DETERMINISTIC-BASED SHIP ANTI-COLLISION ROUTE OPTIMIZATION WITH WEB-BASED APPLICATION

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SUMMARY

Most of the accidents are caused by human error at sea so, decision making process made by navigators should be more computerised and automated. The supported decision making can be a step forward to decrease the risk of collision. This paper, in this respect, aims to present a deterministic approach to support optimum collision avoidance trajectory. This approach involves a collision avoidance course alteration. A web-based application coded with "JavaScript" programming language on the "Processing" software platform which allows the own ship to change her course in a deterministic manner to avoid collision optimally has been introduced. Algorithm structure of the method has been formulated and organized according to the International Regulation for Preventing Collision at Sea (COLREGs). The experimental tests results have revealed that the system is practicable and feasible and considerably outperforms heuristic-based method. It is thought that the developed method can be applied in an intelligent avoidance system on board and provides contribution to ship collision avoidance process, automation of ship motion control and ship traffic engineering.

NOMENCLATURE

ACO	Ant Colony Optimization
AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid
BFO	Bacteria Foraging Optimization
COLREGs	International Regulation for Preventing Collision at Sea
CPA	Closest Point Approach
CSBA	Cat Swarm Biological Algorithm
DLSA	Distributed Local Search Algorithm
DSSA	Distributed Stochastic Search Algorithm
DTSA	Distributed Tabu Search Algorithm
ECDIS	Electronic Chart Display and Information System
GA	Genetic Algorithm
GPS	Global Positioning System
IMO	International Maritime Organization
LOS	Line-of-Sight
OS	Own Ship
TBA	Trajectory Base Algorithm
TBADSS	Trajectory Base Algorithm Decision Support System
TS	Target Ship
USV	Unmanned Surface Vehicle
WBDA	Web-Based Deterministic Algorithm
C_{os}	Course of the OS
C_{ts}	Course of the TS
Δ	Discriminant
$D_{os,ts}(t)$	The instantaneous distance between the ships at time t
kn	Knot (mile/hour)
n/a	Not available
Nm	Nautical mile
RB_{ts}	Relative bearing of TS
RD	A final point distance to return the OS to its original route
s	second
SD	Ship domain size in radius
t1	Moment of entry to SD
t2	Moment of exit from the SD
(X_{os}, Y_{os})	Position of the OS
(X_{ts}, Y_{ts})	Position of the TS
V_{os}	Speed of the OS
V_{ts}	Speed of the TS

1. INTRODUCTION

In parallel with the increasing volume of international trade, the demand for maritime transport is increasing day by day. Due to the fact that the vast majority of world trade is carried out by sea transportaiton, the density of vessel traffic in international navigable waters increases and this causes high risk for collision (Mou et al., 2010: 483; Christiansen et al., 2007). In case of a collision at sea, the environment, economy and life are undoubtedly negatively affected (Kim et al., 2017: 699). Despite of the fact that the many measures and technological advances have been conducted in ship navigation, collision still have the great percentage within maritime accidents (Sormunen et al., 2016). Many maritime accident investigation reveals that 90% of maritime accidents, especially collisons, are caused by human errors. In this respect, collision comprises one major safety concern at sea (Xu, 2014: 268). Enhancing navigation intelligence may be one of the most effective ways to increase maritime safety (Zhang et al., 2015:336).

In practice, the collision avoidance process in sea navigation is usually performed under the navigators' own judgement and experience (Wang et al., 2017: 486). The navigational aids located in a ship which assist the navigators in decision making comprise Automatic Identification System (AIS), Electronic Chart Display and Information System (ECDIS), Global Positioning System (GPS) and Automatic Radar Plotting Aid (ARPA) Radar. The aids are able to provide information about navigational environment such as shallows, obstacles, other ships, etc. ARPA, in particular, can report a potential collision risk. It can not, however, propose an optimal trajectory to avoid collison (Lazarowska, 2014: 1013).

Planning a safe trajectory at sea comprises a complex process which should include precision and optimality (Lazarowska, 2017: 469). Controlling a ship safely depends on a number of factors such as the speed and course of the ships, the distance between them, maneuverabilty, their size, and the feature of the trajectory (Grinyak, 2016: 249).

Although many methods have been proposed, the problem has not been so far completely solved. Because of the complexity of the problem, it is difficult to form a definite solution regarding all of the constraints and demands, illustrated in Figure 1, such as weather condition, maneuveribility of ships, static obstacle, multi-ship encounter, dynamic particulars of ships, etc (Lazarowska, 2016: 1024).

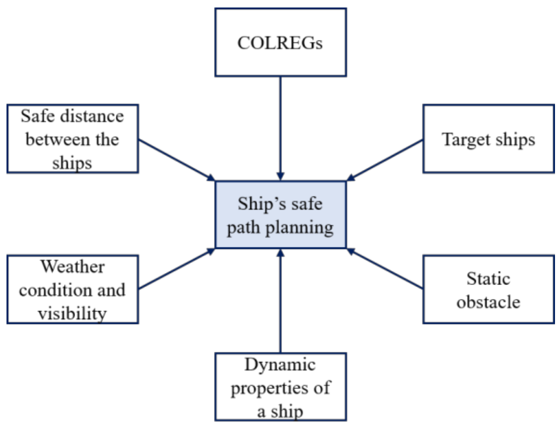

Figure 1. Restrictions regarding a ship's safe trajectory process. Source: Lazarowska, 2016: 1024

