



A Ship Routing System Applied at Short Sea Distances

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ABSTRACT

New generation of high-resolution meteo-oceanographic predictions provides useful tools for routing of ships in short maritime distances. In this work, the optimal ship routing analysis is investigated in maritime routes in the Western Mediterranean Sea for relative short sea distances. A* algorithm is implemented in order to obtain the optimal path under an energetic wave events. The methodological aspects are presented including the grid description and weather prediction systems. The optimized cost function is the travel time and it is obtained considering the added resistance due to waves. A practical example considers the maritime route between Barcelona and Algiers. The results show the influence of this factor in the optimum path recovered by the algorithm. The relevance of the relative direction between wave and ship route is proven comparing the ship routing results.

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1. Introduction

A major factor of competitiveness in the maritime industry is the minimization of fuel consumption for shipping routes. This agrees with an increase of the world tendency to reduce air emissions in the framework to mitigate the climate change effects. From the shipping industry point of view this may be achieved with an optimum route plan design (Simonsen et al., 2015). Academic research has focused the ship routing optimization through pathfinding algorithms (e.g. Takashima et al. 2009, Mannarini et al., 2013, Szłapczyńska and Śmierzchalsk, 2009; Larsson and Simonsen 2014; Hinnenthal and Günther, 2010), which take into account the meteo-oceanographic forecasts (i.e. wind, waves or currents predictions). Some of these contributions have been tested through a 'proof-of-concept' based in oceanic distances (Hinnenthal and Günther, 2010).

However, at relative short-distance the route shipping optimization remains unexplored. In this case, the spatial resolution of the meteo-oceanographic predictions are a severe restriction.

The implementation of ship routing produce multi-objective problem which involves parameters such as the expected time of arrival (ETA), risk minimization or fuel consumption. This leads to a multi-criteria problem solved with advanced optimization algorithms (e.g. NAMOA, genetic algorithm, etc.). However, most of the ships are equipped by weather routing systems to plan a route with the lowest fuel consumption while arriving with a certain time slot (Simonsen et al., 2015).

The objective of this contribution is to implement and discuss a ship routing algorithm in a relative short distance route (e.g. Barcelona - North Africa) using high-resolution wave numerical products. The ship routing is defined as the development of an optimum sailing course and speed for ocean voyages based on nautical charts, forecasted sea conditions and the individual characteristics of a ship for a particular transit (Bowditch, 2002). The contribution is organized as follows: after the introduction (Section 1), the Methods (Section 2) include the description of the algorithm used for route shipping, the wave numerical model description, the estimated of the speed loss due to waves and the grid discretization. The results are presented in Section 3 including the discussion of the wave effect on the ship routing. Finally, the conclusions and future developments are underlined in the last section (Section 4).

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2. Methods

2.1. Pathfinding algorithms and grid discretization

The pathfinding algorithm used in this work is the A* (Dechter and Pearl, 1985). This algorithm is applied at gridded scheme where each gridpoint (node) is connected to a set of vicinity points. To each connection (edge) a weight related with the distance is assigned. The great circle (orthodromic) track distance is used for the spherical coordinates of grid nodes. However it is used for larger distances than the ones proposed in this paper. A* solves routing problems by searching among all possible paths to the solution (goal) for the one that incurs the smallest cost (least distance travelled, shortest time, etc.), and among these paths it first considers the ones that appear to lead most quickly to the solution. A* is formulated in terms of weighted mesh: starting from a specific node of the mesh, it constructs a tree of paths starting from that node, expanding paths one step at a time, until one of its paths ends at the predetermined goal node. At each iteration of its main loop, A* algorithm needs to determine which of its partial paths to expand into one or more longer paths. It does so based on an estimate of the cost (total weight) still to go to the goal node. Specifically, A* selects the path that minimizes the total cost function $F(n)$:

$$F(n) = G(n) + H(n) \quad (1)$$

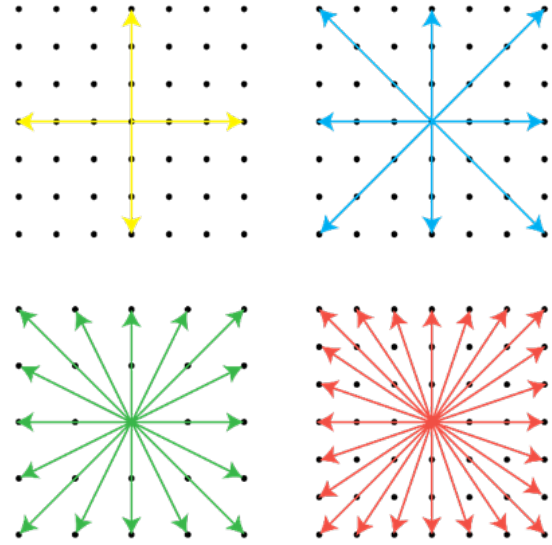
where n is the last node on the path, $G(n)$ is the cost of the path from the start node to n , and $H(n)$ is a heuristic that estimates the cost of the cheapest path from n to the goal. The heuristic is a problem-specific. For the algorithm, to find the actual shortest path, the heuristic function must be admissible, meaning that it never overestimates the actual cost to get to the nearest goal node. In our case, the heuristic function is the minimum distance between origin and destination. The description of the operating principle of the code (pseudocode) is shown in Appendix A.

Nodal connections possibilities per node may varies in function of the grid resolution. In consequence, the sequence of edges followed by the shortest path will be limited by the grid resolution and the connected nodes. Figure 1 shows the edges connecting nodes displayed by arrows for 4 different schemes: 4, 8, 16 and 24 edges. Each arrows represents potential ship courses or directions. Different grid resolution has been tested obtaining similar conclusions than Mannarini et al., (2013), which stated that a minimum 16 edges are required in a prototype level.

2.2. Wind-wave model and wave effects on ship

The wave predictions used are provided by the operational systems distributed by the Puertos del Estado (PdE). PdE together with the Spanish Meteorological Agency (AEMET) run and distribute twice-a-day wave and wind fields forecast for the Western Mediterranean Sea. Wind forecasts, used to force the wave models, come from the HIRLAM (High Resolution Limited Area Model) model, running operationally at the AEMET. The forecast horizon is 72 hours and the system generates wave hourly outputs (among other variables significant wave height

Figure 1: Scheme of the grid resolution in function of the number edges per node. In yellow 4 edges per node, in blue 8 edges per node, in green 16 edges per node and in red 24 edges per node. For a grid cell, central node is the origin and the destination in the contiguous cell.



Source: Authors

(H_s), wave direction and wave period). An initialization procedure is carried out in order to ensure good initial conditions: the model is forced using wind fields 12 hours prior to forecast initialization. The wave numerical model is WAM (WAMDI, 1988), version 4 (GÅ₄ntner et al., 1992). WAM is a third-generation based on the transport of two-dimensional ocean wave spectrum without additional ad hoc assumptions regarding the spectral shape. In this academic example, a wave energetic event was considered (maximum significant wave height correspond to 7 m in the Western Mediterranean Sea) associated at storm that leads waves from the East.

Wave action is the major factor that affects the ship performance [12]. Wave field affects the ship motions, decreasing the propeller thrust and adding a resistance in comparison to absence of waves. A simple formula to include ship's speed reduction into waves is suggested by Bowditch (2002). The final speed is computed in function of the non-wave affected speed plus a reduction in function of the wave parameters:

$$v = v_0 - f(\theta) \cdot H^2 \quad (2)$$

Where H is the significant wave height and f is parameter in function of the relative ship wave direction (see Table 1).

Table 1: Values of the coefficient f

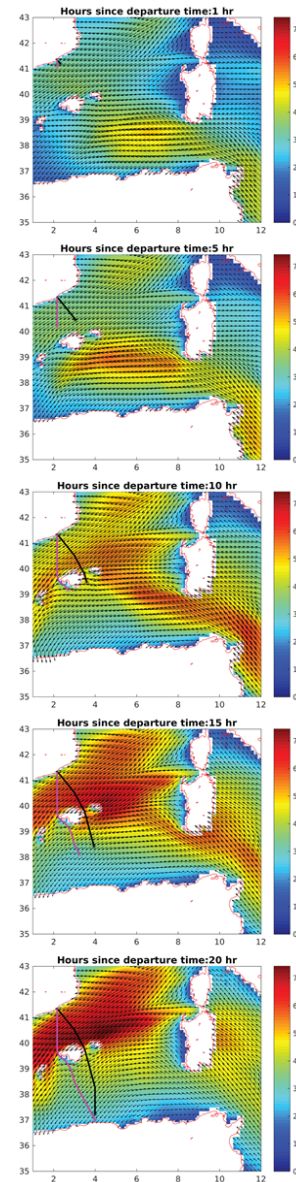
Ship-wave relative direction	Wave direction name from the ship point of view	$f(in kn / ft2)$
$0^\circ \leq \theta \leq 45^\circ$	Following Seas	0.0083
$45^\circ \leq \theta \leq 135^\circ$	Beam Seas	0.0165
$135^\circ \leq \theta \leq 225^\circ$	Head Seas	0.0248
$225^\circ \leq \theta \leq 270^\circ$	Beam Seas	0.0165
$270^\circ \leq \theta \leq 360^\circ$	Following Seas	0.083

