Ships Route Searching with Respect of Sea Waves Danger

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Abstract. The problem of marine traffic safety is discussed in this paper. The problem of ships path planning taking into account heavy weather conditions (sea waves) along the route is considered. As a metric characterizing the safety of traffic, a well-known storm diagram of ships at a passing wave is used. According to it, the level of danger is determined from the data on height and wavelength. The route is formed as a result of solving the problem of finding the shortest path on a weighed graph. As a source of meteorological data, satellite monitoring information is used. It is shown that in spite of the roughness of the initial data, they are able to give a practical solution for choosing the trajectory of the vessel's motion. The work is accompanied by the results of full-scale experiments. The results of the assessment of the vessels safety and path planning in the waters of the Sea of Japan are presented.

1. Introduction

Ensuring sea traffic safety is an urgent, complex and multi-perspective problem. Within this problem the following tasks for route planning are picked out: ship's path in the local area and the route of the passage from the port of departure to the port of destination. The purpose of the ship's path in the local sea area is to ensure navigational safety in conditions of collective traffic [1]. The main task of route planning is traffic optimization, e.g. sailing along the shortest possible route within the shortest time and with the minimum fuel consumption etc. [2].

Weather conditions along the ship's route considerably affect the choice of its route as a pattern of movement in stormy conditions greatly differs from the one in calm weather. Both de-termination of wave parameters, when its unfavorable effect becomes considerable, and plot-ting of a route to avoid dangerous zones are important components of the navigator's work. The use of information provided by special meteorological services according to satellite monitoring data is promising. Integration of some meteorological satellite data can give an adequate picture of current and predicted weather conditions [3].

The present work studies the problem of route planning taking into account information on sea wave parameters: the wave height and length. The mathematical model of the problem is based on the search of the shortest route in the weighed graph and on the conception of the industry concerning
evaluation of safety of navigation shown by storm patterns [4]. The result of the problem solution allows choosing the ship's route ensuring the traffic safety.

2. Basis model conceptions
Basic sea wave parameters, which are taken into account in such evaluation of its danger, are the height $h$ and the length $\lambda$ of waves, direction and rate of their propagation, the ship's length $L$, course and speed of its movement. Thus, wave length-to-ship's length ratio $\lambda / L \in [0.7 \div 1.3]$ is considered to be unfavourable, but with certain (depending on the ship's size) values of the wave height it is dangerous. Figure number 1 shows areas of wave length-to-ship's length ratio and medium wave height $h_{med}$-to-predicted wave height ratio $h_{calc} = 0.22L^{0.175}$, when adverse effect of the following waves on the vessel is considered to be appreciable.

![Figure 1. Storm pattern on the following wave.](image)

The inner (shaded) polygon is the area of the most dangerous waves for the ship; a degree of danger increases as the ratio $\lambda / L$ approximates 1 and the wave height grows. The external polygon corresponds to unfavorable values of sea wave parameters. In this case its safety should be as-sessed with the help of storm patterns [4].

Within the studied problem it is suggested to use the coordinate system $xy$, where the axis of abscesses $x$ corresponds to the geographical longitude, while the axis of ordinates $y$ to the geographical latitude of the ship. The level of wave danger $u(x, y)$ corresponds to every point of the sea area with coordinates $x, y$. When the ship follows the path given in the curve $q$, it is affected by waves described by a curvilinear integral of the first type

$$U = \int_{q} u(x, y) dq$$

To calculate this integral it is easier to present it as

$$U = \int_{q} u(x, y) dq = \int_{t_1}^{t_2} u(x, y) \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$$

(2)

Here $t_1$ and $t_2$ represent the time of the beginning and end of the ship's movement along $q$ curve.

Let us assume that the optimal path of the ship’s movement out of the multitude of possible ones is the curve $q_*$, ensuring minimum of the functional $U$, thus

$$q_* = \arg \min_{q} U(q)$$

(3)

Solution of the problem with the help of mathematical methods of physics, calculus of variation or dynamic programming [5] is characterized by high computation complexity. Therefore the present
work suggests that it should be interpreted by the search of the shortest route on the weighed graph. This method proved itself in problems of navigation [6,7].

The studied sea area is presented as a multitude of \( N \) points \( p_i \) with coordinate's \( x_i, y_i \). The point \( p_1 \) corresponds to the start of the route. One of the points \( p_N \) corresponds to the final point of the route. The weight of the graph verge \( d_{ij} \) joining points \( p_i \) and \( p_j \) corresponds to the functional (1) in assumption of a rectilinear motion.

Thus, a problem can be posed to break up a section of the surface by vertices of the graph \( p_i \), to determine a multitude of cortège of the vertices \( \{ p_1, \ldots, p_N \} \), providing the shortest route in the given graph taking into account the accepted metrics \( d_{ij} \).

