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Minimizing sailing time weather route optimization method for unmanned ship based on intelligent water drops algorithm

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Abstract—**Route is an important factor for safe and efficient navigation of ships. In this paper, the unmanned ship navigation under complex marine meteorological conditions was analyzed.The wind, wave and ship's own conditions were integrated considered. The unmanned ship route energy consumption and voyage time dual objective optimization model based on ideal point method was established. The meteorological and hydrological information for the route were analyzed in this model. Route optimization criteria and dual-objective programming algorithm were combined. The unfavorable influences of meteorological and hydrological were reduced. The energy consumption and voyage time of the ship were saved. And the route was found. The results showed that the great circle route can be obviously optimized in the model. The model can be applied to the weather route planning of unmanned ships in large area under complex meteorological conditions.**

Index Terms— **Minimizing sailing time; unmanned ship; water drops algorithm; weather route**

I. Introduction

With the rapid development of the ship transportation, the global meteorological route has become an important research content to ensure the safe and efficient navigation of unmanned ships. Safety and economy are two indicators to meature the route. The economy of the route was affected by navigation time. Marine meteorological information is considered in the process of route design. Not only severe wind and wave area is avoided, but also the route with the shortest sailing time and the most economic benefit is realized. Ship usage is increased and the operating costs are reduced. Therefore, the research has a strong practical significance for guiding the design of weather routes.

On the research of The shortest sailing time weather route optimization method, Zhang Hao[1] proposed an improved algorithm for automatic generation of shortest time routes based on instantaneous water depth model. Invalid point definition and dynamic envelope rectangle strategy were utilized. Search efficiency of the minimizing time route was improved. The route was found. Fang et al [2] considered land boundaries, effective wave heights and engine speeds. The 3D correction isochron method of the ship's track floating network system was used to design the weather route. Mannarini et al [4] designed a route model based on sea state forecasting. The model can be used to optimize navigation time with optimizing speed to resist wave resistance and loss of ship stability. Padhy et al [5] used Dijkstra algorithm to calculate the shortest time route in known sea conditions by calculating the wind, wave and current on the navigation of the ship.

The shortest sailing time weather route optimization method for unmanned ship based on intelligent water drops algorithm was proposed in this paper. The impact of meteorological on navigation was analyzed. Combined with the hull's own condition, the speed and range of the ship were calculated. Under the assumption that the ship's own output power was fixed, the ship's heading was appropriately changed with adjusting the position of the original waypoints on the great circle route. The marine environment was utilized as much as possible. The actual speed was increased within the critical speed range of the ship. The shortest time global weather route was output after the algorithm iterated multiple times.

II. Method

A. Principle of the shortest sailing time weather route

Weather routes are the most accurate marine environment forecasts, combined with ship performance, loading characteristics, technical conditions and other factors, to select the best weather route recommended for ships across the ocean. Safety and economy are two indicators to meature the route. The sailing time of the ship is determined by the voyage and speed. However, during the actual voyage of the ship, the speed of the ship is affected by the hydrological environment near the route. Wind waves at any angle make the speed of the ship lost. The core of the shortest sailing time weather route is that the waypoints being laid out. Unfavorable factors such as wind and waves are avoided. The ship windward angle is changed. Thereby the loss-speed and the sailing time of the ship are reduced.

As shown in Figure 1, the earth was approximated as a sphere. Make a plane through point A and point B on the surface of the earth and the point O of the earth. The circumferential line $\widehat{AB}$ obtained by intersecting the plane with the surface of the earth was the great circle route. The great circle route is the shortest route between two points on the earth's surface.

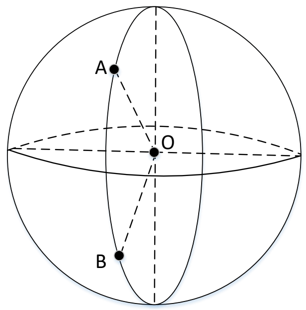

Figure 1 Schematic diagram of the big circle route

As shown in Figure 2. First of all, the great circle route between two points was generated. The large circle route was discretized to obtain the initial waypoints data. Secondly, according to marine meteorological data and optimization criteria, the optimization algorithm was combined to adjust the position of the waypoint. Finally, the adjusted waypoints were connected to generate new routes. The navigation time of the route generated by the algorithm after multiple iterations tends to converge. The route is the the shortest sailing time weather route.

