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Ships Route Planning on Heavy-Traffic Marine Area based on Historical Data

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Abstract. This paper is devoted to the problem of planning the route of the passage of a sea vessel. Ship navigator must adhere to a certain traffic pattern adopted in a particular water area when sailing in heavy traffic conditions. This scheme can also exist informally, being a generalization of the collective navigator's experience. In this case, it seems productive to plan a route based on data on the movement of other vessels that were in the water area earlier (the same idea underlies the methods of "big data" tasks). In earlier papers, such route planning was based on a cluster analysis of historical traffic data. It assumed the division of the water area into sections and the allocation of characteristic values of velocities and courses in them. The problem with this approach was the choice of partitioning parameters, which had to be set for each specific water area separately. In this paper, another approach is proposed, when the graph of possible routes includes a selection of the trajectories of individual ships that were previously implemented in the selected water area. The article considers a method for constructing such a graph of possible routes, estimates the number of its vertices and edges, and gives recommendations on choosing a method for finding the shortest path on this graph. A possible method for interpolating the missing data required to build a graph is discussed, which is based on the idea of combining straight and maneuverable sections of vessel traffic. Examples of route planning in a number of real water areas are given Vladivostok, Tokyo Bay, Tsugaru Strait.

INTRODUCTION

Ensuring navigational traffic safety is the main research and applied problem of the operation of sea vessels. This problem must be considered in the context of three tasks: risk assessment of a dangerous approach, prevention of a dangerous approach, and planning the path of the ship's safety movement. [1] The purpose of the first task is to inform the navigator that the vessel under control is at risk of colliding with an obstacle or approaching it to an unacceptable distance. Proximity warning is the maneuvering of a controlled vessel, which allows avoiding an unacceptable approach to obstacles (developing an evasive maneuver). Path planning involves forecasting the navigational environment and calculating the ship's trajectory in space and time in such a way that it moves at a sufficient distance from obstacles.

Three tasks become insufficient when sailing in the conditions of heavy traffic mentioned. So, with disordered, saturated, and chaotic traffic in the water area, the risk of a dangerous approach will be detected too often and the choice of safe speeds and courses for performing an evasive maneuver will be difficult. Also, path planning will lead to inconvenient or unrealizable trajectories, getting into "navigation traps", etc. It is customary to resort to additional regulation of the collective traffic with such traffic by introducing a system for establishing the routes of ships. The task of this system is to eliminate uncertainties or the possibility of making erroneous decisions by navigators. In other words, a certain traffic pattern is adopted for the water area in the form of a set of restrictions (“rules of motion”). It is believed that ship navigators should adhere to this scheme, plan the route of their vessel according to it. [2]

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The scheme of vessel traffic in a particular water area can be not only directive. Often it exists informally, as the quintessence of many years of collective navigation experience in specific waters. In this case, it seems productive to plan a route based on data on the movement of other ships that were in the water area earlier.

In the already published works, the authors proposed model representations of the route planning problem based on a cluster analysis of retrospective data on vessel traffic. [3]-[5] Currently, such data is provided by specialized information services (for example, marinetraffic.com).

The developed methods assumed the division of the water area into sections and the allocation of characteristic values of the speeds and courses of ships in them. A graph of possible ship routes was built based on the received data. On this vessel, a search was made for the most suitable transition route from the starting point to the final point. Thus, the route of passage through the water area with heavy traffic was planned in such a way that the vessel adhered to the most “popular” speeds and courses in one or another part of the water area.

The main problem of the proposed approach was the choice of water area partitioning. Excessively “small” areas did not provide a data sample sufficient for adequate clustering in those places where the intensity of vessel traffic is low. On the contrary, “large” sections did not allow considering some features of the traffic pattern, for example, fairways with two-way traffic. The solution to this problem could be multidimensional clustering of traffic data, which includes the coordinates, speeds, and courses of ships in its parameters. Even though there are methods suitable for such clustering, they require “tuning” - setting the parameters of the algorithm, the choice of which is not obvious in the general case.

In this paper, we propose another route planning method, in which the graph of possible routes is built based on the trajectories of individual vessels implemented earlier in the selected water area. The new method requires significantly less historical data than those associated with clustering. And it also eliminates the uncertainties associated with the selection of internal parameters of the algorithm.

