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Sailing Vessel Routing Considering Safety Zone and Penalty Time for Altering Course

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ABSTRACT: In this paper we introduce new model for simulation sea vessel routing. Besides a vessel types (polar diagram) and weather forecast, travel security and the number of maneuvers are considered. Based on these data both the minimal travelling costs and the minimal processing time are found for different vessels and different routes. To test our model the applications SailingAssistance wad improved. The obtained results shows that we can obtain quite acceptable results.

1 INTRODUCTION

In sailing regattas the success is impacted by crew and sailing vessel parameters. The role of crew is in making decisions to choose suitable directions of sailing, according with weather conditions and sea state. Experience and knowledge of crew are very useful in decision-making, but through time appear solutions that help make the decision. In the last article (Życzkowski, 2016) presented a short review of sailboat routing. Current solutions include e-navigation aspect (Weintrit & Wawruch, 2007) to support the decision to choose the appropriate sailing route. However, some facts are noteworthy, the big regatta yachts such as in the America's Cup, Cowes Races whether Mug Races, have possibility to optimize sailing routes. However the required data and optimization algorithms are not available for sailing society. Lack of sailing vessel parameters for scientists is an impediment. Despite these difficulties in the articles you can find a variety of approaches in the search for the optimal route (Philpott, Sullivan, & Jackson, 1993), (Verwerft & Keuning, 2008), (Dębski, 2016). In this article sailing vessel parameters are achieved due to a simulation modeling of two boats. However, other result of different vessel modelling can be also used.

The aim of this work is consideration of new different sailing criteria than in the last article (Życzkowski, 2016), which are presented in the following section.

2 OPTIMISATION PROBLEM

The aim of the research is to propose a method, which finds optimal sailing vessel route according to specified criteria, while satisfying given constraints.

The first criteria is taking account of navigation safety in the vicinity of shore and isolated danger marks and all dangerous situations, according with COLREGS and good marine practice (*COLREGS*, 1972), (Jurdziński, 2003). The second criteria is a penalty time for altering course which increased the total time of the voyage.

Further considerations take into account the impact of these factors on the optimization criterion.

In consequence the application developed by author this paper and called SailingAssistance considers both these criteria. To make such possibilities the application was modified towards layered structure. Using the application tests for two different sailing vessels were performed. During testing both safety navigation and the penalty time for a course altering on route of sailing vessel movement is considered. Moreover the type of sailing vessels, the weather forecast, penalty for altering courses and granulity of the navigational area are also taken in to account. The aim of the research is proposed method to find optimal sailing vessel route contains new optimization criteria explained below.

In the previous paper (Życzkowski, 2016), only one level of granulity was assumed for the whole navigational zone. Then, all vessel manoeuvring was modelled with the same accuracy. However in a literal zone precision of vessel sailing should be increased. Therefore in our consideration we assume that sailing area is described by two levels of granulity. The open sea is represented by basic (initial) grid with the suitable granulity, defined below (see Figure 2). A way of conversion sea map on a sea grid is shown in articles (Mannarini, Coppini, Oddo, & Pinardi, 2013), (Tsou & Cheng, 2013), (Szlapczynski, 2006).

Granulity of sea area z is determined by the formula (1):

$$z = \frac{OB}{m \times n} = \frac{(\varphi_{\max} - \varphi_{min}) \times (\lambda_{\max} - \lambda_{min})}{m \times n} \qquad (1)$$

where $\varphi_{\max}$ ($\lambda_{\max}$), $\varphi_{\min}$ ($\lambda_{\min}$) indicate the minimum and maximum latitude(longitude) in degrees. $\varphi_{\min} = \min\{\varphi_i, i = 1, 2, .., m\}$, $\lambda_{\min} = \min\{\lambda_i, i = 1, 2, .., n\}$, $\varphi_{\max} = \max\{\varphi_i, i = 1, 2, .., m\}$, $\lambda_{\max} = \max\{\lambda_i, i = 1, 2, .., n\}$. If z is smaller then amount of squares in a grid is higher.

