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A Concept of Autonomous Multi-Agent Navigation System for Unmanned Surface Vessels

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Abstract: The paper introduces a proposal of an Autonomous Navigation System for Unmanned Surface Vessels. The system architecture is presented with a special emphasis on collision avoidance and maneuver auto-negotiation. For the purpose of maneuver auto-negotiation, the concept of multi-agent systems has been applied. The algorithm developed for the task of collision avoidance is briefly described and the results of the simulation tests, confirming the effectiveness of applied method, are also given. Presented outcomes include solutions of test scenarios from the perspectives of different ships taking part in the considered situations, confirming the applicability of the collision avoidance algorithm in the process of maneuver auto-negotiation.

Keywords: autonomous navigation system; collision avoidance; maneuver auto-negotiation; multi-agent system; obstacle avoidance; real-time path planning; unmanned surface vehicle

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1. Introduction

Navigation is a vital task in the operation of every autonomously moving object. This relates to self-driving cars, autonomous mobile robots, drones and unmanned ships. Autonomous navigation of a craft has to cover perception, obstacle detection and avoidance and path planning and following. Marine units that move autonomously can be divided into autonomous merchant vessels and smaller crafts—Unmanned Surface Vehicles (USVs). The International Maritime Organization (IMO) introduced a term for autonomous merchant vessels—the Maritime Autonomous Surface Ship (MASS), which is used to express *a ship which, to a varying degree, can operate independent of human interaction* [1].

Over the last few years, many research and development projects dedicated to MASSs have been carried out. Examples of such projects, listed in Table 1 and in Figure 1, include the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) [2], ReVolt [3], Advanced Autonomous Waterborne Applications (AAWA) [4], Autosea [5], Autoferry [6], Yara Birkeland [7], Safer Vessel with Autonomous Navigation (SVAN) [8] and Mayflower Autonomous Ship (MAS) [9].

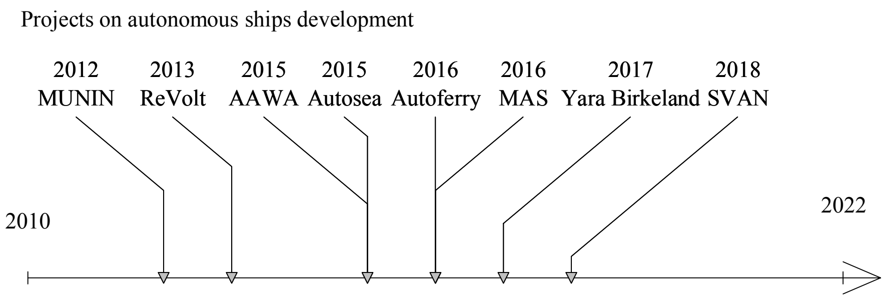

Figure 1. A timeline of recent projects on autonomous ships.

Table 1. Research projects on autonomous ships.

Project	Type of Vessel	Years	Aim	Type of Experiments/Analysis
MUNIN [2]	dry bulk carrier, 75.000 DWT, speed: 16 kn	2012–2015	deep-sea voyage autonomous navigation	feasibility study/theoretical analysis
ReVolt [3]	60 m, 1300 DWT, battery powered	2013	short-sea voyage	ship concept
AAWA [4]	not specified	2015–2018	remotely-controlled ship	theoretical analysis for a proof of concept demonstrator
Autosea [5]	autonomous passenger ferries	2015–2019	methods for guidance and navigation	full-scale experiments
Autoferry [6]	5 m, electric passenger ferry milliAmpère	2016–2019	urban water transport	full-scale prototype
Yara Birkeland [7]	79.5 m, fully electric container feeder, 120 TEU	2017–2022	short-sea voyage	model testing/vessel building and operation planned
SVAN [8]	53.8 m, ferry Finferries Falco	2018	short-sea voyage	fully autonomous ferry demonstration
MAS [9]	5 m trimaran Mayflower 400	2016–2022	oceanographic surveys and research	Atlantic Crossing planned for 2022

The technology of USVs has also developed dynamically in recent years. Examples of recently developed USVs are listed in Table 2. USVs application areas include defense area, such as surveillance, search and rescue, reconnaissance and strike missions, but also ocean surveying, such as collecting oceanographic data (bathymetry, pollution monitoring). A review of USVs with a special emphasis on the design aspects of the GNC system for these marine crafts can be found in [10].