MATERIALS AND METHODS

Assume that the ship's trajectory is given by a set of tuples $\{LAT_i, LON_i, SPEED_i, COURSE_i, TIME_i\}${ 〚where i is the tuple number, LAT_i and LON_i – geographic latitude and longitude, $SPEED_i$ and $COURSE_i$ – speed and course, $TIME_i$ – point in time to which they refer (approximately in this format, vessel traffic data is provided by specialized information services). Let's introduce a coordinate system, where the abscissa axis corresponds to longitude, and the ordinate axis corresponds to latitude. Then the path traveled by the ship will be given by a polyline with vertices $\{LAT_i, LON_i\}$. If there are retrospective data on the movement of N ships, this corresponds to N broken lines $\{LAT_i, LON_i\}_j, j = \overline{1, N}$.

Let us form the indicated broken graph of possible routes of the ship. Such a graph will be directed due to the nature of the trajectory data available. At the first stage, we include in it all the vertices of the polylines and all their edges (considering orientation). At the second stage, we supplement the set of vertices of the graph with intersection points of broken lines, and the set of edges with new edges providing connectivity to these intersection points (see fig. 1).

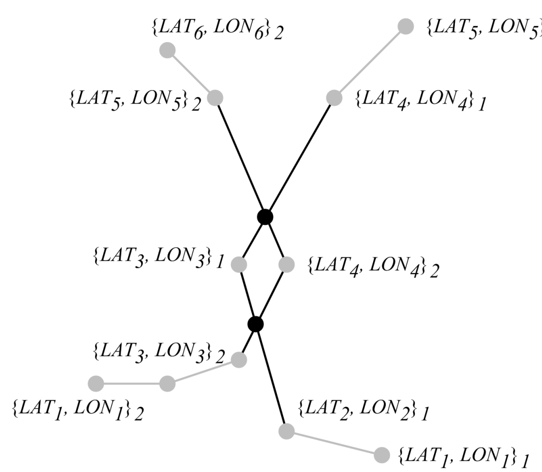

FIGURE 1. Graph of possible ship routes based on historical data.

Figure 1 shows this way of adding new vertices and edges to the graph. The paths of two ships are shown. The light gray dots and lines are the vertices and edges of the graph formed from the initial motion data. Black dots and lines are additional vertices and edges. There are two points of intersection of broken lines in the case shown in Fig. 1. They are incident with two additional edges.

The weight of the ribs can be chosen in various ways. In the simplest case (this is what is meant in the calculations below), it is equal to the length of the Great Circle arc that connects the vertices incident to the edge. Sometimes, when choosing a ship's route, it is also necessary to take into account the "popularity" of a particular route implemented in historical traffic data. Then the weight of the rib decreases in proportion to the number of ships that proceeded in a similar way.

The search for the shortest path on the graph under consideration can be carried out by well-known deterministic methods: Dijkstra, Bellman-Ford, etc. [6] When choosing a method, one should keep in mind the orientation of the graph, its sparseness, and the absence of edges with negative weights. The computational complexity of popular search algorithms is proportional to the square of the number of vertices in the graph. The same complexity will take place when constructing a graph. Namely, when searching for intersection points of broken lines. Historical traffic data in areas with heavy traffic can contain records of about 5×10^3 trajectories per day, each of which contains up to several thousand points. Thus, the construction of a graph and the search for the shortest path on it in the case of a water area with heavy traffic will require about 10^{13} steps of the algorithm. Of course, such many operations is implemented only in individual ("worst") cases. And the time for solving the problem is acceptable for practice when using modern general-purpose software and computing tools. This is confirmed by further examples of calculations.

If water area traffic data is taken over a long period of time (month, year), the graph of possible ship routes will contain 1-2 orders of magnitude more vertices and edges. This makes it difficult to find the shortest path on it by deterministic methods. In this case, heuristic-type methods (for example, the ant colony algorithm [7]-[10]) can be used. The path found in this way will not be optimal, but it will be acceptable for practice.

RESULTS

The following calculations were carried out on the data arrays on the movement of vessels collected from the marinetraffic.com resource using a specially developed program.