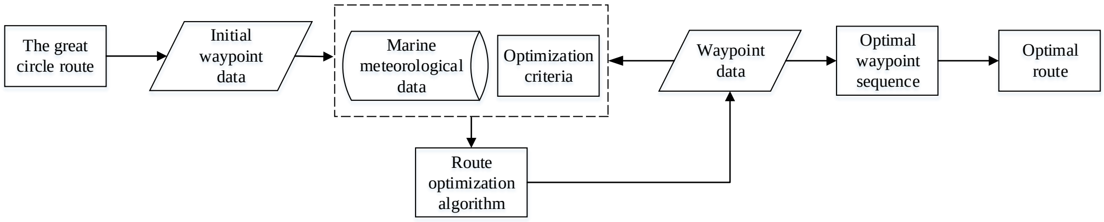

Figure 2 Flow chart of the route being optimized

Set $N-1$ waypoints from the start point to the target point. It meant that the entire route was consisted by N constant lines. The output power of the ship's main engine was constant on the route. The sailing time on the route was:

$$\begin{cases} t = \sum_{i=1}^{N} \frac{S_i}{v_i} \\ v = f(v_0, v_{wind}, h) \end{cases}$$

Where, total sailing time of the voyage was t, length of the i-th constant line was S_i, actual speed of the ship was v, the actual speed of the ship in the i-th segment was v_i, ship still water speed was v_0, wave height was h, wind speed was v_{wind}.

It was necessary to determine the critical speed of the ship in the wind and waves. Routes whose actual speed exceeded the critical speed should be avoided. Therefore the formula provided in literature[15] was used to calculate the critical speed of the ship.

$$\begin{cases} v_{\max} = e^{0.13}[u(q)-h]^{1.6} + r(q) \\ u(q) = 12.0 + 1.4 \times 10^{-4} q^{23} \\ r(q) = 7.0 + 4.0 \times 10^{-4} q^{23} \end{cases}$$

Where, Ship critical speed was $v_{\max}$, Relative wave direction was q. Among them, q was the angle between the direction of travel of the ship and the direction of the wave.

Therefore, the minimizing time route optimization objective function is:

$$f = \begin{cases} \min \sum_{i=1}^{N} \frac{S_i}{v_i} \\ \max v_i, v_i \in [0, v_{\max}] \end{cases}$$

B. Minimizing time model of unmanned ship global route based on intelligent water droplet algorithm

The intelligent water droplet algorithm [16] is that water flowing in the natural to wash the sediment and form a canal being simulated. As shown in Figure 3, soil A contains more sediment than soil B. When two water droplets with identical properties flow through the above soil at the same time, the water droplets are more likely to select soil B with less sediment. When the water droplets run until time $t+1$, as the soil hinder the water droplets from gaining a greater speed increment, the water droplets on the soil B will be gained a greater speed increment, scoured and taken by more sediment. Thus faster speed and larger volume were obtained by water droplets. When iteration completed, the amount of sediment in the soil has been updated. Thereby increase the probability that the optimal path was selected in the next iteration. The path with the minimal amount of sediment was the minimizing time route after the iteration of the algorithm.

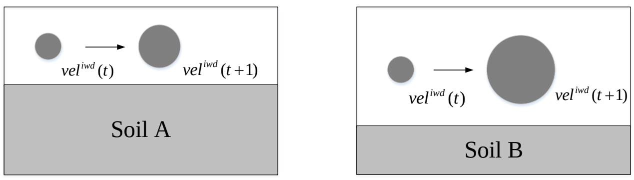

Figure 3 Schematic diagram of water droplet movement

Assumed that the sailing time between the two route points i and j was the sediment amount $soil(i,j)$, water droplet speed was $vel(i, j)$. As shown in Figure 4, a great circle route was generated between the two points after the start point and the target point determined.

