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Verification of Ship's Trajectory Planning Algorithms Using Real Navigational Data

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ABSTRACT: The paper presents results of ship's safe trajectory planning algorithms verification. Real navigational data registered from a radar with an Automatic Radar Plotting Aid on board the research and training ship Horyzont II were used as input data to the algorithms. The algorithms verified in the presented research include the Ant Colony Optimization algorithm (ACO), the Trajectory Base Algorithm (TBA), the Visibility Graph-search Algorithm (VGA) ant the Discrete Artificial Potential Field algorithm (DAPF). Details concerning data registration and exemplary results obtained with the use or real navigational data are introduced and summarized in the paper. Presented results prove the applicability of proposed algorithms for solving the ship's safe trajectory planning problem.

1 INTRODUCTION

Due to the fact that about 90% of global trade is transported by ships (Allianz Global Corporate & Specialty SE 2018), safety of navigation is a vital issue in maritime transport. Recent trends in ship navigation include the development of unmanned ships technology. The latest developments in this area include the concept of a full-electric 120 TEU autonomous ship called Yara Birkeland, designed by Kongsberg Maritime AS (Kongsberg Maritime AS 2018) and construction of a testing site in china for unmanned ships, called the Wanshan Marine Test Field, by China Classification Society, Zhuhai Municipal Government, Wuhan University of Technology & Zhuhai Yunzhou Smart Co. (China Classification Society et al. 2018).

Unmanned ships can be remotely controlled or autonomous ships. For such vessel solutions providing possibility of autonomous navigation are needed. Autonomous navigation system has to determine a safe trajectory for a ship in a collision situation at sea and after that control the ship's motion in order to move along the determined trajectory.

Increase of computing power enables the development of algorithms for determination of a ship's safe trajectory in near real time. Due to that many new algorithms for ship's safe trajectory planning have been developed recently. The latest ship's trajectory planning approaches proposed in the literature include: differential games (Lisowski 2016), fuzzy logic and game theory (Lisowski & Mohamed-Seghir 2019), the fast marching method (Liu et al. 2017), a Collision Threat Parameters Area (CTPA) technique (Szlapczynski & Szlapczynska 2017), a Voronoi diagram (Candeloro et al 2017) and Energy Efficient A* (EEA*) (Lee et al 2015). A recent comparison of different ship's trajectory planning methods in presented in Fişkin et al. (2018).

Modern advanced control methods, such as e.g. a hybrid switching controller (Tomera 2017), Linear Matrix Inequalities (LMI) (Rybczak 2018) or an adaptive backstepping method (Witkowska & Śmierzchalski 2018), are then applied in order to execute the ship movement along the desired trajectory.

Analysis of these approaches enables to state that most of these methods were verified by simulation tests, sometimes with only simple navigational scenarios. Therefore the aim of a research presented in this paper was to verify developed different ship's trajectory planning using real navigational data registered onboard a ship.

2 DATA REGISTRATION

In order to obtain real navigational situations, a system for registration of data from a ship was developed and installed on board Horyzont II a Research/Training ship owned by Gdynia Maritime University, shown in Figure 1. The data were registered during the XLI Horyzont II voyage to Spitsbergen in 2018. A system for data registration installed onboard Horyzont II is shown in Figure 2.

Figure 1. The Research/Training ship Horyzont II.

Figure 2. A system for navigational data registration.