On fig. 2 shows the results of route planning for vessels moving in the water area adjacent to the port of Vladivostok. For calculations, traffic data for one day were taken. The light blue lines show the ship trajectories used to construct the graph of possible routes (about 300 thousand vertices). The red lines show several calculated routes:

- from the anchorage in the Ussuriysky Bay to the oil port on the Pervaya Rechka (line 1),
- from the commercial port area to the exit from the port to the Ussuriysky Bay through the Vostochny Bosporus Strait (line 2);
- from the Ussuriysky Bay to the commercial port area (line 3).

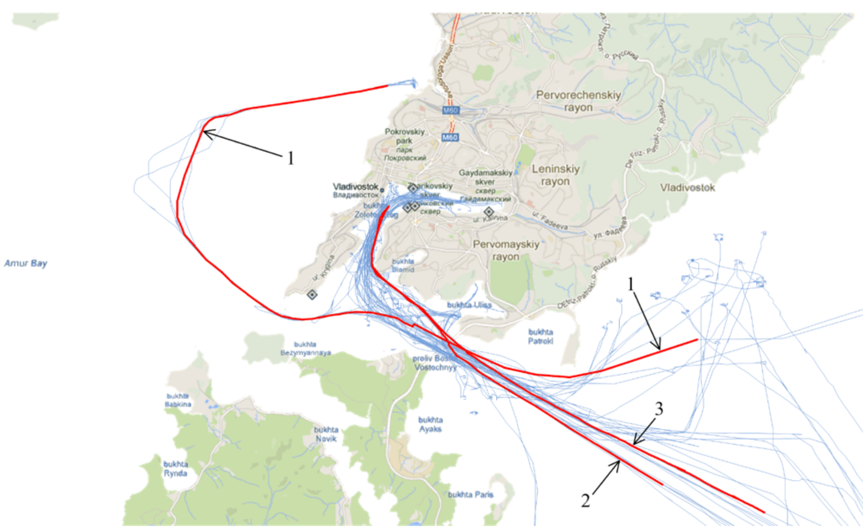

FIGURE 2. Results of route planning near Vladivostok port.

On figure 3 shows the results of route planning in the Tsugaru Strait. For calculations, we took traffic data for one day, which gave a graph of possible routes (light blue lines), which contains about 100 thousand peaks. The red lines show the following routes:

- Port of Hakodate - Mutsu Bay (line 1),
- Mutsu Bay - Hakodate port (line 2),
- Pacific Ocean (Northeast entry) - Sea of Japan (Line 3),
- Sea of Japan - Pacific Ocean (exit to the east, line 4),
- Mutsu Bay - Pacific Ocean (exit to the east, line 5),
- Port of Hakodate - Pacific Ocean (outlet to the northeast, line 6).

On figure 4 shows route planning in Tokyo Bay. For calculations, data on the movement of ships for 6 hours were used, which formed a graph of possible routes from about 300 thousand peaks (light blue lines). The red lines show the following routes:

- port of Yokohama - the mouth of the bay (line 1),
- Kawasaki area - the mouth of the bay (line 2),
- mouth of the bay - Kawasaki area (line 3),
- mouth of the bay - Chiba area (line 4).