3. Results

The methodology presented in the previous section has been applied to a relative short maritime route: Barcelona ? near to Argel (North Africa). The horizontal grid resolution (1.5 minutes) was established in 24 edges per node and a constant ship speed of 16.1 knots has been considered. The path recovered by the A* algorithm correspond to the optimum path without considering the vessel resistance due to the waves. In this case, the route corresponds to the orthodromic distance between the origin and the arrival (i.e. minimum distance path). Then, the optimal path is recovered considering the wave effects on ship. Figure 2 shows the temporal sequence for optimum path recovered by the A* algorithm considering the added resistance of the wave field in the ship speed (magenta line). Also, the minimum distance path is shown in Figure 2 (black line) jointly with the temporal evolution of the wave field. This wave field corresponds to a typical storm in the western Mediterranean Sea which generates NE winds (21-22 of January 2017). During this event, the wave predictions show a maximum significant wave height of 7 m. Differences in both routes (optimal and minimum distance) are clear according to Figure 2: the optimum path considering the wave field sail to the west of Mallorca Island avoiding large significant wave height. On the other hand the minimum distance is obtained passing Eastward Mallorca Island. Considering the wave directions shown in Figure 2, seems clear how the optimum route avoid partially the most critical conditions which corresponds to head and beam seas.

The travel time of the minimum distance path (without the drag resistance due to the waves) is equal to 17.45 hours (minimum distance). However, considering the drag resistance due to waves for the minimum distance path, the value raise to 20.67 hours. Obviously, this value is larger than the cost obtained by the optimal path recovered by the algorithm considering waves (i.e. 19.94 hours). In consequence, the implementation of A* pathfinding algorithm saves more than 0.5 hours with the consequent reduction in fuel consumption and other associated costs (e.g. demurrage, capital, financing or labor costs, ship maintenance, etc.).

Figure 2: Snapshots of the Barcelona - North Africa case (near to Algiers; hours since departure). The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the significant wave height and the black arrows the propagation direction of the waves.



Source: Authors

4. Final remarks

The work presented in this contribution is an implementation of the A* algorithm for the optimum ship routing in a relative short oceanic distance. The methodology is based on the inclusion of the drag resistance due to waves. The methodology has been applied to the maritime route Barcelona - North Africa with substantial differences between the minimum distance and the optimum paths. This example represent a relative short distance in comparison to mentioned applications oriented to oceanic maritime routes. This application is possible due to the new high-resolution products for wave prediction. The results showed here reveals how both wave height and direction have a relevant role in the optimum path due to the effect of the relative direction with the ship. Future works include the implementation of the multi-criteria algorithm (e.g. NAMOA or genetic algorithm), the inclusion of safety restrictions due to the wave conditions (surf riding or rolling motions) in the methodology or the influence of currents and winds in the optimum ship routing.

Appendix A. Pseudocode of A* algorithm

1. initialize the open node list
2. initialize the closed node list
3. put the starting node on the open node list
4. while the open list is not empty find the node with the least f on the open list, call it "q"
5. pop q off the open list
6. generate q's 24 successors (courses) and set their parents to q
7. for each successor
8. Stop the search if successor is the goal,
9. $\text{successor.g} = \text{q.g} + \text{sailing time between successor and q}$
10. $\text{successor.h} = \text{sailing time from goal to successor}$
11. $\text{successor.f} = \text{successor.g} + \text{successor.h}$
12. if a node with the same position as successor is in the OPEN list \
13. which has a lower f than successor, skip this successor
14. if a node with the same position as successor is in the CLOSED list \
15. which has a lower f than successor, skip this successor
16. otherwise, add the node to the open list
17. end
18. push q on the closed list
19. end

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