Table 2. Examples of recently developed USVs.

USV	Country	Length [m]	Max Speed	Payload	Mission Endurance	Application
Katana [11]	Israel	11.9	60 kn	2200 kg	350 nm	Defense/military
Protector [12]	Israel	11 or 9	40 kn	-	>48 h	Naval & security missions
C-Target 9 [13]	USA	9.6	50 kn	-	-	Defense/military
C-Target 6 [14]	USA	6.5	35 kn	-	-	Defense/military
Edredon [15,16]	Poland	5.7	30 kn	1000 kg	8–130 h	Defense/military
C-Worker 7 [17]	USA	7.5	6 kn	500 kg	25 days @ 2 kn	Ocean Surveying
C-Worker 6 [18]	USA	5.8	6.5 kn	-	30 days	Ocean Surveying
Sounder [19]	Norway	8	12 kn	-	20 days @ 4 kn	Hydroacoustic Applications

Recently, different classification societies, maritime organizations and companies have been developing classifications of ships based on their degrees of autonomy [20]. The Maritime Safety Committee (MSC) of the IMO defined 4 degrees of ship autonomy, as shown in Table 3 [1].

Table 3. Degrees of ship autonomy according to IMO.

Degree of Autonomy	Description
One	Ship with automated processes and decision support
Two	Remotely controlled ship with seafarers on board
Three	Remotely controlled ship without seafarers on board
Four	Fully autonomous ship

The aim of this paper is to present the developed concept of the Autonomous Navigation System for the USV. The main contributions of the research presented in this paper are:

- An analysis of recent projects on autonomous ships and USVs with a special emphasis on ANSs and the collision avoidance feature;
- The definition of an USV Autonomous Navigation System structure based on the analyzed projects;

- The definition of the agent architecture and control flow in the autonomous multi-agent navigation system for USVs, on the basis of a general structure of an agent system;
- The development of an effective collision avoidance algorithm to be applied for the maneuver auto-negotiation in the proposed multi-agent system;
- Evaluation of the deterministic collision avoidance method for the purpose of the possibility to apply collaborative strategies to avoid collisions with other agents by the calculation of multiple trajectories for all USVs taking part in the considered navigational scenario.

Section 2 introduces the general structure of the Autonomous Navigation System for USVs. Section 3 presents the concept of the Multi-agent system for USV maneuver auto-negotiation. In Section 4, the collision avoidance algorithm developed for the application in the ANS for USVs has been briefly described. In Section 5, simulation tests results obtained with the use of the collision avoidance algorithm are shown, with a special emphasis of solutions achieved from the perspectives of different USVs taking part in the considered encounter situations. Discussion on the results is given in Section 6 and the paper is summarized in Section 7.

2. Autonomous Navigation System Structure

The Autonomous Navigation System is responsible for the navigation of the USV. The main tasks of the Autonomous Navigation System of every vehicle include: perception of the environment, path planning and path following (vehicle control).

One of the main subsystems of the ANS is the Collision Avoidance (CA) module. The CA module is responsible for the collision risk assessment on the basis of information obtained from the system that fuses data from various navigational sensors. The second task of the CA module is to ensure the safe navigation of the USV, both on the open sea and in restricted waters. The main element of the CA module is the collision avoidance algorithm, responsible for determining a safe maneuver or a safe trajectory for the vehicle, when a risk of collision has been detected. Besides the CA module, the route planning module is also applied. This subsystem is responsible for the calculation of a global path between the initial and final position, e.g., two harbors, including the craft's mission, but also weather conditions (therefore known also as weather routing). Figure 2 presents a general structure of the Autonomous Navigation System for USVs.

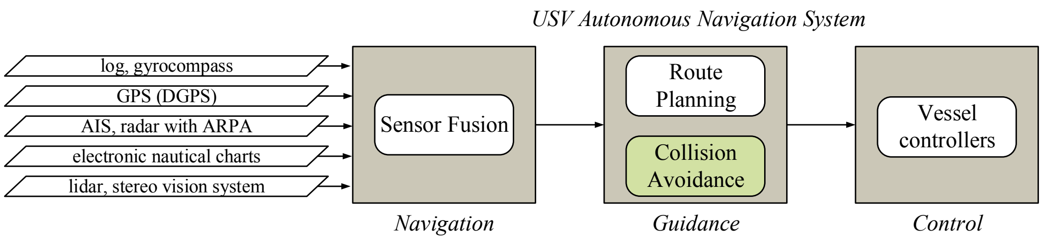

Figure 2. Autonomous Navigation System for USVs.