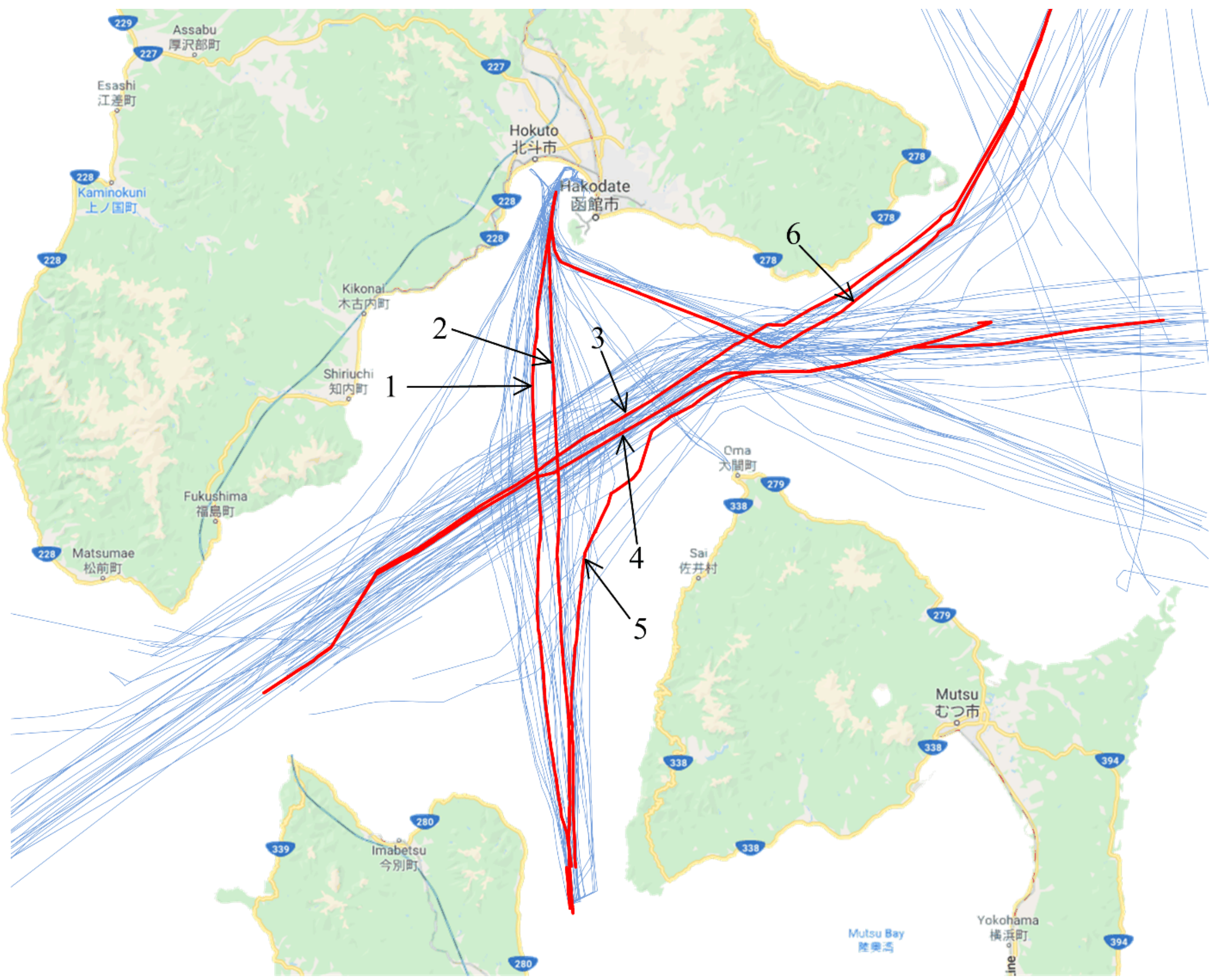

FIGURE 3. Results of route planning in the Tsugaru Strait.