In case of an encounter situation at sea, ships are obliged to obey COLREGs defined by the International Maritime Organization (IMO). The situations are classified by COLREGs as head-on, crossing and overtaking which is illustrated in Figure 2. The role of ships to avoid collison for each situation is determined by COLREGs through Rule 13 to Rule 17. Rule 13 (Overtaking) states that *any vessel overtaking any other shall keep out of the way of the vessel being overtaken.* Rule 14 (Head-on) defines that *when two power-driven vessels are meeting on reciprocal or nearly reiprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.* Rule 15 (Crossing) makes it clear that *when two power driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.* Rule 16 (Give-way vessel) orders *that every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to avoid collison.* Rule 17 (Stand-on vessel) demands that *where one of two vessels is to keep out of the way the other shall keep her course and speed.*

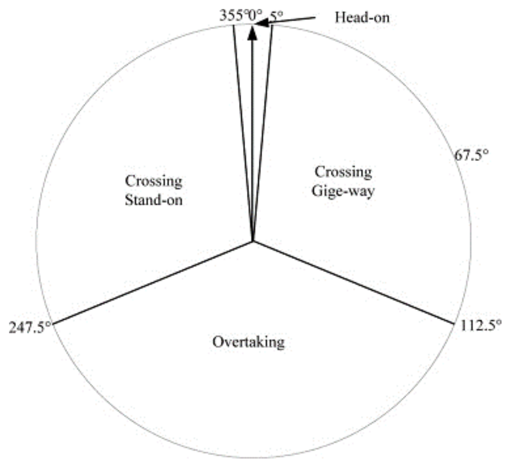

Figure 2. Diagram for encounter situation at sea

In this study, unlike the studies in related literature, a Web-Based Deterministic Algorithm (WBDA) to solve encounter situation at sea has been introduced in compliance with the general requirements of COLREGs. The proposed system allows the own ship (OS) to change her course in a deterministic manner to avoid collision optimally. It guarantees that the global optimum is revealed. The study is restricted to one-to-one ship encounter situation because of the nature of COLREGs. The developed system is a guidance system, which contributes to navigator decision-making capability. It can be integrated into any autonomous system like an Unmanned Surface Vehicle (USV). It is believed that the presented approach provides guidance to navigators on the decision-making process and constitutes a valuable contribution to intelligent marine systems.

The remaining sections of the paper are organized as follows: section II introduces and discusses related studies in the literature, section III gives information about the methodology and model description of the developed system including the framework and terminology, and section IV provides experimental test results and findings which indicate the efficiency of the method. The conclusion is also presented at the end of the paper.

2. LITERATURE REVIEW

The ship collision avoidance problem has attracted quite interest of researchers by means of the technological development (Tam and Bucknall, 2013: 25). On the other hand, the increase of marine traffic density has led to research to find out the new solutions to the problem (Szlapczynska and Szlapczynski, 2017: 591).

Many studies have been proposed through the years to solve collision avoidance trajectory planning. These studies have been reviewed and discussed with different frameworks by Tam et al. (2009), Statheros et al. (2008) and Fışkın et al. (2018). On the other hand, some studies recently introduced are as follows:

Wei et al. (2015) has developed a minimum fuel consumption based solution model to solve collision avoidance problems at sea. In this study, problem solving has been achieved by using the Cat Swarm Biological Algorithm (CSBA). The simulation tests have showed that the model is effective and applicable.

Lazarowska (2015) has presented a swarm intelligence application using Ant Colony Optimization (ACO) to form a decision support system. The capability of the system contains collision avoidance path planning in restricted waters as well as open sea. In this study, polygonal ship domain has been used instead of circular which is commonly used and static objects have also been taken into account to generate collision-free trajectories. The other ACO based method has been introduced by Tsou and Hsueh (2010). The main difference between these two studies is solution construction. The former one takes into account all target ships (TSs) in the vicinity at the same time to construct a collision avoidance path. The latter one, however, the TS with the highest collision risk is first to be disposed. The collision avoidance calculation has been performed with regard to collision risk degree of the TSs.

On the other hand, Lazarowska (2017) has also presented a deterministic approach, called the Trajectory Base Algorithm Decision Support System (TBADSS), to generate a decision support system providing an optimal and safe trajectory for ships. The system has been formed to solve the trajectory planning problem for complex environment with dynamic and static obstacles. The TBADSS composes of four submodules as Data Input Module, Database Module, TBA Module and Solution Output Module. The database constituting all possible solution trajectory has been created and the TBADSS aims to find the optimal one. The deterministic algorithm has been compared with the ACO-based method. The TBA-based approach provides better performance concerning lengths of path and execution time.

Nguyen et al. (2012) has developed a Bacteria Foraging Optimization based automatic tool for navigators by determining the optimal collision avoidance strategy. The proposed algorithm has been applied for various scenarios to confirm its efficiency. The scenario implementations have showed that the algorithm is robust, efficient and applicable.

Naeem et al. (2012) has proposed a COLREGs-based collision avoidance strategy for USV. The developed system is a reactive path planning algorithm providing feedback to autopilot of USV or navigator of manned ship for altering the course. A* algorithm and Line-of-Sight (LOS) algorithm has been used to generate a safe trajectory and both could produce a realistic trajectory.

Lisowski (2012) has introduced a game control process in marine navigation. In this study, multi-step matrix and multi-stage positional, cooperative and non-cooperative, optimal and game control algorithms in encounter situation has been implemented. The simulation of control game algorithm has revealed that the model of game theory for the optimal manoeuvring has made it possible to form the safe route of the OS passing through a large number of TSs.

Tam and Bucknall (2013) has developed a deterministic based algorithm to generate a practical and COLREGs-complaint navigation trajectory for ships with collision risks. The algorithm structure has been categorized into two main subdivisions. The first subdivision is to determine the collision risk for each target in the vicinity. The second subdivision comprises the calculation of avoidance manoeuvre to overcome the collision risk. It is emphasized in the study that the algorithm is based on a deterministic form so, it can produce the exact and unique solution in every execution.