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14-Jul-2018 11:21:27
$RAOSD,160.9,A,160.9,W,11.6,W,,,N*70
$RATTM,50,1.67,338.1,T,7.62,273.6,R,1.52,-5.4,N,,T,,,M*36
$RATTM,64,5.10,257.8,T,7.87,315.2,R,4.30,-21.0,N,,T,,,M*09
$RATTM,65,2.73,16.4,T,22.43,340.9,R,1.59,-6.0,N,,T,,,M*3A
$RATTM,66,2.20,73.1,T,19.44,341.2,R,2.20,0.2,N,,T,,,M*18
$RATTM,67,1.84,12.1,T,11.09,337.7,R,1.04,-8.2,N,,T,,,M*36
$RATTM,68,4.43,16.3,T,10.71,340.8,R,2.57,-20.2,N,,T,,,M*0F
$RATTM,70,8.44,169.1,T,16.69,340.1,R,1.31,30.0,N,,T,,,M*1D
$RATTM,71,3.74,236.3,T,17.47,350.2,R,3.42,5.2,N,,T,,,M*22
$RATTM,72,2.55,246.1,T,17.53,353.1,R,2.44,2.6,N,,T,,,M*27
$RATTM,73,3.93,182.4,T,5.37,134.2,R,2.93,-29.3,N,,T,,,M*09
$RATTM,74,5.05,210.1,T,17.22,352.1,R,3.11,13.9,N,,T,,,M*19
$RATTM,75,5.33,212.4,T,17.25,354.8,R,3.25,14.7,N,,T,,,M*1C
$RATTM,76,6.92,205.1,T,17.16,353.5,R,3.63,20.6,N,,T,,,M*1A
$RATTM,77,9.08,200.8,T,17.34,353.4,R,4.19,27.9,N,,T,,,M*18
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Figure 3. OSD and TTM sentences of an exemplary navigational situation registered on board Horyzont II.

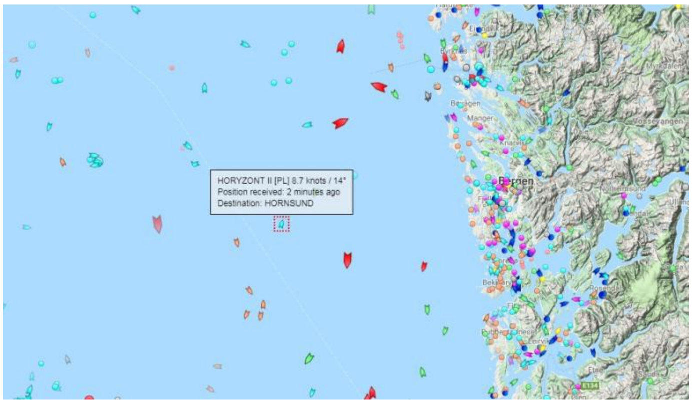

Figure 4. Horyzont II position registered by Marine Traffic on the 12th of September 2018.

Input data to the algorithms were registered form the radar with ARPA with the use of the NMEA standard, a serial asynchronous data transmission protocol used for communication between marine electronic equipment and external devices. The sentences marked as OSD (Own Ship Data) and TTM (Tracked Target Message) are needed for ship's trajectory calculation. OSD and TTM sentences of an exemplary navigational situation registered on board Horyzont II are shown in Figure 3. Navigational situation showing Horyzont II position is presented in Figure 4 and Horyzont II track is shown in Figure 5, both registered by Marine Traffic on the 12th of September 2018.

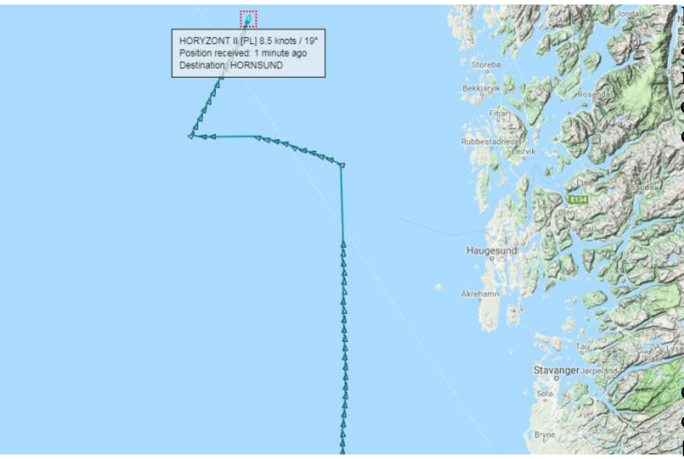

Figure 5. Horyzont II track registered by Marine Traffic on the 12th of September 2018.