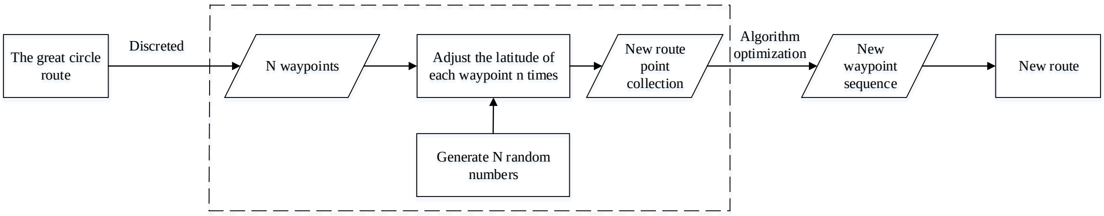

Figure 4 Route point adjustment strategy flow chart

As shown in Figure 5, water droplets depart from waypoint i. The next adjacent waypoint on the original route was j. Generated n new waypoints after the original route were disturbed. Water droplets tend to through the path with less sediment when the path was selected. $p(i,j)$ was expressed as the probability that the water droplet at position i selects j as the next position. The probability formula for a node to be selected was:

$$p(i, j) = \frac{f(soil(i, j))}{\sum f(soil(i, j))}$$

$$f(soil(i, j)) = \frac{1}{\varepsilon + g(soil(i, j))}$$

Where, minimal positive real number was ε, which prevented the denominator to being zero.

$$g(soil(i, j)) = \begin{cases} soil(i, j) & \min(soil(i,k)) \geq 0 \\ soil(i, j) - \min(soil(i,k)) & else \end{cases}$$

Where, k was all nodes that may be selected by water droplets, $k \in [1, n]$.

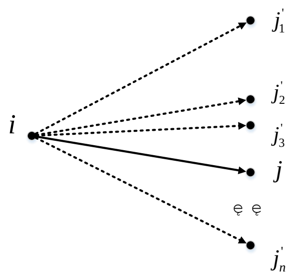

Figure 5 Schematic diagram of water droplet optimization

The speed increment Δvel of the water droplet was nonlinearly inversely proportional to the sediment content $soil(i, j)$ of the path (i, j). Δvel was calculated by the following formula:

$$\Delta vel = \frac{a_v}{b_v + c_v \cdot soil(i, j)}$$

Where, a_v, b_v and c_v were custom coefficients. The value of a_v was generally small to prevent the denominator from being zero. $a_v = 1$, $b_v = 0.01$, $c_v = 1$.

The amount of sediment $\Delta soil$ that was washed away by water droplets was nonlinearly inversely proportional to the time variable $time(i, j, vel)$ required for the water droplet to pass through path (i, j), equal to the amount of sediment $\Delta soil(i, j)$ reduced by path (i, j).The expression was as follows:

$$\Delta soil(i, j) = \Delta soil$$

$$\Delta soil(i, j) = \frac{a_s}{b_s + c_s \cdot time(i, j, vel)}$$

Where, a_s, b_s and c_s were custom coefficients. The value of a_s was generally small to prevent the denominator from being zero. $a_s = 1$, $b_s = 0.01$, $c_s = 1$.

$time(i, j, vel)$ was the time for the water droplet to move from position *i* to *j*. It was shown as follow:

$$time(i, j, vel) = \frac{HUD(i, j)}{vel(i, j)}$$

Where, $HUD(i, j)$ was the heuristic function of the road segment (i, j). In the algorithm, $HUD(i, j)$ was interpreted as the distance between two waypoints.

When the water droplets were from *i* to *j*, the amount of sediment contained in the path (i, j) will be updated to form a feedback mechanism for the movement of other water droplets. The sediment content of path (i, j) was updated as follows:

$$soil(i, j) = (1 - \rho) \cdot soil(i, j) - \rho \cdot \Delta soil(i, j)$$

Where, ρ was a coefficient between 0 and 1.