Xu (2014) has presented a Danger Immune Algorithm-based method to accomplish ship collision avoidance route optimization regarding economy and safety. In this study, ship domain and ship arena have been utilized to evaluate the collision risk to calculate the fitness function. The simulation tests have revealed that the algorithm is feasible and valid.

Zhang et al. (2015) have studied on a multi-ship collision avoidance decision support using Linear Extension Algorithm under the requirements of COLREGs. The model has been developed to form a safe path for the OS to keep her clearance from all the TSs in the navigation area. The study concludes that the speed changing to avoid collision gives better performance than course alteration for encounter situations with small crossing angle while course alteration performs better for large crossing angle.

Johansen et al. (2016) has described a model predictive control based approach for collision avoidance system for ship. A set of control behaviours for an autonomous ship have been constituted by diversifying two parameters: course command and propulsion command. Simulation experiment has showed that the model can be set to determine control behaviours for various cases and effectively manages complex situations with multiple obstacles.

Wang et al. (2017) has proposed a finite-time observer based accurate tracking control plan for path tracking of a marine vehicle with complex uncertainties. The simulation studies carried out in the study have showed that the marine vehicle system under the thoroughly uncertain dynamics conditions can be properly tracked regarding velocity and position.

Kim et al. (2017) has developed a Distributed Stochastic Search Algorithm (DSSA)-based method which enables each ship to alter her course in a stochastic manner according to the intentions of the TSs. The experimental test results have showed that the DSSA yields better performance than the Distributed Local Search Algorithm (DLSA) (developed by Kim et al, 2014) and the Distributed Tabu Search Algorithm (DTSA) (developed by Kim et al., 2015). Wang et al. (2018a) has developed a yaw-guided method to accurate trajectory tracking control problem of an asymmetric underactuated surface vehicle to overcome both complex uncertainties and underactuations. In the study, a finite-time uncertainty observers-based yaw-guided tracking control scheme has been developed and the experimental tests have revealed that the scheme provides remarkable performance. Wang et al. (2018b) has also proposed a fuzzy based scheme for the same problem and has achieved reliable consequences from the simulation tests.

To sum up, Table 1 provides the major features and comparison of the recent studies. The studies have been evaluated in accordance with the eight characteristics: the method used to reach solution, action type to avoid collision, ship domain type used for calculation and which ship is surrounded, expression of ship domain, problem solving capability in complex environments, consideration of dynamic and static obstacles and compliance to the COLREGs.

Table 1. Comparison of the recent studies.

Reference	Method	Action Type	Domain Type	Expression of Domain	Complex Env.	Static Obstacle	Dynamic Obstacle	COLREGs Compliance
COLREGs, 1972	regulation	course alteration/ speed change	n/a	safe distance	no	no	yes	-
Tsou and Hsueh, 2010	ACO	course alteration	circular (around the OS)	safety domain	no	no	yes	yes
Lisowski, 2012	game theory	course alteration/ speed change	polygonal (around obstacle)	ship domain	yes	no	yes	yes
Naeem et al., 2012	A*, line-of-sight	course alteration	circular (around obstacle)	safety zone	yes	yes	yes	yes
Nguyen et al., 2012	BFO	course alteration	polygonal (around obstacle)	ship domain	yes	yes	yes	yes
Tam and Bucknall, 2013	deterministic	course alteration	circular (around the OS)	domain of interest	yes	yes	yes	yes
Xu, 2014	danger immune algorithm	course alteration	circular (around the OS)	ship domain	no	no	yes	yes
Zhang et al., 2015	linear extension algorithm	course alteration/ speed change	circular (around the OS)	ship domain	yes	no	yes	yes
Wei et al., 2015	CSBA	course alteration	circular (n/a)	safety distance	no	no	yes	yes
Lazarowska, 2015	ACO	course alteration	polygonal (around obstacle)	ship domain	yes	yes	yes	yes
Johansen et al., 2016	deterministic	course alteration/ speed change	circular (around the OS)	safe distance	no	no	yes	yes
Lazarowska, 2017	deterministic	course alteration/ speed change	Polygonal (around obstacle)	ship domain	yes	yes	yes	yes
Kim et al., 2017	DSSA	course alteration	circular (around the OS)	safety domain	yes	no	yes	yes
The method proposed in this study	WBDA	course alteration	circular (around the OS)	ship domain	no	yes	yes	yes

3. ALGORITHM STRUCTURE

This section describes how to form an evasion route by course alteration in encounter situations at sea using the developed method. The method is based on two phases: the control and solution phases whose framework is illustrated in Figure 3. In the control phase, briefly, after the navigation data of the ships have been defined, the motions of the ships are calculated and it is checked whether the relative motion of the TS violates the ship domain. If there is a violation and the OS is the give-way ship, it passes through to the solution phase to calculate the necessary course alteration to avoid collision. In the solution phase, the optimal course to avoid collision is calculated and assigned to the OS as a new course.

The proposed method for collision avoidance aims to meet the requirements below:

- real time taking action,
- compliance to COLREGs,
- ability to disclose the optimal collision avoidance trajectory.

The optimal collision avoidance trajectory in the navigation environment is generated by the method. The OS are formed with a circular ship domain used for collision risk assessment and calculation of the safe trajectory. The ship domain is a safe area around a ship to keep free from the other ships and objects in the navigation environment (Goodwin, 1975). It provides a safe distance between ships during navigation. If the domain is violated by any obstacles, it is considered to be a risk of collision and evasive action should be taken in compliance with COLREGs.