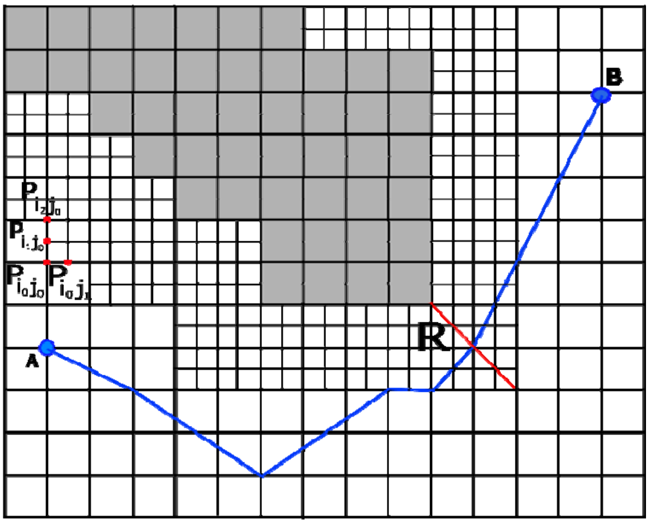


Figure 1. Increasing granulity of area in vicinity of shore

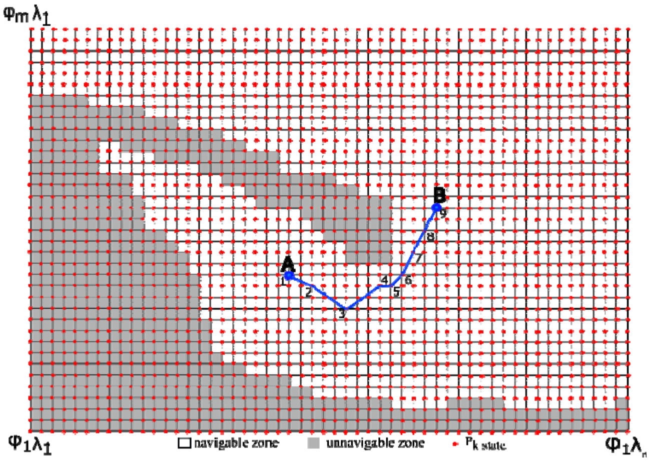


Figure 2. Descritazed chart with constant granulity of area with example of route from start point A to finish point B with 32 possible movements of a sailing vessel from each point P_k, illustrated are 9 points P_k, where in point designed by 7, 8, 9 is course

For sea area near the shore and any obstacles it should be described by higher granulity. For this case one single square is decreased 2^s time in comparison the basic square, where s is granulity coefficient and in our consideration s is equals 1.

Below it is assumed that in vicinity of shore, isolated dangerous, or other situations require higher awareness. In consequence it is necessarily to apply higher granulity of the area. Because this increases accuracy of route optimization, and safe navigation. Higher granulity of the area is also placed around the peninsula. Such zones, in this article, is called the safety zones. The safety zone area is determined by minimal radius R from contour shore or contour others obstacles to open navigation zone. Figure 1 shows such a grid, which corresponds to one small part of the Figure 2. The way of ncreasing granulity of area is defined by following formula (2):

```
if checkRadius($P_{ij}$, unnavigable zone)<R {                (2)
    for x=0 ; x=$2^s$ ; x++
        for y=0 ; y=$2^s$ ; y++
            create new point $P_{i_x j_y}$
}
```

where checkRadius is a function which determined the fragment of sea grid determined by the contour shore or contour others obstacles and distance R of from them. Parameter R determines safety zone radius (R=1 is equal one diagonal of a square in the basic grid), parameter s is the coefficient of granulation in the safety zone when s=1 than one square of grid represents four new safety squares, when s=2 than in one basic square there is sixteen new squares. Formula (2) allows to indicate new all points $P_{i_x j_y}$ for all possible directions of vessel sailing from point P_{ij}. Coordinates x, y directly shows location of all points $P_{i_x j_y}$.