3 SHIP'S TRAJECTORY PLANNING ALGORITHMS

Navigational data registered on board a ship were used to verify the performance on four different ship's trajectory planning algorithms: the Ant Colony Optimization algorithm (ACO), the Trajectory Base Algorithm (TBA), the Visibility Graph-search Algorithm (VGA) ant the Discrete Artificial Potential Field algorithm (DAPF). These algorithm represent both stochastic and deterministic optimization methods. Below a short description of the algorithms is presented.

3.1 *The Ant Colony Optimization algorithm (ACO)*

This algorithm belongs to the heuristic methods, to the subgroup called the Swarm Intelligence (SI) methods. The SI methods are approaches inspired by the collective behaviour of colonies of insects or other animal communities. The SI algorithm utilize features of insect colonies such as self-organization, flexibility and robustness. The operation principle of ACO is inspired by the ant colony foraging behaviour. Foraging ants deposit a chemical substance on the ground, called a pheromone. Other ants can smell this substance and they choose a path, where the pheromone concentration is higher. By using this trail-lying and trail-following behaviour, ants are able to find the shortest path between the food source and their nest. This behaviour is applied to artificial ants used in the ACO algorithm to solve different optimization problems.

In the ACO algorithm for ship's safe trajectory planning artificial ants move on the graph composed of admissible own ship positions in order to find the shortest trajectory between the current own ship position and the defined final waypoint. After data initialization, which includes the definition of parameters such as alpha and beta coefficients, initial pheromone trail amount at each of the possible waypoints, pheromone evaporation coefficient, number of ants, maximum number of steps to be made by an ant and number of iterations, every ant constructs its path from the current OS position to the final waypoint using the action choice rule given as Equation 1, where $\tau_{wp_j}(t)$ is the pheromone trail amount deposited on the neighbouring vertex, $\eta_{wp_{ij}}$ is the heuristic information called visibility, which is expressed as an inverse of the distance between the current vertex (i) and the neighbouring vertex (j).

$$P_{wp_{ij}}^{ant}(t)=\frac{\left[\tau_{wp_j}(t)\right]^{\alpha}\cdot\left[\eta_{wp_{ij}}(t)\right]^{\beta}}{\sum_{l\in wp_i^{ant}}\left[\tau_{wp_l}(t)\right]^{\alpha}\cdot\left[\eta_{wp_{il}}(t)\right]^{\beta}} \tag{1}$$

After that the pheromone trail update is applied, composed of pheromone evaporation and pheromone deposit according to Equation 2. After achievement of the maximum number of iterations or the maximum run time, the shortest trajectory is returned as a final solution.

$$\tau_{wp_j}(t+1)=(1-\rho)\cdot\tau_{wp_j}(t)+\sum_{ant=1}^{m}\Delta\tau_{wp_j}^{ant}(t) \tag{2}$$

3.2 *The Trajectory Base Algorithm (TBA)*

This algorithm belongs to the deterministic group of methods. In this method a database storing trajectories, constituting candidate solutions is searched through in order to find the shortest trajectory solving a considered navigational situation. Trajectories in the database are stored according to increasing value of their fitness function Equation 3, defined as the length of a trajectory.

$$I=\sum_{i=1}^{M-1}\sqrt{\left(x_{i+1}-x_i\right)^2+\left(y_{i+1}-y_i\right)^2}\rightarrow\min \tag{3}$$

COLREGs compliance of the solution, similarly as in ACO approach, of the solution is assured by a proper shape and size of the target ship domain. Trajectories are evaluated in the same order as they are sorted in the database, therefore when a trajectory not exceeding the constraints is found, the selection process in stopped, and found trajectory constitutes the shortest trajectory solving the considered situation.

3.3 *The Visibility Graph-search Algorithm (VGA)*

This algorithm belongs to the graph theory methods. the navigational environment is represented with the use of a visibility graph composed of vertices including the start and final own ship waypoints and the vertices belonging to the areas of obstacles and edges connecting these vertices, for which the connection does not intersect the areas occupied by obstacles.