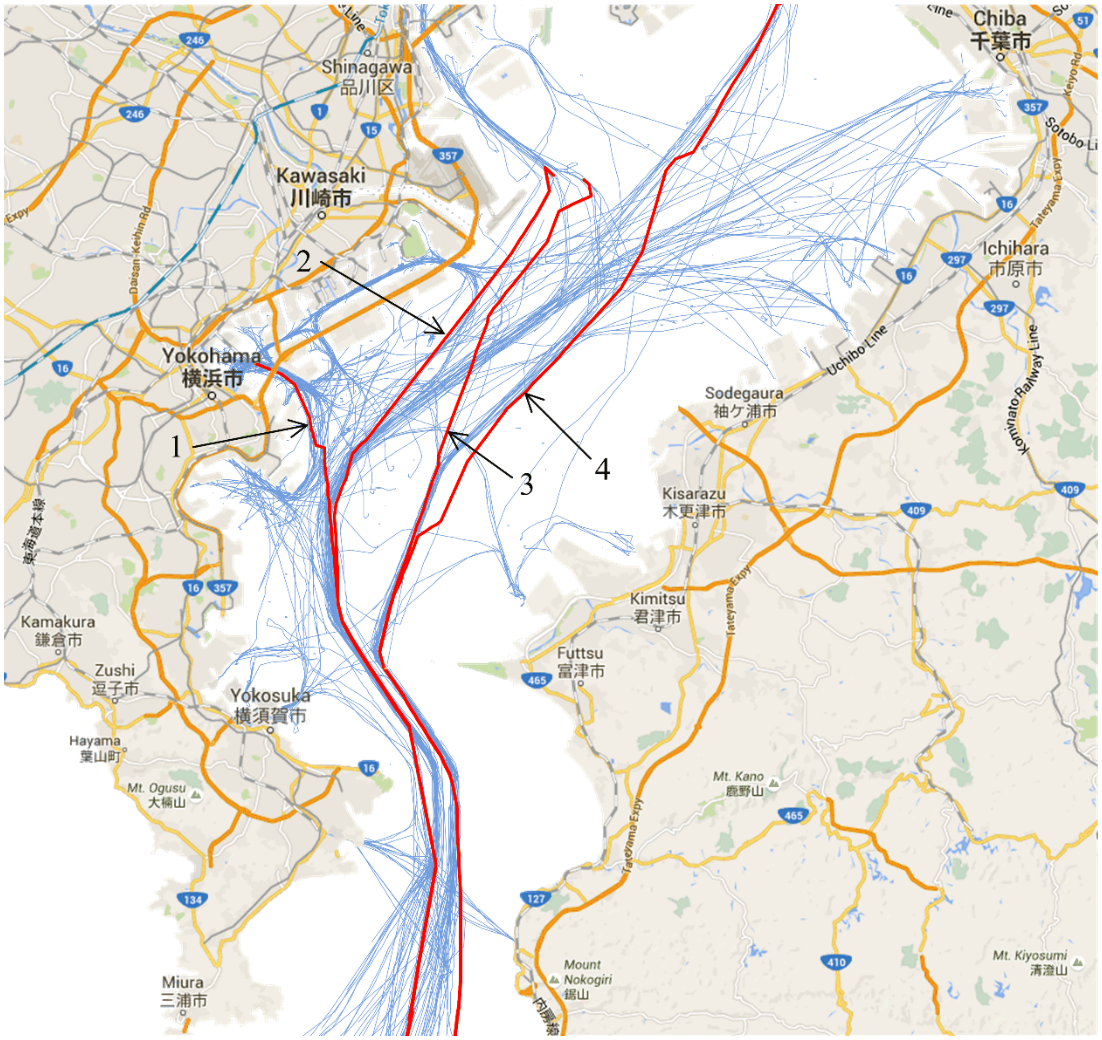

FIGURE 4. Results of route planning in Tokyo Bay.

Shown in fig. 2-4 data demonstrate an adequate solution to the route planning problem in such a way that ships move along trajectories characteristic of the selected water area. So, routes 2 and 3 in fig. 2, 1 and 2 fig. 3, 2 and 3 fig. 4 take the right side of the movement (in navigation, right-hand traffic is accepted). The observed "brokenness" of some routes (1 in fig. 2, 5 in fig. 3, 4 in fig. 4, etc.) is associated with a limited set of initial data and can be eliminated by increasing the sample. A significant drawback of the calculated trajectories is the lack of consideration for the "popularity" of a particular path.

This forms the shortest possible route, but not the most feasible in historical data. This effect is seen, for example, in fig. 2. Routes 2 and 3 pass close to the coast, although most ships pass at some distance from it. The indicated consideration of the "popularity" of the trajectory is possible by assessing the "influence" of the edges of the graph of possible routes on each other using various heuristics. The authors plan to devote a separate study to this problem.

DISCUSSION

As already noted, in water areas with heavy traffic, the graph of possible routes can contain about 106 - 108 vertices and edges (if traffic data is taken for its formation for several days). The graph is formed once and its construction can be carried out gradually, as data accumulates. Therefore, this is not a problem from the point of view of the computational complexity of the problem of finding intersections of broken lines. The search on such a graph for routes of small length, which consist of several tens or hundreds of edges, is quite feasible using well-known deterministic methods in an acceptable time. For long routes consisting of thousands of edges, it is possible to use heuristic methods.