The module responsible for navigational data reception and fusion is the Advanced Sensor Module—ASM, also known as the Situation Awareness module or Sensor Fusion module. Applied sensors include: nautical charts, long-range radars, the Automatic Identification System (AIS), stereo vision systems, short-range radars, lidars and the Global Positioning System (GPS). In relation to the ANS of USVs, the term Obstacle Detection and Avoidance (ODA) system is also used, which reflects a combined version of the Situation Awareness and Collision Avoidance modules. Motion Control system is responsible for the calculation of appropriate control forces to steer the USV along the calculated trajectory or to execute a maneuver determined by the CA module. Table 4 presents a comparative analysis of ANSs proposed in different research projects on autonomous ships, listed in

Figure 1 and Table 1. The ANS structure applied in the research presented in this paper was developed based on the solutions proposed in the mentioned projects.

Table 4. ANSs in research projects on autonomous ships.

Project	Module for Collision Avoidance	Module for Data Perception and Data Fusion	Sensors	Autonomous Navigation System	Algorithms	Other Systems
MUNIN [2]	Collision Avoidance (CA) module	Advanced Sensor Module (ASM)	marine radar, AIS receiver, daylight and infrared cameras, nautical data	Deep Sea Navigation System, track pilot and rudder and engine control: path following, weather routing, collision avoidance	safe weather routing: A-star algorithm, collision avoidance algorithm: formalized description of COLREGs	Autonomous Engine and Monitoring Control system, Shore Control Centre
AAWA [4]	Collision Avoidance (CA) module	Situation Awareness (SA) system (sensor fusion)	visual and IR cameras, short range and long range radars, lidar, GPS, inertial sensors, electronic navigational charts	Route planning module, SA module, CA module, Ship state definition module	Velocity Obstacles (VO) method	Dynamic positioning system, Propulsion control system, Remote operator
Autosea [5]	Collision Avoidance (CA) module	Sensor Fusion (SF) module	AIS, radar, camera, charts	CA module (collision detection, avoidance, guidance), SF module (target tracking)	Model Predictive Control (MPC)	other systems not considered

3. Multi-Agent System for USV Maneuver Auto-Negotiation

Multi-agent systems are regarded as a powerful concept for solving real-world problems, especially in complex, dynamic environments, enabling to achieve increased autonomy within control systems [21]. Table 5 presents a summary of multi-agent systems proposed in the recent literature in relation to ships and different types of unmanned vehicles: USVs, UUVs (Unmanned Underwater Vehicles) and UAVs (Unmanned Aerial Vehicles). The comparison lists the control objects, the purpose of proposed systems, the type of tasks solved by the system, i.e., cooperation and/or competition, the type of applied method and information about the optimization of the task. The last column contains additional remarks, concerning advantages, limitations or other comments with regard to the relation between the mentioned methods and the approach described in this paper. Some of the proposed multi-agent systems are intended for solving a different task than collision avoidance, considered in this paper, such as formation control [22,23], training a team of USVs [24], searching water region by a team of UUV [25] and/or consider a different type of vehicle, such as UAV [26], UUV or a car [27].

The concept of the maneuver auto-negotiation system in relation to autonomous cars was proposed in [27], to UAV in [26] and to ships in [28–30]. In [28], collision avoidance and maneuver auto-negotiation is based on geometrical relationships. Two ships encounters are considered in this approach and the solutions might not be COLREGs compliant. In [29], a concept stage of the task has been presented. The authors assumed the application of evolutionary sets of safe trajectories, where the best set of reciprocal trajectories is calculated, but results of the collision avoidance approach are not presented in the paper. In [30], the author proposes a structure of the maneuver auto-negotiation system with the concentration on the data acquisition aspect. Safe trajectories are assumed to be calculated as evolutionary sets of safe trajectories. This approach has been presented in the author's previous works [x, y]. The author proposed a control flow, in which one of the vessels is a leader ship. The leader is responsible for data gathering, determination and optimization of maneuvers and distribution of the results among other participants of the encounter.

