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Verification of a Deterministic Ship's Safe Trajectory Planning Algorithm from Different Ships' Perspectives and with Changing Strategies of Target Ships

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ABSTRACT: The paper presents results of a ship's safe trajectory planning method verification - the Trajectory Base Algorithm, which is a deterministic approach for real-time path-planning with collision avoidance. The paper presents results of the algorithm's verification from different ships' perspectives and with changing strategies of target ships. Results prove the applicability of the algorithm in the Collision Avoidance Module of the Autonomous Navigation System for Maritime Autonomous Surface Ships.

1 INTRODUCTION

In recent years a dynamically growing interest in autonomous vehicles can be observed both in academia and industry. Starting from self-driving cars, through autonomous mobile robots and autonomous drones, and reaching out to autonomous ships. The last group recently obtained a specific term expressing such vehicles, which was introduced by the International Maritime Organization (IMO). Autonomous vessels are referred to as Maritime Autonomous Surface Ships (MASS) and this term became very popular nowadays and is commonly used by researchers, classification societies, equipment manufacturers and technology providers. According to the American Bureau of Shipping (ABS) "an autonomous ship is a marine vessel with sensors, automated navigation, propulsion and auxiliary systems, with the decision logic to follow mission plans, sense the environment, adjust mission execution for the environment, and operate without human intervention." [1]

Bureau Veritas categorizes ship autonomy levels in a 5-points scale from 0 to 4. Level 0 is a conventional, fully manned ship, where staff make and execute decisions based upon acquired data. Level 1 is a smart ship, which is defined as a vessel guided by humans, which uses sensors and systems for data acquisition and support in decision making. Levels 2 and 3 are semi-autonomous ships. Their operation is supervised by humans, but relies on decision making systems. Level 4 is a fully autonomous ship, which is an unmanned ship that does not need any human intervention other than in an emergency. [4]

Further details on ship autonomy levels and autonomous vessels classification can be found in [2] and [21].

In the last decade many research projects on the development of autonomous ships technology were carried out. Among them are: Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) [22], ReVolt [5], Advanced Autonomous Waterborne Applications (AAWA) [26], Autosea [25], Autoferry [24], Yara Birkeland [11] and Safer Vessel with Autonomous Navigation (SVAN) [27].

In table 1 research projects on autonomous ships are listed in a chronological order from the oldest to the newest.

Table 1. Research projects on autonomous ships

Project	Type of vessel	Years
MUNIN [22]	not specified	2012-2015
ReVolt [5]	60 m, 1300 DWT, battery powered	2013
AAWA [26]	not specified	2015-2018
Autosea [25]	not specified	2015-2019
Autoferry [24]	5 m, electric passenger ferry milliAmpère	2016-2019
Yara Birkeland [11]	79.5 m, fully electric container feeder, 120 TEU	2017-2022
SVAN [27]	53.8 m, ferry Finferries Falco	2018

According to [2] Autonomous Surface Vehicles (ASVs) are divided into Maritime Autonomous Surface Ships (MASS) and Unmanned Surface Vehicles (USVs), which are small crafts without a crew onboard, that can be controlled remotely or can operate fully autonomously. Development projects are also conducted in relation to USVs. Table 2 presents examples of recently developed USVs.

Table 2. Recently developed USVs

USV	Country	Length [m]	Speed
Katana [7]	Israel	11.9	60 kn
Tianxing-1 [33]	China	12.2	over 50 kn
C-Target 9 [15]	USA	9.6	50 kn
Edredon [8, 10]	Poland	5.7	30 kn

2 AUTONOMOUS NAVIGATION SYSTEM

According to the European Maritime Safety Agency (EMSA) [6] in the years 2014–2019 19418 marine casualties and incidents were reported in the European Marine Casualty Information Platform (EMCIP). During 833 safety investigations carried out in the years 2014–2019, 1801 accident events were distinguished and analyzed. 54% (969) of these accident events were categorized as human actions and 28% as system/equipment failures. Collisions (1769), contacts (2268) and grounding/stranding (1765) represent 44% of all casualty events that took place in the analyzed period of time. 78 fatalities were reported in collisions that occurred in the years 2014–2019. According to the results of an investigation presented in [35] application of unmanned ships should cause the reduction of groundings and collisions. Therefore, the introduction of autonomous vessels might be regarded as a desired phenomenon, which will contribute to the increase of safety at sea.

Collision avoidance is one of the most important tasks that has to be performed during ship navigation. That is true not only for conventional ships, but it equally applies to autonomous vessels. In order to better understand the importance of collision avoidance and safe trajectory planning algorithms for a proper functioning of an autonomous ship, a brief overview of recent concepts on Autonomous Navigation Systems (ANSs) will be described below.