Vessel traffic data obtained using the services of the Automatic Identification System (such data is available on open Internet resources) has several features. One of them is missing data. So, on the marinetraffic.com resource, the typical data update interval is one minute. It is implemented for maneuvering ships. For ships moving in a straight line and uniformly, the data is updated less frequently. Their update period can be from several minutes to several tens of minutes and even several hours. In the event that such data omissions lead to a strong distortion of ship routes (trajectory segments cross land, pass through areas prohibited for navigation, etc.), ship trajectory interpolation should be resorted to, which can partially eliminate the effect of excessive data sparseness. Such interpolation should consider not only the geometry of the trajectory, but also the specific mechanics of the movement of vessels, a combination of straight and maneuverable sections of movement. Popular interpolation methods (polynomials, splines) are not applicable for this. Let's consider a possible approach for interpolating the ship's trajectory based on data about its coordinates, courses and speeds.

First, let's move from the geographic to the rectangular coordinate system. Such a transition depends on the accepted model of the Earth's surface. For water areas with a size of several tens of kilometers and not located at high latitudes, it is possible, with a good degree of approximation, to consider the Earth as a ball of known radius R and use the following coordinate transformation formulas:

$$x = R(LON - LON_*)cos(LAT_*),$$
$$y = R(LAT - LAT_*),$$

where LON and LAT are the longitude and latitude of the point on the sea surface, LON_* and LAT_* are the longitude and latitude of the point taken as the origin of the rectangular coordinate system.

Consider one of the segments of the ship's trajectory. Let the coordinates and components of the ship's velocity vector be known at the beginning - $x(t_1)$, $y(t_1)$, $v_x(t_1)$, $v_y(t_1)$ - and at the end - $x(t_2)$, $y(t_2)$, $v_x(t_2)$, $v_y(t_2)$ - segments. Let's divide the segment into a segment of uniform rectilinear motion and a segment of uniformly accelerated motion (fig. 5).

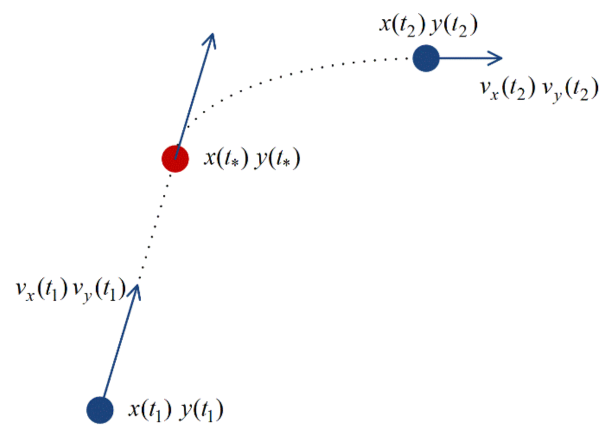

FIGURE 5. Segment of the ship's trajectory. Red indicates a point with unknown coordinates.

Let us assume that from the point $x(t_1)$, $y(t_1)$ to the point $x(t_*)$, $y(t_*)$ the ship moves in a straight line with a constant speed $v_x(t_1)$, $v_y(t_1)$. From the point $x(t_*)$, $y(t_*)$ the ship starts moving with the speed $v_x(t_1)$, $v_y(t_1)$ and moves uniformly to the point $x(t_2)$, $y(t_2)$, where it reaches the speed $v_x(t_2)$, $v_y(t_2)$. This corresponds to the following six equations of motion:

$$x(t_*) = x(t_1) + v_x(t_1)(t_* - t_1),$$
$$y(t_*) = y(t_1) + v_y(t_1)(t_* - t_1),$$
$$x(t_2) = x(t_*) + v_x(t_1)(t_2 - t_*) + \frac{a_x(t_2 - t_*)^2}{2},$$

$$y(t_2) = y(t_*) + v_y(t_1)(t_2 - t_*) + \frac{a_y(t_2 - t_*)^2}{2},$$
$$a_x = \frac{v_x(t_2) - v_x(t_1)}{t_2 - t_*},$$
$$a_y = \frac{v_y(t_2) - v_y(t_1)}{t_2 - t_*}.$$

Quantities $x(t_1)$, $y(t_1)$, $v_x(t_1)$, $v_y(t_1)$, $x(t_2)$, $y(t_2)$, $v_x(t_2)$ correspond to the original data and are considered known. The quantities $x(t_*)$, $y(t_*)$, t_1, t_*, t_2 are unknown. If $t_1 = 0$, we substitute the fifth and sixth equations into the third and fourth, respectively, obtaining a system of four linear algebraic equations for the quantities $x(t_*)$, $y(t_*)$, t_*, t_2. Solving this system of equations, we obtain the ship's motion parameters from the point $x(t_1)$, $y(t_1)$ to the point $x(t_2)$, $y(t_2)$, based on which it can be interpolated trajectory.