Some assumptions have been accepted to simplify the complexity of the problem before the algorithm is designed. The assumptions are as follows:

- A circular ship domain is formed with radius determined by the system user. The violation of the domain by obstacles in the vicinity means the risk of collision.
- Own Ship (OS) and Target Ship (TS) are the terminology to define the ships. The OS is the ship that has to take action to avoid collision, the TS is the ship to be avoided.
- The speed and course of the TS is steady and do not change during the process.
- The algorithm is designed to be applied to course alteration at the current position of the OS once the calculation is conducted.
- A final point where the OS can return to its original route is determined.
- The navigational data of the ships to be entered into the developed interface are assumed to be provided. On board, these data are provided by ARPA and AIS.
- Once the right angle between the TS and the OS occurs, the return course alteration to original route is conducted by the OS.
- Each of the ships is assumed to obey COLREG rules.

The collision avoidance problem is associated with the unpredictable conditions. In this respect, to define this uncertainty, the motion of the obstacles and ships must be estimated. The kinematic model of the ship motion is presented by the equation 1, the instantaneous distance between the ships $D_{os,ts}(t)$ at time *t* can be calculated by the Euclidean distance formula by the equation 3 and the initial position of the OS (X_{os}, Y_{os}) is located in the origin *(0,0)* of the Cartesian system to ease the calculation presented by the equation 2,

$$\begin{aligned} X_{os}(t) &= X_{os}(0) + Sin(C_{os})V_{os}(t) \\ Y_{os}(t) &= Y_{os}(0) + Cos(C_{os})V_{os}(t) \\ X_{ts}(t) &= X_{ts}(0) + Sin(C_{ts})V_{ts}(t) \\ Y_{ts}(t) &= Y_{ts}(0) + Cos(C_{ts})V_{ts}(t) \end{aligned} \tag{1}$$

$$X_{os}(0) = 0, \qquad Y_{os}(0) = 0 \tag{2}$$

$$D_{os,ts}(t) = \sqrt{(X_{os}(t) - X_{ts}(t))^2 + (Y_{os}(t) - Y_{ts}(t))^2} \tag{3}$$

where V_{os} is the speed of the OS, C_{os} is the course of the OS, V_{ts} is the speed of the TS, C_{ts} is the course of the TS, *X* is the abscissa value and *Y* is the ordinate value of the ships in the Cartesian system.

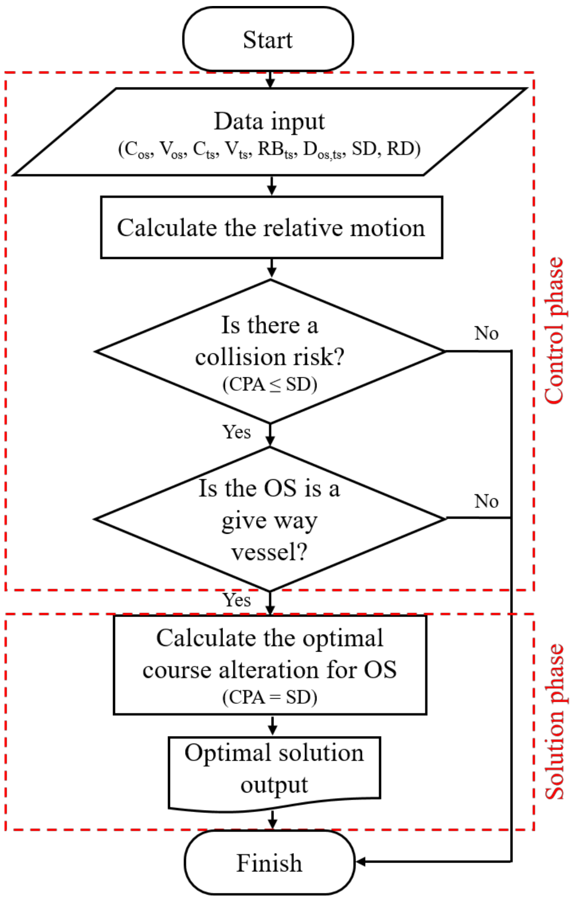

Figure 3. The brief flowchart of the proposed algorithm

The display of the simulation presents a situational view from the OS viewpoint. The current speed and course of the TS are known. On the other hand, the initial position of the TS(X_{ts}, Y_{ts}) is determined by the user using the web-based user interface shown in Figure 4. The interface for data receiving also provides the following information:

- course (C_{os}) and speed (V_{os}) of the OS,
- course (C_{ts}), speed (V_{ts}), relative bearing (RB_{ts}) of the TS and distance between ships ($D_{os,ts}$),
- ship domain size in radius (SD),
- a final point distance to return the OS to its original route (RD).

The web-based user interface developed with the "JavaScript" programming language on the "Processing" software platform is created for a practical collision avoidance decision support function. The reason why the web-based implementation has been developed is that it is easily accessible and does not require installation. The lower side of the interface shows the spatial operation and displays the simulation of the optimal collision avoidance route. The red lines represent the routes of the ships, the green line represents the relative motion line, the yellow area represents the ship domain of the OS that must not be violated by other objects, the green point represents the return point of the OS to its original route. The horizontal bar with red and green colour indicates the distance between ships during the process. The red side represents the ship domain. The upper side of the interface provides the course, speed, safety domain area and return distance to original route of the OS, the relative bearing, distance, course and speed of the TS. The interface can simulate relative motion and true motion of the collision avoidance process.