These points directly follow from the neighbors points existent in the grid area. If these points are situated in the safety zone, than higher granulity must be considered. To take in account the time penalty related to maneuvers of vessel we should calculate an angle determined by previous position P_{k-1}, current position $P_k = P_{ij}$ and one of next positions $P_{k+1} = P_{t\_t\_}$. in the grid. To optimize the next vessel movement to two known criteria such as the weather forecast in points P_k and P_{k+1} and the polar diagram of specific sailing vessel (Stelzer & Jafarmadar, 2012) must be take into account. These possibilities was implemented in SailingAssistance application (Życzkowski, 2016). Additionally two new criteria can be added: the safety zone and penalty time of the current vessel movement. Moreover we can also consider the possible number of vessel flow direction from point P_k to P_{k+1}. In practice is determined by coefficient wr, which can be one of three values: 8, 16, 32. In further consideration we assume the ambition value wr = 32. The penalty time of vessel maneuver from point P_k to point P_{k+1} can be corresponded to angle Ω determined by three vessel position in points: P_{k-1}, P_k, P_{k+1} (see Figure 3). In the further considerations it is assumed that difficulty of maneuver execution corresponding to value of angle Ω. If angle Ω is higher than difficulty of maneuver is also higher and takes more time. Such time delay can be evaluated by formula (3).

```
PenaltyTime($P_{k-1}$, $P_k$, $P_{k+1}$ )                                    (3)
{
    X= $P_k$; Y= $P_{k-1}$;Z= $P_{k+1}$;
    $\Omega = 180° - \cos^{-1}\frac{\overrightarrow{XY} \circ \overrightarrow{XZ}}{|\overrightarrow{XY}||\overrightarrow{XZ}|}$
    $\Omega = \left[\Omega \frac{360}{wr}\right]$
    if (Ω > 0.5*wr)
        Ω = 0.5*wr - Ω%(0.25 * wr)
    return timeTochangeCourse = Ω * p;
}
```

where p be specific coefficient following from characteristics of a sailing vessel. If considered points existing on boundary of basic and safety zone the required calculations of the above parameters are more complicated.

To calculate the next acceptable direction of vessel sailing we consider all possible maneuvers for different possible points P_{k+1}. For each of them we calculate also possible values of penalties time for altering course. Taking into the polar diagram of the sailing vessel and current weather in these points we can evaluate admissible maneuvers basic on algorithm calculating the optimal safety route (Stelzer, 2012). This can be printed out by SailingAssistance. application.

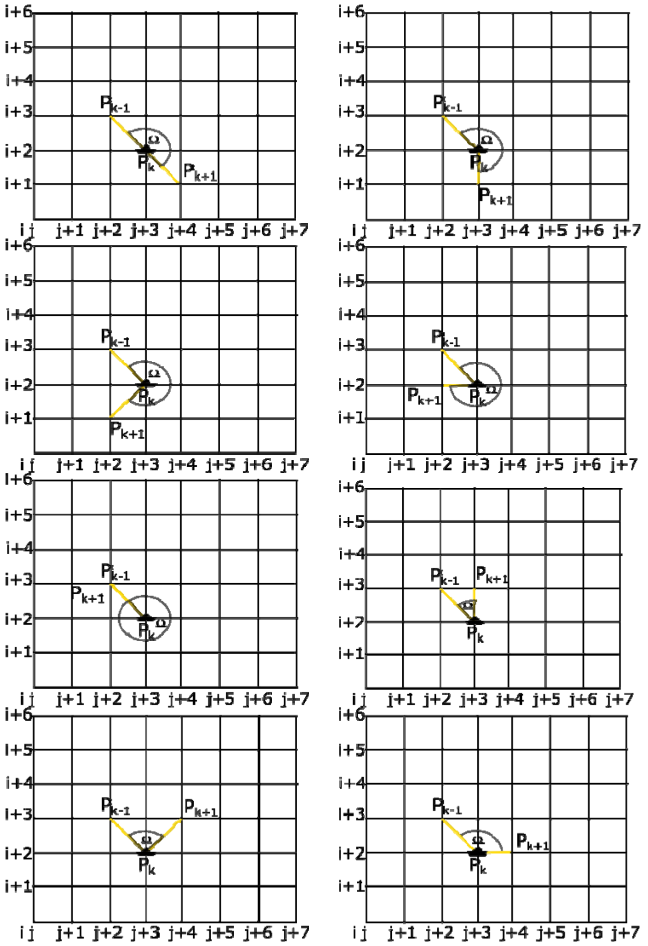


Figure 3 Penalty time for altering course, where possible sailing movement wr = 8. Sailing vessel is coming from P_{k-1} to P_k and following to P_{k+1}. For wr = 8 sailing vessel possible movement. From picture on the top right to down left : Ω is 0°,45°, 90°,135°,180°,225°,270°,315°and penalty time at p=1 equals :0, 4.5’, 9’,13.5’,18’, 13.5’,9’,4.5’.

