also been used for the search method. This method searches all network nodes and connections and estimates the cost of reaching the destination from various routes. Finally, by searching all the available routes, it can obtain the optimal route with the minimum cost function.

In this research, the simple cost function of the distance between network nodes is used, so by searching the network nodes by Dijkstra's algorithm from the departure point to the destination point, the same great circle route is obtained. By calculating the great circle route between the departure and destination points, it can be concluded that the weather routing algorithm works correctly and calculates the optimal route according to the selected cost function.

One of the practical suggestions for future research is that by applying meteorological data on network nodes and defining a newer cost function, it can increase safety or save money in ocean navigation.

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Authors contributions

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