III. Results

A. Data processing and Calculation

Wind farm data on March 2010 was selected. The data[6] came from the Scattermeter Climatology of Ocean Winds website published by Scattermeter Climatology of Ocean Winds. In the range of latitude -69.875 ° ~ 69.875 °, longitude 0.125 ° ~ 359.875 ° raster map was obtained after reading the wind field data. Wind direction and speed data from longitude and latitude components were recorded. As shown in Figure 6, the horizontal axis of the graph was represented as latitude, the vertical axis was represented as longitude, the gray region was represented as land, and the numbers under the colored horizontal bars below the figure were expressed as wind speed. The wind speed unit was $m \cdot s^{-1}$. In the figure 6, the wind speed in the ocean area was corresponding to the color in the horizontal bar. The distribution of wind fields throughout the marine environment can be observed in the figure.

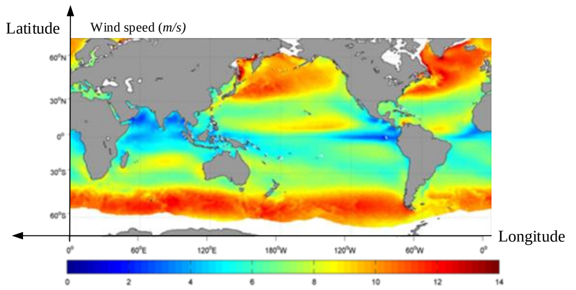

Figure 6 Global wind speed distribution map for March 2010

The wind direction at a grid point was calculated from the wind direction data on the longitude and latitude components. The formula for wind direction calculation was:

$$\alpha = \arctan\frac{Lon}{Lat}$$

Where, wind direction angle was α, longitude direction wind value was Lon, latitude direction wind value was Lat, the range of angles obtained by this formula was $[-\pi, \pi]$.

The wind direction was measured as the positive direction of the x-axis, and the measured reference of the ship's heading C was the positive direction of the y-axis. Both of them had an angle range of $[0, \pi)$. Therefore, it was necessary to adopt a unified measured basis and method for the wind direction and heading. Firstly, the metrics was changed as $\alpha = \frac{\pi}{2} - \alpha$. Thus the benchmark of the wind direction was changed to north. The measured range was became $[-\frac{\pi}{2}, \frac{3\pi}{2}]$. Secondly, the measured range was changed as $\alpha = rem(\alpha + \pi, \pi)$. The $\alpha = rem(\alpha + \pi, \pi)$ function acted as:

$$\alpha = \begin{cases} \alpha & \alpha < \pi \\ \alpha - \pi & \alpha \geq \pi \end{cases}$$

The hull upwind angle β refers to the angle between the ship's heading C and the wind direction α. The Cartesian coordinate system was established as shown in Figure 7. The positive direction of the y-axis was specified as north. According to Figure 7, the formula for the upwind angle was:

$$\beta = \left| \, 180^\circ - |C - \alpha| \, \right|$$

Where, wind direction angle was α, ship's heading was C. The range of angles obtained was $[0, \pi)$.

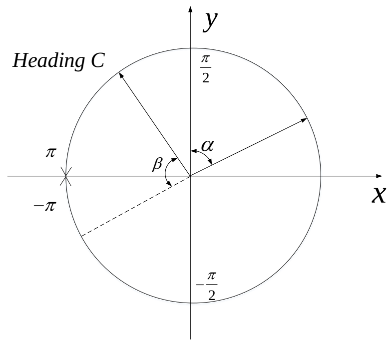

Figure 7 Wind direction calculation diagram

To ensure the accuracy of the wave data, the following formula was used to calculate the wave height according to literature[6]:

$$h = \frac{0.7\left(\frac{gF}{v_{wind}^{\ 2}}\right)^{\frac{1}{3}} \times v_{wind}^{\ 2}}{g}$$

Where, gravity acceleration was *g*, *g*=9.8m/s. The length of the wind zone was *F*. The length of the wind zone refers to the area of the sea where the wind condition was almost the same.