3 ENLARGMENT OF FUNCTIONALITY OF SAILINGASSISTANCE APLICATION

The present architecture of the application SailingAssistance is shown in Figure 4. It consists of three layers: USERS responsible for cooperation with sailors, ROUTE determining the fast and safety route, DATA allowing to collect the required set of data. Each layer consists of many functions, which some of them are shown in Table 1. Such architecture is flexible and allows to make further modifications.

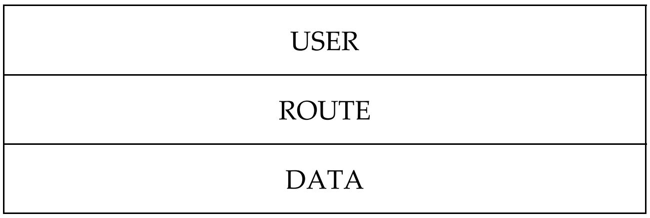


Figure 4. SailingAssistance layer structure application

Table 1. SailingAssistance functions.

Function	Layer	Description
Input(SV, A, B, cr)	DATA	Start point A, finish point B, sailing vessel SV, cr criteria fixed.
Create(OB, m, n)	DATA	Create m · n grid of OB specific area.
ChangePD(PD)	DATA	Polar diagram PD transformation to matrix C_{ab}
Area(P_{ij},t)	DATA	Read area state in P_{ij} point at t time, ie. S (P_{ij},t) = Area(P_{ij},t) for i = 1, 2, .., m; for j =1, 2, .., n.
Object (P_{ij},t)	DATA	Determine object state in point $P_k = P_{ij}$
CreateRoute (A,B,wr,t)	ROUTE	Implementation of Dijkstra's algorithm (Dijkstra, 1959) (Neumann, 2014) for graph G (V, E, O, S) with fixed Parameters (a variant of movement wr, and with a predetermined criteria. The result is a list of waypoints from start point A to finish point B.
Timeto(P_k,P_{k+1})	ROUTE	Time from P_k to $P_{k+1,}$ (potential next point in defined route.)
IncGranulity(R, s)	DATA	Increase granulity in safety zone, R is safety zone radius with coefficient s.
PenaltyTime (P_{k-1}, Pk, P_{k+1})	ROUTE	Calculate penalty time for altering course during searching another waypoints.
Display (chart, route)	USER	Display on assumed chart waypoints of designated route

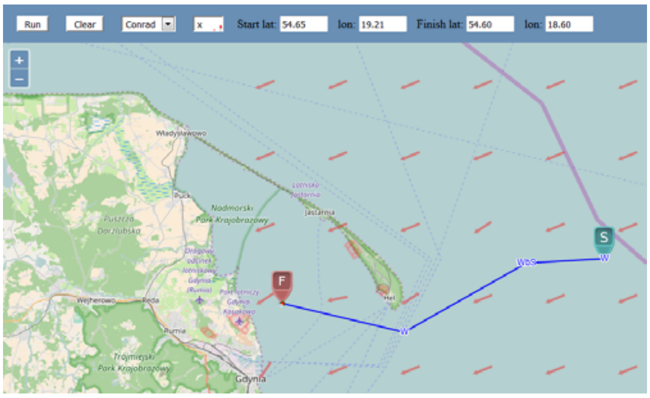
4 THE RESULTS FOR TWO SAILING VESSELS OBTAINED

SailingAssistance application carries out tests for two specific sailing vessels: Conrad and Oceania. Some technical details for these boats are in Table 2.