The ANS is a system responsible for the navigation of an unmanned vessel. Table 3 shows an analysis of the ANSs applied in recent projects on autonomous ships. In the MUNIN project the ANS is composed of two subsystems, responsible for weather routing and collision avoidance. An important system providing input data to the ANS is the Advanced Sensor Module (ASM) [23]. In the AAWA project the ANS is composed of four modules: Route Planning (RP), Situation Awareness (SA), Collision Avoidance (CA) and Ship State Definition (SSD) [26]. The CA module is responsible for the collision risk assessment, based upon data obtained from the SA module. The second task of the CA module is an assurance of safe navigation of the ship, both in the open sea and in restricted waters. The SA module, which is an analogy to the ASM in the MUNIN project, fuses data from different navigational sensors. In the Autosea project the CA module is composed of: Collision Detection, Collision Avoidance and Guidance subsystems [3, 14]. Input data are acquired from the Sensor Fusion Module, which gathers data from different navigational sensors and systems, such as navigational charts, AIS and radar. To sum up, despite the difference in the nomenclature used in the projects, the functions of modules for collision avoidance and data fusion are identical or very similar, with very slight difference in their design and operation.

The main component of the CA module of the ANS is a collision avoidance algorithm, responsible for the determination of a safe maneuver or a safe trajectory of unmanned vessel, when a collision risk has been detected. Table 4 lists the collision avoidance algorithms applied in recent projects on autonomous ships. Table 5 lists other recent most promising collision avoidance methods for ships, applicable also to unmanned and fully autonomous vessels.

Table 3. ANSs in research projects on autonomous ships

Project	Module for collision avoidance	Module for data reception and fusion	Data sensors
MUNIN [23]	Collision Avoidance (CA) module	Advanced Sensor Module (ASM)	marine radar, AIS receiver, daylight & infrared cameras, nautical data
AAWA [26]	Collision Avoidance (CA) module	Situation Awareness (SA) module	visual cameras, IR cameras, radar, lidar
Autosea [3, 14]	Collision Avoidance (CA) module	Sensor Fusion Module	AIS, radar, camera, charts

Table 4. CA algorithms in research projects on autonomous ships

Project	Collision avoidance algorithm
MUNIN [23]	Based upon formalized description of COLREGs
AAWA [26]	Velocity Obstacles (VO) method
Autosea [3, 14]	Model Predictive Control (MPC)

Table 5. Recent CA algorithms

Author algorithm	Year	Collision avoidance
Kang Y. et al. [9]	2021	Differential Evolution (DE) algorithm
Zhang W. et al. [34]	2021	Velocity Obstacles (VO)
Koszelew J. et al. [12]	2020	Beam Search Algorithm (BSA)
Lazarowska A. [16]	2020	Discrete Artificial Potential Field (DAPF)
Lisowski J. [18, 19]	2020	game theory
Kuczkowski Ł. and Śmierzchalski R. [13]	2017	Evolutionary Algorithm (EA)
Lazarowska A. [17]	2017	Trajectory Base Algorithm (TBA)
Mohamed-Seghir M. [19, 20]	2017	fuzzy sets
Szłapczyńska J. and Szłapczyński R. [28]	2017	heuristic method based on Collision Threat Parameters Area (CTPA)
Tam Ch. and Bucknall R. [31]	2013	deterministic method
Szłapczyński R. and Szłapczyńska J. [29, 30]	2012	Evolutionary Algorithm (EA)
Tam Ch. and Bucknall R. [32]	2010	Evolutionary Algorithm (EA)

In order to validate the ship's trajectory planning algorithm a number of simulation tests is performed and results of these experiments are evaluated. Solutions are assessed in terms of their safety, compliance with COLREGs, efficiency, which is evaluated by one or a few of the following criteria: path length, time of passage, number and value of course alteration maneuvers, deviation from the initial course. A complex validation of a collision avoidance algorithm for ships should include also tests assessing solutions from different ships' perspectives and with changing strategies of target ships. Results of algorithms' evaluation including these two above mentioned criteria are not commonly presented in the literature. Examples of an algorithm's assessment from the perspectives of different ships taking part in considered situation can be found in [9, 29–32]. Changing strategies of target ships are regarded in an approach based upon an evolutionary algorithm, introduced in [13]. Another example is the game theory approach, presented in [18, 19], which in its operation principle includes changing strategies of dynamic obstacles. As stated in [18] games can be a cooperative or non-cooperative interaction between players (ships).

This paper presents results of an evaluation of a deterministic algorithm for ship's trajectory planning, called the Trajectory Base Algorithm (TBA). Assessment of the algorithm was concentrated on the two above mentioned aspects: compliance of trajectories from different ships' perspectives and the algorithm's behavior considering changing strategies of target ships.