The visibility graph-search algorithm used for finding the shortest collision-free own ship trajectory applies a version of A* algorithm. Applied fitness function (Equation 4) is composed of two components: the first one g(v), defined as the length of the currently considered path from the start waypoint to the currently considered vertex and the second component h(v), defined as the Euclidean distance from the current vertex to the final waypoint.

$$f(v) = g(v) + h(v) \tag{4}$$

3.4 *The Discrete Artificial Potential Field algorithm (DAPF)*

This method utilizes the concept of an Artificial Potential Field and applied it to a discrete two-dimensional configuration space, constituting a grid-based map composed of a number of cells, including free cells, cells occupied by obstacles, a start cell and a goal cell. every cell is described by three parameters: the position of its centre (x and y coordinates) and its potential. The goal cell has a potential equal to zero, cells occupied by obstacles have a potential equal to infinity, free cells are assigned with increasing potentials from goal cell to start cell, cells on the right side from the line segment connecting the start and goal cell have lower potentials than these on the left side in order to enforce fulfilment of rules 14 and 15 of COLREGs. The search algorithm calculates a ship's safe trajectory by choosing at every step from the neighbouring cells the next cell with the lowest value of its potential. After the cell has been chosen, it is assigned a potential equal to infinity in order to avoid generation of loops in the trajectory constituting the solution.

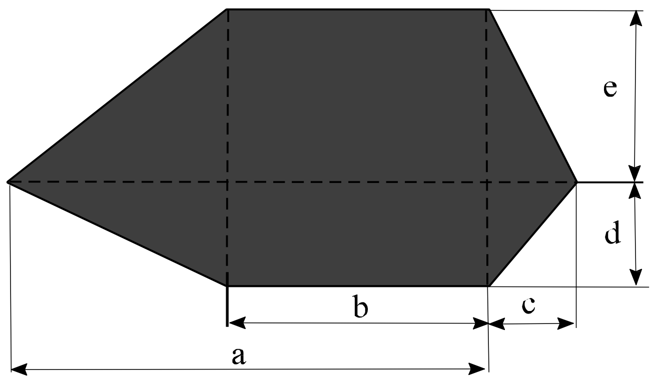

Figure 6. Target ship hexagon domain.

4 RESULTS

The ship's safe trajectory planning algorithms concisely described above were tested with the use of navigational data registered on board the ship Horyzont II. Two exemplary situations were chosen for presentation in this paper, encounters with four and fourteen target ships. Ship's trajectory planning algorithms were implemented in MATLAB programming language. Target ships were modeled with the use of hexagon domains shown in Figure 6. The dimensions of the target ship domain used in the algorithms are: a = 1.05 NM, b = 0.65 NM, c = 0.4 NM, d = 0.4 NM and e = 0.65 NM. The following parameters of ACO algorithm were used: $\tau_0 = 1$, $\varrho = 0.1$, $\alpha = 1$, $\beta = 2$, iterations = 20 and ant_number = 10.

4.1 *Test case 1 an encounter with four target ships*

Table 1. Input data for test case 1.

Ship	Ψ [º]	V [kn]	D [NM]	N [º]
0	132.2	10.7	-	-
1	137.5	3.48	1.39	346.1
2	144.3	5.02	1.61	109.7
3	318	19.04	12.55	123.5
4	307.8	17.02	5.02	170.9

Test case 1 is an encounter situation between an own ship and four target ships. Input data describing this navigational situation are given in Table 1, while numerical results for all of the algorithms including the length of the safe trajectory in nautical miles, calculated course of an own ship at consecutive stages of its movement along the determined trajectory in degrees and the run time of the algorithm in seconds are listed in Table 2. Graphical results obtained for the VGA algorithm, for which the shortest safe own ship trajectory was calculated, are shown in Figure 7 along with the instantaneous positions of all of the target ships. Figure 8 presents a comparison of trajectories obtained by different algorithms. All of the algorithms found a solution for the considered encounter situation. As it can be seen the trajectories do not differ significantly. TBA achieved the lowest run time, while VGA obtained the shortest trajectory in a reasonable amount of time.

Table 2. Results of test case 1.