Table 2. Technical details of Conrad 1200 RT and R/S Oceania

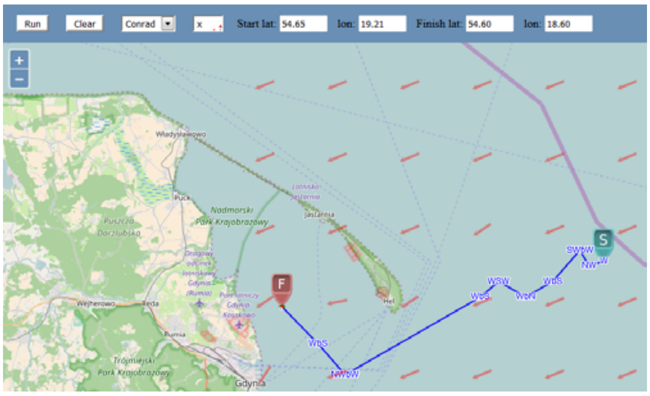
Parameters	CONRAD 1200 RT	R/S *OCEANIA*
Sail area [m^2]	80	520
Sail type	*Bermuda* rig	Sch. 3 masted
Length [m]	12.00	48.50
Beam [m]	4.04	9.00
Draught [m]	2	3.60
Free board [m]	1.08	2.00
Waterplane [m^2]	32.889	430.133
Lwl/Bwl [-]	3.161	4.711
Bwl/T [-]	4.844	3.000

SAS_VPPN.v03 program (developed in The Faculty of Ocean Engineering) has been used to create a polar diagram based knowledge of sailing vessel design details. The result of program are presented below as Table 3. It is fragment of polar diagram of sailing vessel Conrad. The first row means wind speed equals 1 knot, the second equals 2 knots, the first column means sailing direction equals N, the second NbE at true wind from N. During testing we used the followings settings: granulity gr_1 is equal 293 10^{-6} for 42 n points and 84 m points. The dedicated area is designed by rectangle $\varphi_{min}(\lambda_{min})$ =54.217 N (18.069 E) and $\varphi_{max}(\lambda_{max})$ =54.936 N(19.508 E), and granulity gr_2 is equal 73 10^{-6} for 168 n points and 84 m points variants of sailing vessel movement wr = 32. Start point A is $\varphi_A(\lambda_A)$= 54.65 N(19.21 E) and end point B is $\varphi_B(\lambda_B)$ = 54.60 N(18.60 E). We measured such parameters: ω number of changes course (if P_{k-1} P_k P_{k+1} is not one straight line then ω= ω+1), route time T and the distance voyage D, number of point P_k on designated route and time of work procedure to find route. All simulation results are in Table 4. and are illustrated in Figure 5 to Figure 8 (only Conrad sailing vessel route on chart).



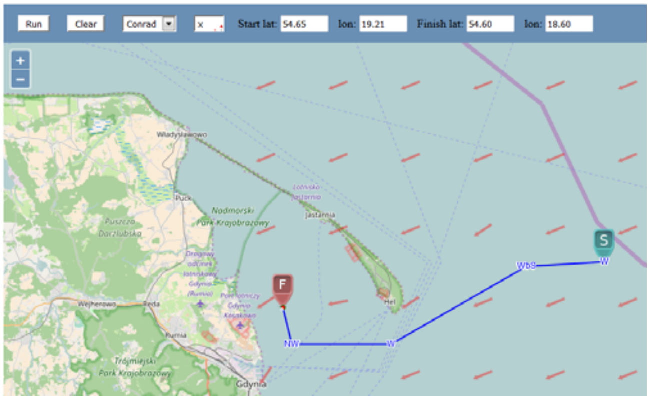
Start lat: 54.65 lon: 19.21 Finish lat: 54.60 lon: 18.60