The rest of the paper is organized as follows. In section 3 the tested algorithm is briefly introduced. Section 4 presented results of simulation tests, in the first part from different perspectives of ships and in the second part with changing strategies of dynamic obstacles. Section 5 presents conclusions resulting from the presented outcomes.

3 THE METHOD DESCRIPTION

Applied algorithm is a deterministic approach. The advantage of such algorithm is the certainty of achievement an identical solution for every run of calculations with the same input data as there is a lack of stochastic mechanisms in the algorithm's operation. Simplicity of the approach contributes to the achievement of relatively low run time of the algorithm what makes the approach applicable in practical applications of real time path planning in Collision Avoidance Modules of Autonomous Navigation Systems for unmanned and fully autonomous ships.

```
Input: Ψ, V, Ψj, Vj, Dj, Nj, positions_of_static_obstacles
for (t = 1; t <= t_max; t++) do
      candidate_path = path(t);
      divide candidate_path into k steps
      for (step = 1; step <= k; step++) do
            collision check procedure
            if (collision == true) then
                  reject candidate_path
                  break;
            end if
      end for
      if (collision == false) then
            break;
      end if
end for
if (collision == false) then
    solution_found
    Output: path_length, transition_time, ΔΨ
else
    Output: lack_of_solution
end if
```

Figure 1. Pseudocode of the TBA.

The operation principle of the Trajectory Base Algorithm (TBA) for ship's collision avoidance is based upon the search through a base of trajectories. Stored trajectories constitute candidate solutions. A solution to the problem is the best collision-free trajectory with the minimal path length. Trajectories are evaluated by the division into a number of steps. In every step an own ship is moved into a new instantaneous position along the evaluated trajectory and target ships, modeled with the use of ship domains are moved into corresponding instantaneous positions resulting from their motion parameters. After that the algorithm checks, whether their current instantaneous positions do not cause a collision. When an evaluated own ship trajectory does not cause a collision with any of the target ships during an own ship's movement along it, then it becomes the final solutions and further calculations are terminated. The reason for that is the order of trajectories in the base, which are sorted according to the increasing length. The COLREGs fulfillment is achieved by a proper shape and size of applied ship domain. The ship domain size also takes into account the conditions of good and restricted visibility at sea. A ship domain applied in presented simulation tests is a hexagon domain with the following dimensions: distance towards the bow = 1.3 nm, distance of amidships = 0.6 nm, distance towards the starboard side = 0.6 nm, distance towards the stern = 0.5 nm and distance towards the port side = 0.5 nm, suitable for good visibility conditions. Figure 1 presents a pseudocode of the TBA. A more detailed description of the TBA can be found in [17].

4 SIMULATION EXPERIMENTS

The TBA was implemented in the MATLAB programming language and tested with the use of a number of test cases. Examples of obtained solutions were chosen for the presentation in this paper. Simulation experiments, as it was mentioned above, were concentrated on the evaluation of solutions' consistency from the perspectives of different ships taking part in the considered test case. In the second part of experiments the algorithm was tested including changing strategies of target ships. The changes of target ships strategies covered course alterations. Calculations were carried out using a PC with Intel Core i7-10750H 2.60 GHz, 32 GB RAM, 64-bit Windows 10 operating system.

4.1 *Different perspectives*

In the first part of experiments different test cases were evaluated from the perspectives of all ships taking part in an encounter situation. Solutions of a few test cases chosen for the presentation in the paper are shown in Figures 2-4. The scales in figures are in nautical miles. An own ship trajectory is marked with OS abbreviation and target ships' trajectories are analogously marked with TS abbreviation followed by the number of the ship if more vessels take part in the situation. Consecutive positions of OS and TSs in figures are marked with numbers indicating the corresponding time in minutes (rounded to integers). Analysis of these results enables to state that trajectories calculated by the TBA for all of the ships participating in the considered encounter situation are compliant and do not lead to a collision between any of the vessels.

4.2 *Changing strategies*

In the first part of simulation experiments the algorithm was evaluated in terms of its performance for situations with changing strategies of target ships. An example of such test case is presented in Figure 5, where the target ship alters its course during its movement along an initial trajectory. As it can be seen in Figure 5 a trajectory calculated by the algorithm for an OS constitutes a safe trajectory. Obtained results lead to the conclusion that the algorithm assures calculation of a safe solution also with regard to situations of changing strategy of a target ship.

An analysis of performed simulation tests enable to state the following conclusions. The algorithm calculates compliant solutions from the perspectives of different ships taking part in the considered encounter situation. Calculated solutions are compliant with COLREGs (are large enough to be readily apparent for other vessels (rule 8b) and are performed to the proper side of the vessel (rules 13, 14 and 15).