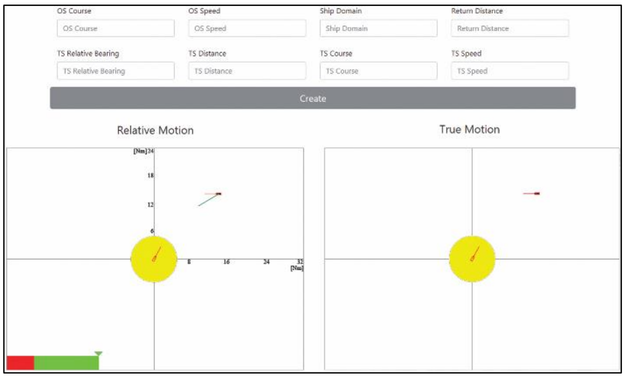

Figure 4. Web-based user interface

The aim of the collision avoidance path planning is to keep free the ship domain of the OS from the obstacles. It means that the distance between ships at the Closest Point Approach (CPA) should be large enough from the ship domain radius ($D(t)_{atCPA} \geq SD$). In the opposite case ($D(t)_{atCPA} < SD$), the ship domain is violated and there are moments of entry to (*t1*) and exit from the domain (*t2*). Ultimately, in order to provide optimal trajectory which has the shortest length, the distance has to be equal to ship domain radius ($D(t)_{atCPA} = SD$). In this case, the moment $t1 = t2$ represents that the TS passes through the tangent of the ship domain illustrated in Figure 5 which is an exemplary encounter situation. In order to achieve this situation, the following quadratic equation (equation 4) can be formed.

$$D(t)_{atCPA} = SD$$
$$SD = \sqrt{(X_{os}(t) - X_{ts}(t))^2 + (Y_{os}(t) - Y_{ts}(t))^2} \tag{4}$$

When the quadratic equation is solved, the *t1* and *t2* roots are obtained by the function 5.

According to the values of Δ, there are three different cases;

If $\Delta < 0$ then, there is no real root which means that there is no violation to ship domain. In this case, there is no risk of collision, so no calculation is conducted.

If $\Delta > 0$ then, risk of collision exists and the t_1 *and* t_2 roots to be obtained from the equation gives the entrance and exit moments to the ship domain.

If $\Delta = 0$ then, roots are equal to each other ($t_1 = t_2$) and it represents that the TS passes through the tangent of the ship domain.

$$V_{ix} = Sin(C_i)V_i$$
$$V_{iy} = Cos(C_i)V_i$$
$$t_1 = \frac{-b - \sqrt{\Delta}}{2a} \qquad t_2 = \frac{-b + \sqrt{\Delta}}{2a}$$
$$a = {V_{osx}}^2 + {V_{osy}}^2 + {V_{tsx}}^2 + {V_{tsy}}^2 - 2(V_{osx}V_{tsx} + V_{osy}V_{tsy}) \tag{5}$$
$$b = 2((V_{tsx}X_{ts}(0) + V_{tsy}Y_{ts}(0)) - (V_{osx}X_{ts}(0) + V_{osy}Y_{ts}(0)))$$
$$c = X_{ts}(0)^2 + Y_{ts}(0)^2 - SD^2$$
$$\Delta = b^2 - 4ac$$

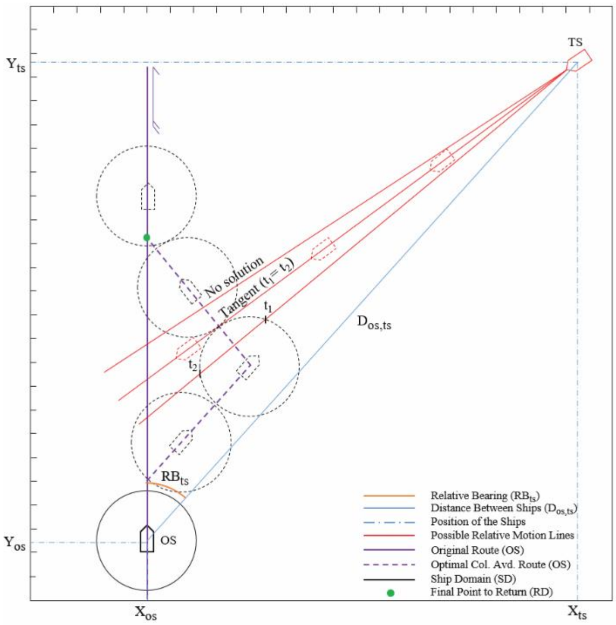

Figure 5. An exemplary pattern of an encounter situation

Calculating C_{os} via equation 5, the only unknown variable in the $b^2 - 4ac = 0$, reveals the new course which is optimal to avoid collision. In this case which provides the optimal course, there are four routes in which the TS passes through the tangent of the domain as illustrated in Figure 6 which is created with *GeoGebra* software. Three unsuitable ones from these routes are shown in red colour. Routes marked with *C* and *D* are not suitable solutions since they are tangent at negative time. Besides, route marked with *A* which passes through the head of the TS is also not a suitable solution due to the requirements of COLREGs. Only the route marked with B shown in green colour is obtained as a suitable solution.

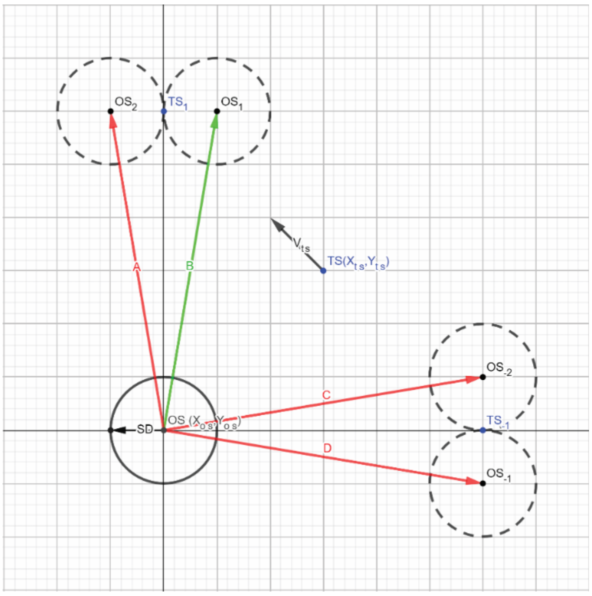

Figure 6. Cluster of routes that the TS passes through the tangent of the ship domain