Unmanned ships were shown loss-speed affected by meteorological and hydrological factors during the voyage. Among the various factors, the ship was particularly affected by wind and waves. The resistance of the ship during navigation was far greater than the resistance it receives in still water. This phenomenon was known as loss-speed. The following formula was used to calculate the wave height according to literature[9]:

$$v = v_0 - (a_1 h - a_2 qh + a_3 v_{wind} cos\beta)(1 - a_4 D v_0)$$

Where, ship actual speed was v, ship still water speed was v_0, wind speed was v_{wind}, wave height was h, ship upward angle was β, ship displacement was D, undetermined coefficient was a_1, a_2, a_3, a_4. To simplify the calculation, the wave direction was assumed to be consistent with the wind direction. Therefore, the relative wave direction q was consistent with the hull upward angle β.

B. Model Simulation

The start port and target port established in this paper were Japan Yokohama Port (34°40'N, 140°E) and the US Long Beach Port (34°25'N, 120°W). The wind field data for March 2010 was used to solve the shortest sailing time weather route optimization model. The number of waypoints N was set to 10. Initial waypoints table 1 was obtained. The great circle route was improved to solve the route of the unmanned ship based on the intelligent water droplet algorithm.The shortest time weather route based on the intelligent water droplet algorithm was expressed by *IWD* below.

Table 1 Initial waypoints latitude and longitude value

Waypoint number	1	2	3	4	5
Latitude values	34.7	39.20965	42.88555	45.50392	46.86084
Longitude values	140	149.3015	159.7502	171.3163	-176.277
Waypoint number	6	7	8	9	10
Latitude values	46.83193	45.41999	42.75384	39.03933	34.5
Longitude values	-163.562	-151.181	-139.657	-129.256	-120

The container ship "Long Lin" was selected for the simulation ship. The parameters in the ship stall formula were solved by iterative method through the parameters. So the formula of ship loss-speed was:

$$v = v_0 - (1.08h - 0.126qh + 2.77v_{wind}cos\beta)(1 - 2.33Dv_0)$$

The initial parameters of the intelligent water droplet algorithm were shown in Table 2. t was the sailing time between the two waypoints.

Table 2 Intelligent water drop algorithm parameters table

Parameters	symbols	walues
Number of water drops	N^{iwd}	50
Number of iterations	$Itermax$	100
Initial sediment amount	$initsoil$	t
Initial velocity of water droplets	$initvel$	100
Water droplets contain initial sediment	$soil^{iwd}$	0

The simulation platform was MATLAB R2016a. The waypoints sequence of the shortest sailing time route obtained by the intelligent water droplet algorithm was shown in Table 3. The algorithm was run 100 times. The average running time of the algorithm, the voyage of the route and the sailing time were counted in Table 4.

Table 3 waypoint latitude and longitude values of the shortest sailing time route

Waypoint number	1	2	3	4	5
Latitude values	34.7	39.625	44.625	47.625	48.625
Longitude values	140	149.625	161.625	171.125	-175.875
Waypoint number	6	7	8	9	10
Latitude values	47.125	46.625	42.625	42.375	34.5
Longitude values	-161.625	-149.625	-139.875	-129.125	-120

Table 4 Simulation statistics results

Name	running time (s)	total voyage (km)	Sailing time(h)
IWD	61.074776	8735.8216	260.58

IV. Discussions

A. Model verification

The model respectively designed by the great circle route, random iterative algorithm and artificial fish swarm algorithm were run in the same environment in order to confirm the superiority of the shortest sailing time route model based on the intelligent water droplet algorithm. The results were compared with the model based on *IWD*. The shortest sailing time weather route based on the random iterative algorithm and artificial fish swarm algorithm were separately expressed by *RIA* and

AFSA below.*GCR*, *AFSA*, *RIA* and *IWD* were separately indicated by blue, red, green and cyan-blue line in Figure 9.