Method	distance [NM]	course [º]	run time [s]
ACO	9.22	144, 118	13.99
TBA	9.22	146, 121	0.27
VGA	9.08	141, 126	1.41
DAPF	9.22	145, 120	0.99

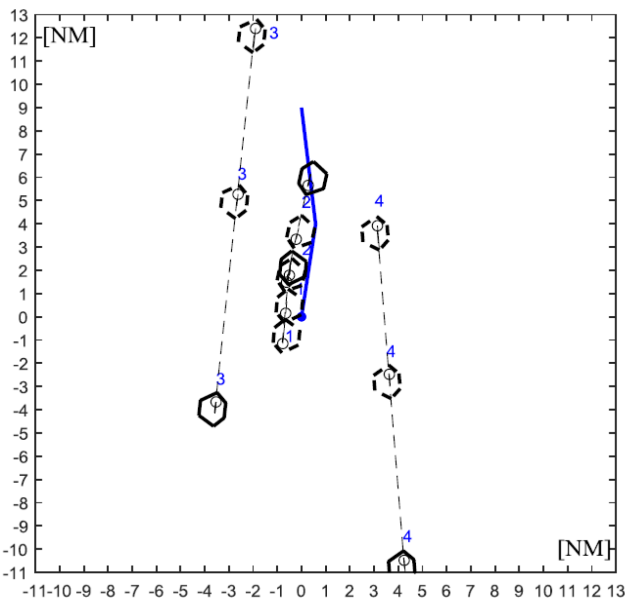

Figure 7. Safe trajectory calculated by VGA for test case 1.

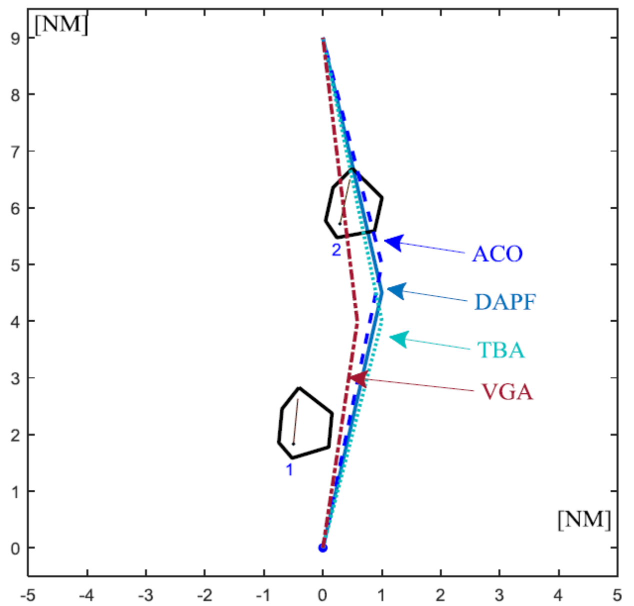

Figure 8. Comparison of safe trajectories calculated by different algorithms for test case 1.

4.2 *Test case 2 an encounter with fourteen target ships*

Test case 2 is an encounter situation between an own ship and fourteen target ships. Input data defining this navigational situation are shown in Table 3. Numerical results are listed in Table 4. Graphical results obtained for the VGA algorithm are presented in Figure 9. In Figure 10 a comparison of trajectories obtained by different algorithms is shown. A safe own ship trajectory for this test case has also been found by all of the algorithms. for this situation the results obtained by different algorithm also do not vary considerably. For this test case TBA also reached the lowest run time and VGA achieved the shortest trajectory.

Table 3. Input data for test case 2.