The literature analysis shows that the development of a multi-agent system for collision avoidance with maneuver auto-negotiation is an open research problem, as algorithms for the calculation of multiple trajectories are rare in the recent literature. There exists a demand in the industry for the development of an effective, robust and reliable multi-agent system, which will enable for the calculation of a set of safe trajectories for all ships or USVs taking part in an encounter. The development of such a solution is the aim of the research presented in this paper.

Table 5. Multi-agent systems for ships and unmanned vehicles.

Authors	Year	Control Object	Purpose	Type of Task	Method	Optimization	Remarks
Huang et al. [26]	2022	UAV	collision avoidance in UAV swarms	cooperation	multi-agent reinforcement learning	safety, energy consumption, response time	different control object
Xue and Wu [22]	2021	USVs + UAV	formation control	cooperation	leader-following consensus	APF path planning + sliding mode control	different task
Han et al. [24]	2019	USV	training a team of USVs	cooperation within the team, competition with other teams	genetic-based fuzzy rule training algorithm	optimizing agents' coordination decisions	different task
Wang et al. [23]	2019	USV	formation control	cooperation	leader-following consensus	sampled-data consensus protocol	different task
Żak [25]	2019	UUV	searching water region by a team of UUVs	cooperation	UUV operation algorithm	minimize the total time	different task
Visintainer et al. [27]	2016	car	maneuver negotiation	cooperation	algorithms for automated lane change, distance keeping	no optimization	concept stage
Szlapczynska [30]	2015	ship	maneuver auto-negotiation, collision avoidance	cooperation	evolutionary sets of safe trajectories	the best set of reciprocal trajectories	data acquisition
Hornauer and Hahn [29]	2013	ship	maneuver auto-negotiation, collision avoidance	cooperation	evolutionary sets of safe trajectories	the best set of reciprocal trajectories	concept stage
Hu et al. [28]	2008	ship	maneuver auto-negotiation, collision avoidance	cooperation	geometrical relationships	details not given	two ships encounter, might not be COLREGs compliant

Extending the ANS architecture for the purpose of maneuver auto-negotiation was based on multi-agent systems. Multi-agent systems are classified as an approach of Distributed Artificial Intelligence (DAI) [31]. A multi-agent system is composed of a number of agents, which interact with each other and the environment in order to achieve their goals. Such approach has been applied for modeling and solving problems by cooperation between local solvers and the design of complex systems. An agent is an object, being in a certain situation, that has the ability to perceive the environment and influence it through an autonomous action to achieve a defined goal. In the approach presented in this paper an agent is an USV, perceiving the environment through navigational equipment such as AIS, radar with ARPA, GPS, log, gyrocompass, lidar and stereovision systems. The USV also interacts with other USVs in the surroundings and acts on the environment by changing its course and/or speed.

Assumed agent architecture and control flow is shown in Figure 3 [25,32]. The algorithms related to detecting obstacles are included in the layer of reflex action. The planning layer implements obstacle avoidance algorithms [33–35] and these responsible for the control of the vehicle along a set trajectory. At the level of cooperation, the vehicle exchanges data with other vehicles and conducts negotiations about planned collision avoidance actions.

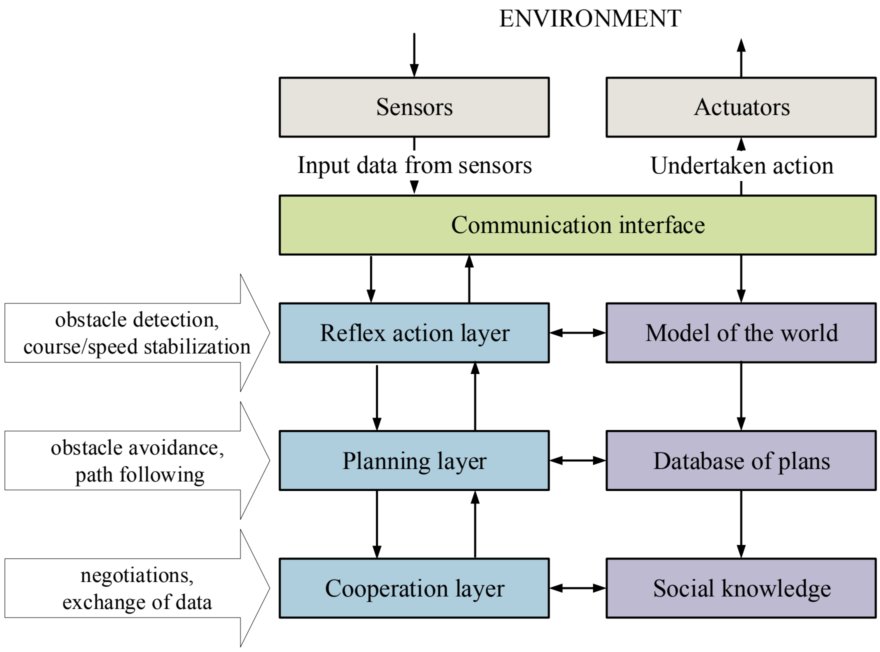

Figure 3. Agent architecture and control flow.