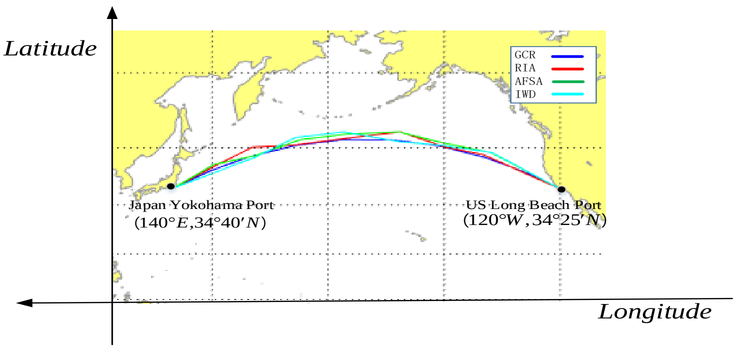

Figure 9 route diagram

GCR, *IWD*, *AFSA* and *RIA* were simulated 100 times respevtively. The results were shown in Table 5.

Table 5 Comparison of route results

Route	voyage（km）	Sailing time(h)	Algorithm average time consuming (s)
GCR	8698.7359	273.62	4.21
RIA	8766.3267	270.53	56.85
AFSA	8711.2147	265.21	68.16

According to the results in Table 5, time consuming of *GCR* was just 4.21s, which voyage was 37.0857km less than the *IWD*, but the sailing time was 13.04h more. The results meant that *IWD* had a significant effect on the improvement of the original waypoint sequence and the optimization of sailing time. The average running time of the *IWD* was 9.58s higher than the *RIA*, but the voyage and sailing time were decreased 30.5051km and 9.95h respectively, which were shown that *IWD* had higher superiority to *RIA* for solving the minimizing time route model. The average time of the intelligent water droplet algorithm was just 1.73s lower than the artificial fish algorithm, and the advantage was not significant. The voyage of *AFSA* was relatively short, but its sailing time was 4.63h higher than *IWD*. The results showed that *IWD* had a better solution for the problem of the shortest sailing time route.

B. Comments

Static ocean meteorological information was used in the model. When the unmanned ship was on sailing, the route cannot be automatically adjusted according to the real-time meteorological information, and the shortest sailing time route cannot be achieved. That was why route dynamic adjustment strategy should be further researched. In order to reduce the complexity of the model, the ship's output power was assumed constant. But the marine environment was complex and changeable in the actual navigation of the ship. "Deceleration" or "speed increase" was selectively implemented under the premise of ensuring the safety of the ship. The route might be changed once the output power of ship had changed, and the original route was no longer the shortest time route. So the secondary planning of the route should be redesigned after the ship's power changed. Ship loss-speed data was calculated based on a hypothesis that wind direction was consistent with wave direction. Although the wave data in this paper was reckoned from the wind speed and direction, but strictly speaking, the wave direction did not entirely depend on the wind direction, but also the change in air pressure and the inertia of the waves. The latter two factors had less influence on the direction of the wave, so the wave direction was temporarily approximated, which had little effect on the calculation of ship loss-speed. The probability that the next waypoint was selected by the water droplets can be calculated from the wind wave data in the solution process of the model. The amount of sediment was updated after the water droplets had passed through the path. At the same time the current waypoint was selected, the probability that the next water droplet selects the waypoint was increased, while the possibility that other waypoints were selected by others water droplets was retained, and the local optimal solution was avoided. In addition, the results of the *IWD* were compared with *GCR*, *RIC* and *AFSA*. Simulation results showed that the sailing time of *IWD* was 4.77%, 3.68%, and 1.75% respectively less than the other three routes, which was proved that the problem of the shortest sailing time weather route solved by *IWD* was better.

V. Conclusion

The navigation environment of unmanned ships under complex marine meteorological conditions was analyzed in this paper. Marine meteorological conditions, especially wind, waves and other factors were integrated considered. The shortest sailing time global weather route model of unmanned ship based on intelligent water droplet algorithm was established. The impact of the ship's own conditions and external meteorological factors on the navigation of the ship were analyzed on the basis of the great circle route. The sailing environment was reasonably reacted. Intelligent water droplet algorithm was used to solve the shortest sailing time route model. The purpose of shortening the sailing time was achieved. This model can be used to design the shortest sailing time route. Global route decision method under complex marine meteorological conditions was provided.

VI.References

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