2.1. Breaking up the graph by vertices

Let the multitude of possible ship's routes lie on the plane \( xy \) inside of the square with the side equal to the length of a segment with vertices in initial and final points of the route (\( p_1 \) and \( p_N \) respectively). The point \( p_1 \) lies in the middle of the square side while point \( p_N \) is in the middle of the opposite side (i.e. segment \( p_1p_N \) divides the square in two. The square is filled with points in order to form the correct rectangular grid. Let \( n \) be a number of points breaking up a segment \( p_1p_N \), while \( m \) is a number of point lines on the right and on the left of this segment. Then \( mn+n \) is a number of points lying inside of the square, and a total number of graph vertices taking into account the beginning and end of the route is equal to \( nm+n+2 \).

2.2. Determination of a multitude of graph verges

The simplest multitude of graph verges is a case when every vertex is connected with each other obtaining \((nm+n+2)(mn+n+2)/2\) verges. For longer routes, where \( n \) is big, it leads to unjustified increase of time for searching the shortest route. A number of verges can be decreased considerably taking into account a specific character of navigational practice. The vertices of the graph lying on segments perpendicularly to segments \( p_1p_N \) will be called layers of vertices. It is made a condition that only transitions from one layer of vertices to the next nearest one are possible, while motions between vertices of the same layer or between vertices of far staying layers are prohibited. Keeping in mind that there are \( n \) layers having \( m+1 \) vertices in each one as well as vertices of the beginning and end, a number of verges becomes equal to \((n-1)(m+1)^2+2(m+1)\).

2.3. Search of the shortest route in the graph

Peculiarity of the studied problem is presence of prohibited sailing areas stipulated by geography in the area. In case one of the vertices or a part of its verge finds itself in a prohibited area (e.g. land), the weight of the verge is assumed to be equal to infinity. In other cases the weight of graph verges is given according to the metrics (1). Search of the shortest route from the vertex \( p_1 \) up to the vertex \( p_N \) can be made with the help of any known algorithm of general purpose (Dijkstra, Bellman-Ford and others).

3. Results of field studies

Results of calculations in accordance with data on sea waves are presented below. The data were obtained in compliance with results of satellite monitoring. The danger level of sea waves was given in accordance with the diagram in picture 1 as follows: if a point lies inside the inner polygon in figure 1, then \( u = 10 \) (high degree of ganger); if a point lies outside of the external polygon in figure 1, then \( u = 1 \) (safe sea waves); if a point lies inside the external polygon in figure 1, then \( u \) takes on a value within the range from 1 to 10 proportionally to the distance up to the limits of external and inner polygons. Search for the shortest route in the graph is made with the help of Dijkstra Algorithm.
Figure 2 shows calculation results of the safest route for a vessel of 70 meters long moving from the Tsushima strait to La Pérouse strait according to meteorological data dated 23 January, 2018. Figure 2a demonstrates values of medium wave height, figure 2b presents danger levels of following sea waves which conform to the diagram in figure 1. You can also find results of route calculations when breaking up the graph vertices for $n = 30$, $m = 40$ (a red line with points). Medium wave height in some areas reaches 4-6 meters (yellow, orange and red zones in figure 2a). A great part of the water area is characterized by a high level of danger (inner polygon of the diagram in figure 1 is a dark red zone, figure 2b). It is clear that a sea wave character mainly makes the ship’s movement along the coast relatively safe. The ship can not avoid a zone of dangerous sea waves, and a part of the route passes across a dangerous section.

Figure 2. Calculation results of the safest route for a vessel which is 70 metres long. (a) on the background of data on wave height, (b) on the background of danger level values.

Figure 3. Calculation results of the safest route for a vessel with the length of 130 metres. (a) on the background of data on wave height, (b) on the background of danger level values.
Figure 3 shows analogous calculation results of the safest route for a vessel with the length of 130 meters. It is evident that there is rather an extensive zone of safe movement for such a ship that gives a navigator some "flexibility" when choosing a route.

The ship's passage from an initial route point to a final one can take quite a time within which meteorological situation may change considerably. If a quick movement of cyclones and atmospheric fronts is typical in the examined area, it may result in false calculations for a long period of time. Keeping in mind that in practice the problem of choosing a safe route should be solved iteratively, immediate calculations must be done when receiving new meteorological data.

4. Conclusion
The suggested method of searching safe routes allows forming a systematized idea of potential danger degree, "waiting for" a navigator along the ship's route to the point of its destination.

High calculation complexity of the task for searching the shortest route in graphs when using a precise algorithm presents a certain problem. Here application of algorithms of heuristic types is promising. Thus, the authors of the work [2] suggest that a genetic algorithm should be used for searching optimum routes both in time and economy. Sotnikova M.V. in her work [5] offers to form a multitude of admissible paths lying on the "right" and on the "left" of the arc of the great circle. When graph dimension is big, application of ant algorithms also reveals certain prospects [2]. It is also possible to use an approach connected with decrease of a number of vertices, 'taking part" in the search of the shortest route [7]. Despite the fact that there are methods of approximation giving not precise but only close to it solution. Such an approach is justified in the examined problem: because of dynamically changing meteorological situations even precise algorithms of a route search will find only a “sectionally-statistical” optimum solution, which, of course, will not be an optimum solution to a dynamical problem.

The present work has studied functional dangers on the basis of a storm pattern on the following wave. Other metrics of danger in meteorological situations are possible.

5. References
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