4. EXPERIMENTAL TESTS

The purpose of the experimental test is to reveal the performance of the proposed method. The experiment deals with various cases which include head-on, crossing and overtaking encounter situation. In all cases, the different parameter settings are used and the OS is approaching to the TS critically which will cause a collision if there is no course alteration. The experimental results are illustrated in figures representing the situations. Calculations have been conducted with the use of a PC characteristic with an Intel Core i5-3470 3.20Ghz processor, 4GB RAM, 64-Bit Windows 10 Pro. Many cases have been implemented, but three of them have been selected to be shared in this study. Two more cases which are presented at the end of this section as a Case 4 and Case 5 are also implemented to make a comparison with other methods and systems. The navigational data of ships identified in the cases and the results of the cases are listed in Table 2 and Table 3, respectively. In all these cases, the OS proceeds at constant speed, and collision avoidance action is performed via course alteration.

Table 2. Navigational data identified in the cases.

		Navigational Data of Ships							
		Own Ship				Target Ship			
Case	Encounter Type	C_{os} [º]	V_{os} [kn]	SD [Nm]	RD [Nm]	C_{ts} [º]	V_{ts} [kn]	$D_{os\text{-}ts}$ [Nm]	RB_{ts} [º]
1	Crossing	000	15	2	15	270	15	8	045
2	Overtaking	000	17	2	23	340	9	6	020
3	Head-on	088	14	2	22	263	12	25.4	357
4	Crossing	000	14	2	19.45	240	15	32	030
5	Crossing	000	14	2	3.82	240	15	4	021.90

Table 3. Results of the experimental tests.

Case	Length of Trajectory [Nm]	Extra Navigating Distance [Nm]	Optimum Anti-Collision Course [º]	Course Alteration to Return Original Route [º]	Computational Time [s]
1	15.77	0.77	028.96	-042.68	≈ 0.02
2	23.34	0.34	012.34	-022.83	≈ 0.02
3	22.36	0.36	095.10	-018.37	≈ 0.02
4	20.02	0.57	005.12	-051.44	≈ 0.02
5	4.53	0.71	043.20	-071.11	≈ 0.02

4.1 CASE 1: CROSSING SITUATION

In Case 1, the TS is approaching to OS from its starboard bow and the current motion of the ships lead to collision, so the OS should take action to eliminate the risk of collision. It is assumed that the navigational data of the ships comes from ARPA and AIS, the initial course of the OS is 000º, the course of the TS is 270º, the speed of both ships are set at 15 knots, the relative bearing of the TS is 045º, the distance between two ships is 8 Nm, the return distance to original route of the OS is 15 Nm and ship domain radius is set at 2 Nm. Figure 7 and Figure 8 show the time passed (T1, T2, T3, T4) of dynamic simulation of collision avoidance route in relative motion and true motion, respectively since the beginning of the simulation.

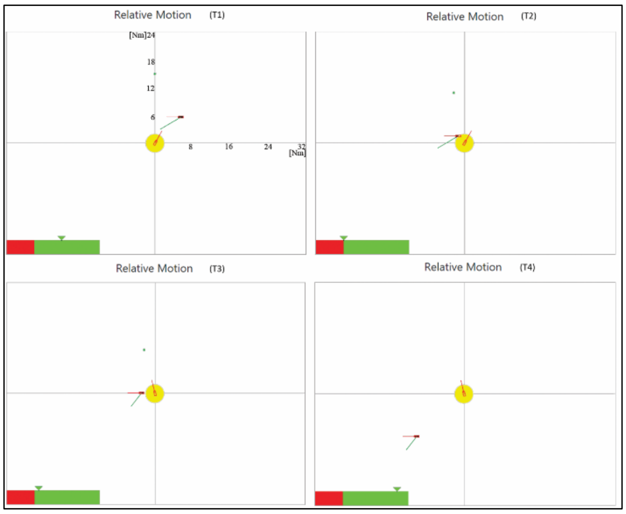

Figure 7. Dynamic simulation of collision avoidance route in relative motion for case 1

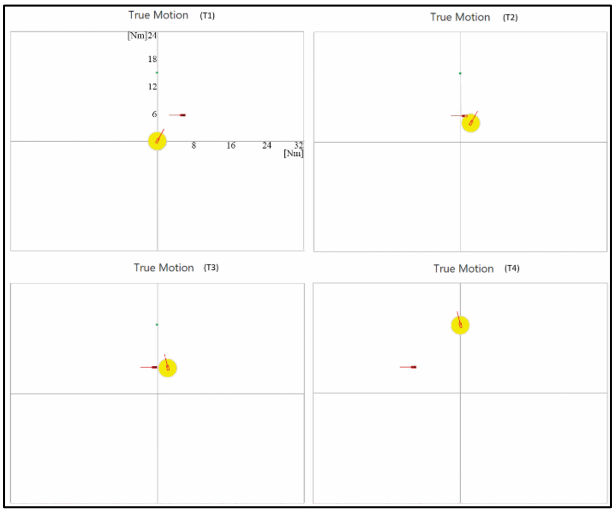

Figure 8. Dynamic simulation of collision avoidance route in true motion for case 1

As shown in the figures, the OS can pass safely regarding the requirements of the sea navigation rules (COLREGs). As a result, in this scenario, the developed method has revealed that the OS should alter her course to 028.96° and proceed on this course until the course alteration, which is -042.68°, to return the original route. The length of the optimal trajectory is measured 15.77 Nm and the extra distance navigated by the OS is 0.77 Nm. The execution time to reach the solution is only 0.02 s.