The problem of route planning based on historical water area traffic data has repeatedly attracted the attention of researchers. One of the first works on this subject is the article [11]. It discusses the features of the trajectory data provided by the Automatic Identification System and concludes that clustering ideas can be applied to them. The article gives an overview of possible mathematical methods, presents the results of solving various applied problems: identifying anchorage areas, entry and exit points from water areas, assessing the configuration of regular traffic flows and their intensity. Attention is paid to the problem of assessing anomalies in the movement of ships. Model representations of the route planning problem are proposed, which are based on clustering and methods of probability theory, and examples of route calculations in the northern part of the Adriatic Sea are given. The disadvantage of the proposed approach is the need to select methods for clustering trajectory data and their parameters, which will be different for water areas with different traffic patterns.

The route planning problem is also solved in [12]. The proposed method is based on the division of the water area into small sections and the assessment of the characteristic values of the course of ships during the passage of each of them. The possibility of the vessel moving from section to section is assessed based on the data obtained. That is, a graph of possible ship routes is implicitly formed. After that, a suitable route is found from the start to the end point. The disadvantage of the method is the need to select the parameters of the division of the water area and the "indentation" of the resulting trajectory of the vessel, which requires additional smoothing.

The work [13] is devoted to the study of one of the possible approaches to the clustering of trajectory data. In it, broken lines (the trajectories of ships that passed through the water area earlier) act as clustering objects, and the characteristic distance between the points of broken lines acts as a distance metric. As a result of solving the problem, "bundles" of ship routes characteristic of the selected water area are identified. The k-medoids clustering method is used. A similar approach is implemented in [14], where the DBSCAN method is used for clustering. The authors note the possibility of planning routes based on the identified movement patterns, although the central result of these studies is the identification of anomalously moving objects. The disadvantage of the approach is also the need to select the parameters of clustering algorithms.

Finally, [15] also proposes a method for detecting anomalous behavior of ships from the point of view of traffic parameters characteristic of a particular area of the water area. Such normative parameters can be used for route planning. The disadvantage of the approach, as in other works, is the division of the water area into small areas, which gives rise to the problem of choosing their sizes, "reference points" and the discreteness of the result.

The route planning method proposed in this paper is free from all these shortcomings.

CONCLUSION

The article considers a method for solving the problem of planning the route of the vessel's crossing in such a way as to consider the navigator's experience and the pattern of vessel traffic that has developed in a particular water area. The proposed method does not use clustering, unlike widely known approaches. It builds a graph of possible routes as a set of intersecting broken lines representing the trajectories of ships that have passed through the water area earlier. The absence of explicit data clustering makes it possible to avoid the need to select an appropriate clustering method and select its parameters.

In water areas with heavy traffic, the number of ship trajectories in the initial data can be several thousand, each of which can contain up to several thousand segments. The construction of a graph of possible routes is associated with the traditional task of geometric modeling - the search for intersection points of segments. In the case of a large amount of initial data, this task will have a high computational complexity. Also, the formation of a graph of possible routes can occur gradually, as data accumulates and is quite feasible in practice. Finding a suitable (shortest) path on such a graph would also be computationally difficult. In the case of extended routes, it can be carried out by heuristic-type algorithms.

The source of data on the movement of vessels in the water area are the services of the Automatic Identification System, which are available on existing Internet resources. One of the features of these data is their sparseness, which can sometimes lead to the construction of incorrect elements of the graph of possible vessel routes. The article proposes a method for additional determination (interpolation) of missing data, based on the alternation of uniform and accelerated sections of movement.

The paper gives examples of calculations of routes for ships to cross some water areas (Vladivostok, Tsugaru Strait, Tokyo Bay). From these examples, the found routes reflect the characteristic features of the traffic quite well. This confirms the prospects for the practical use of the proposed approach.

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