Figure 5. Conrad sailing route for parameters gr2 po



Start lat: 54.65 lon: 19.21 Finish lat: 54.60 lon: 18.60

Figure 6. Conrad sailing route for parameters gr1 p1



Start lat: 54.65 lon: 19.21 Finish lat: 54.60 lon: 18.60

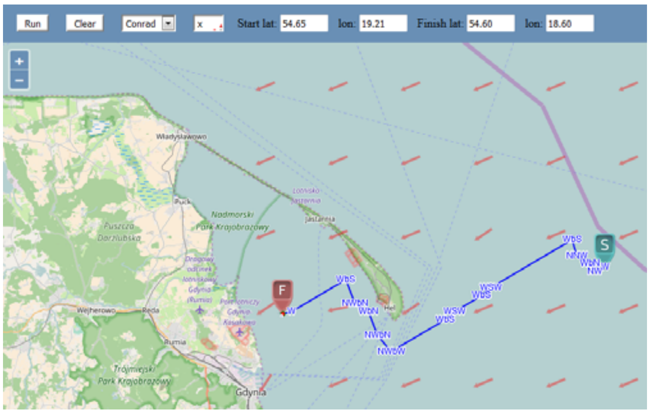
Figure 7. Conrad sailing route for parameters gr1 po

Table 3. Fragment of polar diagram of sailing vessel Conrad.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1.05	2.00	2.96	3.61	4.03	4.31	4.39	4.22	3.92	3.46	2.99	2.46	2.08	1.99
0	0	0	1.48	2.52	3.57	4.32	4.80	5.11	5.19	5.03	4.70	4.19	3.63	2.98	2.60	2.50
0	0	0	1.92	3.05	4.18	5.02	5.57	5.91	5.99	5.84	5.48	4.93	4.28	3.50	3.11	3.01
0	0	0	2.35	3.57	4.79	5.54	6.05	6.33	6.40	6.29	6.01	5.53	4.89	4.02	3.59	3.48
0	0	0	2.46	3.82	5.17	6.05	6.52	6.75	6.81	6.74	6.53	6.13	5.49	4.54	4.07	3.95
0	0	0	2.94	4.25	5.55	6.34	6.78	6.99	7.06	7.00	6.83	6.49	5.95	5.04	4.53	4.39
0	0	0	3.04	4.46	5.88	6.64	7.04	7.24	7.31	7.27	7.12	6.85	6.42	5.54	4.99	4.84
0	0	0	3.43	4.82	6.21	6.83	7.21	7.42	7.51	7.48	7.35	7.09	6.68	5.92	5.43	5.28
0	0	0	3.53	4.93	6.34	7.01	7.39	7.61	7.71	7.70	7.57	7.34	6.94	6.31	5.86	5.71

Table 4 The result of testing of searching sailing route for two sailing vessel depends on penalty time for altering course(p1) or without penalty (po), lower(gr1) or higher(gr2) granulity, Start point A is $\varphi_A(\lambda_A)$= 54.65 N(19.21 E) and end point B is $\varphi_B(\lambda_B)$ = 54.60 N(18.60 E).

Parameters	CONRAD 1200 RT					R/S OCEANIA		
	gr1 p0	gr2 p0	gr1 p0	gr1 p1	gr1 p0	gr2 p0	gr1 p1	gr2 p1
Route time T [h]	6.22	6.20	7.17	7.12	6.21	6.19	7.30	7.25
Overall distance D [NM]	38.69	38.58	41.89	41.64	38.55	38.35	40.24	39.82
Sum up penalties time to for altering course [h]	0	0	0.68	0.70	0	0	0.81	0.75
Number of Course Changes ω [-]	5	4	10	16	5	5	11	18
The number of P_k points on route [-]	27	54	15	29	28	58	15	28
Processing time to find the route from point A to point B [s]	0.93	1.91	1.06	1.91	0.80	1.54	0.96	1.52



Start lat: 54.65 lon: 19.21 Finish lat: 54.60 lon: 18.60

Figure 8. Conrad sailing route for parameters gr2 p1

5 CONCLUSIONS

Modeling of the sailing vessel depends on many factors, but mainly PD, which are difficult to access. The accuracy of PD depends on maneuvers, and consequently the travel time. An important role is played by a granulity of area, which allows a new look at safety as well as the need to modify the algorithms on the border between the two zones: basic and safety. To analyzed more practical situations of vessel sailing the application SailingAssistance were improved and examples of travels modelling of two vessels for different conditions are considered The paper presents several experiments that confirm the correctness of the developed algorithms and confirm the usefulness of SailingAssistance application.

Of course there is the opportunity to further develop these algorithms in order to strive to optimize travel time. If knowledge about sailing vessels is deeper, weather forecasting is more true, and sea area description is more realistic our modelling results can be more useful for real user competition.

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