4.2 CASE 2: OVERTAKING SITUATION

In Case 2, the OS is approaching to TS from its stern and the current motion of the ships cause collision, so the OS as an overtaking ship should take action to eliminate the risk. The initial course of the OS is 000°, the course of the TS is 340°, the speeds of the OS and the TS are set at 17 knots and 9 knots respectively, the relative bearing of the TS is 020°, the distance between the ships is 6 Nm, the return distance to original route of the OS is 23 Nm and ship domain radius is set at 2 Nm.

Figure 9 and Figure 10 show the time passed (T1, T2, T3, T4) of dynamic simulation of collision avoidance route in relative motion and true motion, respectively since the beginning of the simulation. As seen in the figures, the OS can pass safely regarding COLREGs. As a result, in this scenario, the developed method has revealed that the OS should alter her course to 012.34° and proceed on this course until the course alteration, which is -022.83°, to return the original route.

The length of the optimal trajectory is measured 23.34 Nm and the extra distance navigated by the OS is 0.34 Nm. The execution time to reach the solution is only 0.02 s.

Figure 9. Dynamic simulation of collision avoidance route in relative motion for case 2

Figure 10. Dynamic simulation of collision avoidance route in true motion for case 2

4.3 CASE 3: HEAD-ON SITUATION

In Case 3, to illustrate a real encounter situation, the navigational data of ships are obtained from *www.marinetraffic.com* which keeps a real time data of ships provided from AIS. The situation which is shown in Figure 11 takes place close to the Gulf of Antalya. In this case, the ships are approaching each other head-to-head and the current motion of the ships leads to collision, so the collision avoidance action should be taken to eliminate the risk. The initial course of the OS is 088°, the course of the TS is 263°, the speeds of the OS and the TS are set at 14 knots and 12 knots respectively, the relative bearing of the TS is 357°, the distance between the ships is 25.4 Nm, the return distance to original route of the OS is 22 Nm and ship domain radius is set at 2 Nm. Figure 12 and Figure 13 show the time passed (T1, T2, T3, T4) of dynamic simulation of collision avoidance route in relative motion and true motion, respectively since the beginning of the simulation. As seen in the figures, the OS can pass safely regarding the requirements of the sea navigation rules. As a result, in this scenario, the developed method has revealed that the OS should alter her course to 095.1° and proceed on this course until the course alteration, which is -018.37°, to return original route. The length of the optimal trajectory is measured 22.36 Nm and the extra distance navigated by the OS is 0.36 Nm. The execution time to reach the solution is the same as the above cases.

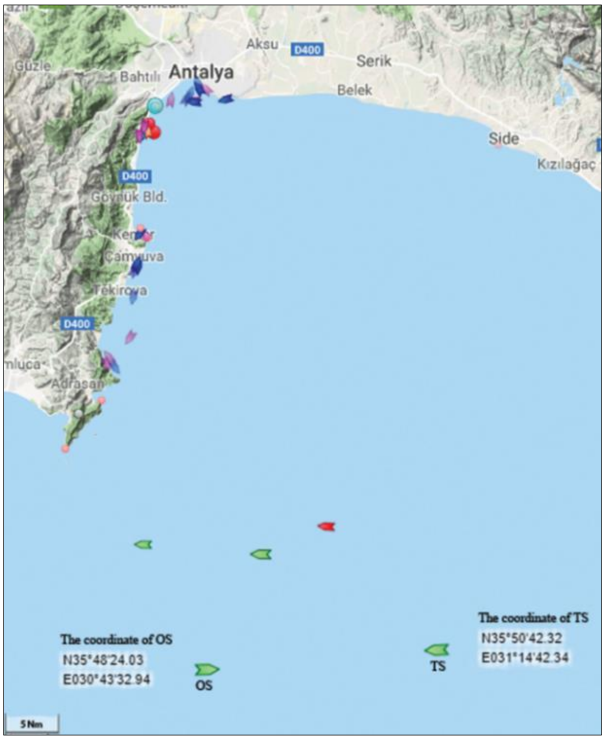

Figure 11. Real encounter situation.
Source: www.marinetraffic.com

4.4 IMPLEMENTATION FOR COMPARISON AND DISCUSSION

The proposed method has been compared to other methods and systems. In order to demonstrate the advantage of the approach, Case 4 and Case 5 have been implemented. For this purpose, the results received from heuristic-based method, the Genetic Algorithm (GA) (introduced by Tsou et al., 2010), has been used to make a comparison. The initial navigational data of ships for these cases are listed in Table 2. Comparison results of the cases are shown in Table 4 in detail.

Figure 12. Dynamic simulation of collision avoidance route in relative motion for case 3

Figure 13. Dynamic simulation of collision avoidance route in true motion for Case 3

Table 4. Comparison results.

Case		Method	Length of Trajectory [Nm]	Extra Navigating Distance [Nm]	Optimum Anti-Collision Course [°]	Course Alteration to Return Original Route [°]	Computational Time [s]
Case	4	WBDA	20.02	0.57	005.12	-051.44	≈ 0.02
		GA	21.18	1.73	046.00	-093.00	14-26
	5	WBDA	4.53	0.71	043.20	-071.11	≈ 0.02
		GA	5.55	1.73	046.00	-093.00	14-26

4.4 (a) Case 4: Crossing Situation

A comparison of the OS trajectories determined by the WBDA and the GA-based algorithm is shown in Figure 14. Numerical results are compared in Table 4. The solution generated by the WBDA considerably outperforms GA-based algorithm. The difference with regard to the length of the trajectory is 1.16 Nm. On the other hand, with respect to execution time, the computational time of the WBDA (≈ 0.02 s) is much shorter than the GA-based approach (14-26 s). The WBDA based trajectory comprises of 2 leg, while GA-based trajectory is composed of 3 leg.