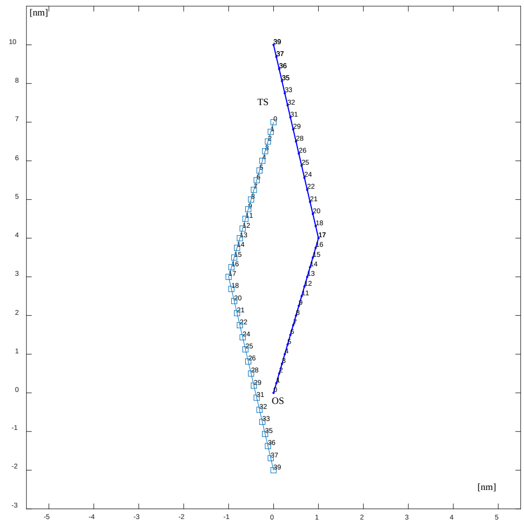

Figure 2. Solutions returned by TBA from both ships' perspectives for test case 1 (head-on scenario, good visibility).

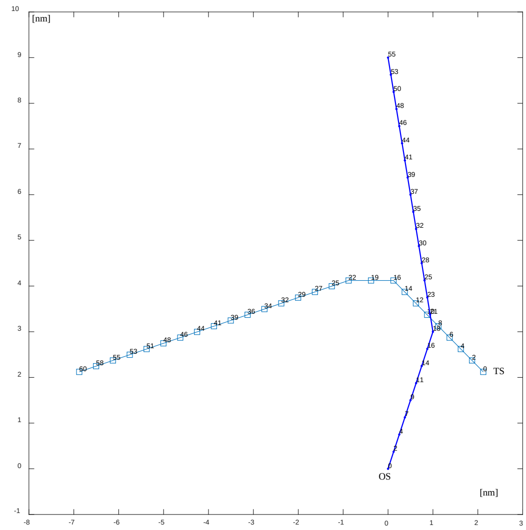

Figure 3. Solutions returned by TBA from both ships' perspectives for test case 2 (crossing scenario, good visibility).

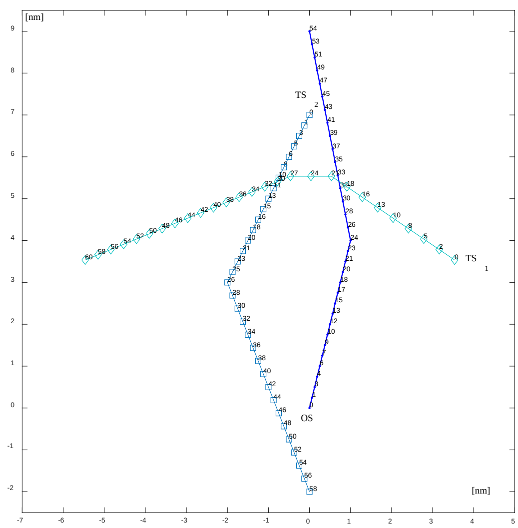

Figure 4. Solutions returned by TBA from all ships' perspectives for test case 3 (with 2 target ships, good visibility).

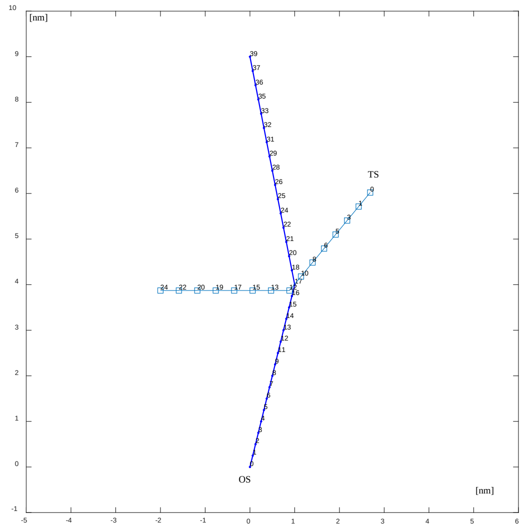

Figure 5. Solution returned by TBA for test case 4 (changing strategy of the target ship, good visibility).

5 CONCLUSIONS

The paper presents results of complex simulation experiments with regard to an algorithm for ship's real-time path-planning with collision avoidance. The Trajectory Base Algorithm, to which these studies relate, is a deterministic approach developed by the author of the paper and introduced in previous works. This paper presents results of extended tests of this algorithm including verification from different ships' perspectives and with changing strategies of target ships. Results constitute the next step of validation of this approach in terms of its applicability in the Collision Avoidance Module of the Autonomous Navigation System for Maritime Autonomous Surface Ships. Obtained solutions prove a successful validation of the method with the use of above described tests. It is planned to test the algorithm in real life operating conditions onboard a ship with input data from ARPA and AIS fed into the algorithm in real time. Preliminary real-life tests of the algorithm have already been performed, but more extensive testing is still needed before commercial application can be regarded.

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