Ship	Ψ [º]	V [kn]	D [NM]	N [º]
0	160.9	11.6	-	-
1	273.6	7.62	1.67	338.1
2	315.2	7.87	5.1	257.8
3	340.9	22.43	2.73	16.4
4	341.2	19.44	2.2	73.1
5	337.7	11.09	1.84	12.1
6	340.8	10.71	4.43	16.3
7	340.1	16.69	8.44	169.1
8	350.2	17.47	3.74	236.3
9	353.1	17.53	2.55	246.1
10	134.2	5.37	3.93	182.4
11	352.1	17.22	5.05	210.1
12	354.8	17.25	5.33	212.4
13	353.5	17.16	6.92	205.1
14	353.4	17.34	9.08	200.8

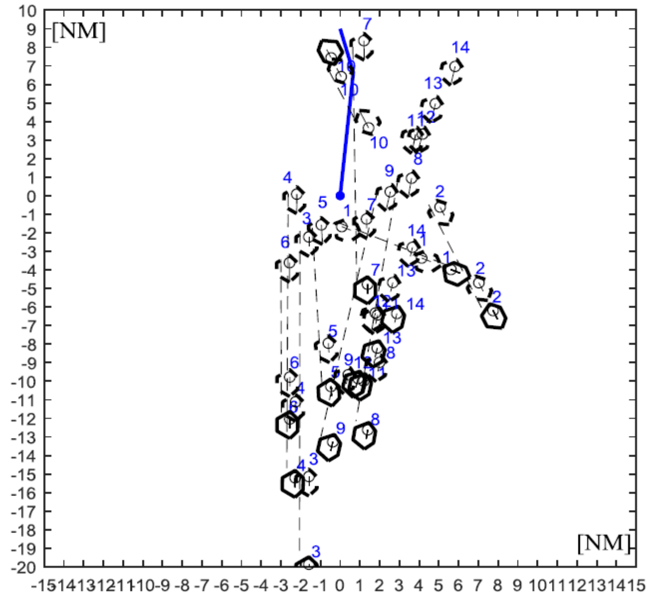

Figure 9. Safe trajectory calculated by VGA for test case 2.

Table 4. Results of test case 2.

Method	distance [NM]	course [º]	run time [s]
ACO	9.25	170, 142	20.91
TBA	9.22	172, 147	0.32
VGA	9.13	167, 145	8.36
DAPF	9.37	168, 127	0.71

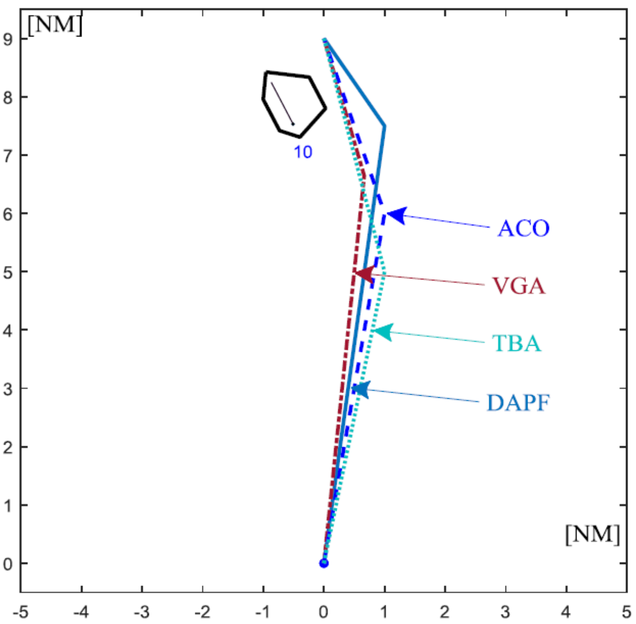

Figure 10. Comparison of safe trajectories calculated by different algorithms for test case 2.

5 DISCUSSION AND CONCLUSIONS

The paper presents results of research on verification of ship's safe trajectory planning algorithms based upon real navigational data registered on board a ship. Real navigational data used as input data for the algorithms enable for an in depth evaluation of the algorithms performance, before their application in safe ship control system onboard a ship.

All of four tested algorithms were able to find a solution to the considered encounter situations. Solutions obtained by different algorithms varied slightly in terms of the length of the determined trajectory and with regard to their run time. The best results were achieved with the use of the VGA algorithm, the TBA algorithm was characterized by insignificantly longer trajectories but achieved in lower run time.

Further research will include tests of the algorithms applied in safe ship control system onboard a ship. It would also be valuable to include data from the Automatic Identification System, what will allow for taking into account the dimensions of the vessels in the process of ship's safe trajectory calculation.

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