4.4 (b) Case 5: Crossing Situation (adjusted)

In the GA-based approach, the OS alters her course to avoid collision after proceeding for a while (called as *T1* in the study). The WBDA, however, calculates the optimal course assuming that the OS alters her course in its current position without proceeding for a while. Therefore, in order to able to compare the length of trajectories from beginning collision avoidance course alteration, the input data, especially the distance between ships and the relative bearing of the TS, to be entered into the WBDA is needed to be adjusted according to data within GA-based approach. The calculation for the adjustment is shown in Figure 1A. Trajectory solutions for the OS provided by both approaches according to adjusted data is shown in Figure 15. Numerical results are listed in Table 4. The case has similar conclusions as Case 4 and the length of trajectory calculated by the WBDA is 1.02 Nm shorter than that generated by the GA-based algorithm.

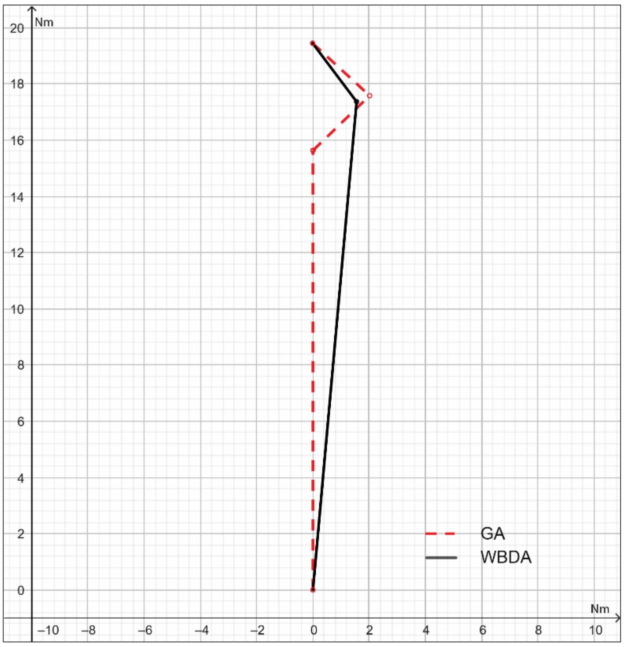

Figure 14. Comparison of trajectories generated by WBDA and GA for Case 4

5. CONCLUSION

A new web-based deterministic method is introduced in the study to solve the ship collision avoidance optimization problem. Experimental tests comprising five encounter situations have been implemented to prove the effectiveness of the proposed method. The experimental test results have revealed that the system is practicable and feasible to solve the optimal collision avoidance problem. The WBDA is compared to GA-based approach and it is revealed that the solution calculated by the method considerably outperforms the heuristic-based approach. The other advantage of the method is that it can produce an identical solution for every run which is not generally possible for heuristic-based algorithms.

In this method, the action taken by the OS to eliminate the collision risk is limited to course alteration. The speed change which is not frequently applied in real operation unless critical situations occur, can be considered in order to upgrade the proposed method which can provide more flexible control. The scope of the study is one-to-one encounter situations because of the nature of COLREGs but, as a further study, the algorithm structure of the method can be adapted to multiple encounter situations. The proposed system can provide guidance to navigators in case of encounter situation at sea. It is believed that the method introduced in the study can contribute to extend the navigation characteristic of the modern ships as well as automation of ship motion control, ship traffic engineering and e-navigation strategy.

To summarize, the following features of the method have come into prominence:

- meeting the requirements stipulated by COLREGs.
- easy to use,
- web accessibility and not require an installation,
- very short execution time,
- the constant solution value and the same execution time for every run,
- the OS can return to its original route at specified point.

Figure 15. Comparison of trajectories calculated by WBDA and GA for Case 5

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APPENDIX A. POSITION CALCULATION FOR CASE 5.

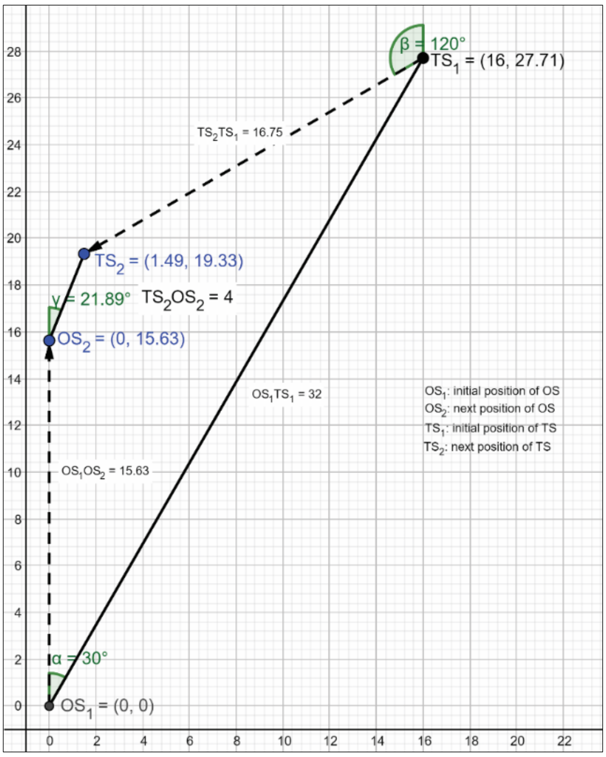

Figure A1. Calculation for the adjustment of the navigational input data for Case 5