The agent architecture applied in this research is the InteRRaP model [36], which means Integration of Reactive behavior and Rational Planning. This architecture utilized the BDI model of reasoning, which comes from Beliefs, Desires (Goals) and Intentions [37,38]. In such an architecture, two types of interaction between different layers are possible. These are: bottom-up activation and top-down execution. In the first type, when a lower layer is not able to deal with the current situation, it passes control to a higher layer. In the second type of interaction, a higher layer uses the functionality assured by a lower layer in order to reach its goal. In the InteRRaP architecture, when new data from sensors arrive at the lowest reflex action layer, it evaluates whether it can deal with the situation. When the layer is not able to perform the task, the control will be passed in the bottom-up activation manner to the planning layer. This layer will also asses the task and when it will be able to deal with the it, after which it will apply a top-down execution. Otherwise, it will pass control to the highest cooperation layer. Such an architecture, in comparison with other layered architectures of multi-agent systems, has as an advantage that only the lowest layer has direct access to actuators. This excludes the occurrence of conflicting decisions between different layers. A different layered approach was proposed in [39], where appropriate filtering and suppression mechanisms have to be applied in order to prevent the system from conflicts among the actions of different layers.

Agents communicate with each other, while maintaining their autonomy of action and decision-making, which translates into actions taken by individual agents. Such interaction between agents leads to the modification of knowledge and actions of individual agents based on the behavior of other agents. A single agent is equipped with a strategy, leading it to achieve the assumed goal, which in this case is to reach a specific geographical position—the end point of the trajectory. However, as part of a multi-agent system, it must implement collaborative strategies to avoid collisions with other agents. The key feature of agents in a multi-agent system is their collaboration and competition. Therefore, agents exchange information on individual actions taken in order to avoid a collision.

The collision avoidance process with the use of the proposed autonomous multi-agent navigation system for USVs can be performed in one of the two following ways, both of which are possible with the use of the applied collision avoidance algorithm:

(a) A decentralized system, where collision avoidance calculations are performed by individual agents (USVs), these partial solutions are then used in the auto-negotiation process;
(b) One USV calculates the complete solution of the current navigational situation and then distributes the partial solutions to other agents.

4. USV Collision Avoidance Algorithm

Collision avoidance and safe path planning algorithm applied in the introduced concept of Autonomous Multi-agent Navigation System is a deterministic approach. The algorithm's operation is based on the search through a database with stored candidate trajectories in order to find the best safe path solving the currently considered situation; therefore, the approach has been called the Trajectory Base Algorithm (TBA). This algorithm has been chosen for further development due to its competitive results in relation to other deterministic and non-deterministic methods. A comparative analysis of different methods, along with the TBA, can be found in [40].

The main advantages of this approach are: the solution repeatability for every run of calculations with the same input data, achievement of COLREGs compliant solutions with minimal path length and run time of the algorithm enabling the application of this approach for real-time path planning.

The input variables, shown in Figure 4, are:

- Ψ—the course of an own ship (USV no. 0, for which the safe trajectory is currently calculated by the algorithm);
- V—the speed of an own ship;
- Ψ_j—the course of the j-th USV (also called target ship);
- V_j—the speed of the j-th USV;
- N_j—the bearing of the j-th USV;
- D_j—the distance of the j-th USV from an own ship (USV no.0);
- t—the number of a currently evaluated candidate trajectory retrieved from the database;
- t_{max}—the maximum number of candidate trajectories in the database.

The inputs from the database of trajectories are: candidate trajectories composed of a number of waypoints (x and y coordinates of the USV position). The output variables are: safe trajectories composed of a number of waypoints (x and y coordinates of the USV position) and the values of the USVs course at the consecutive parts of the trajectories.

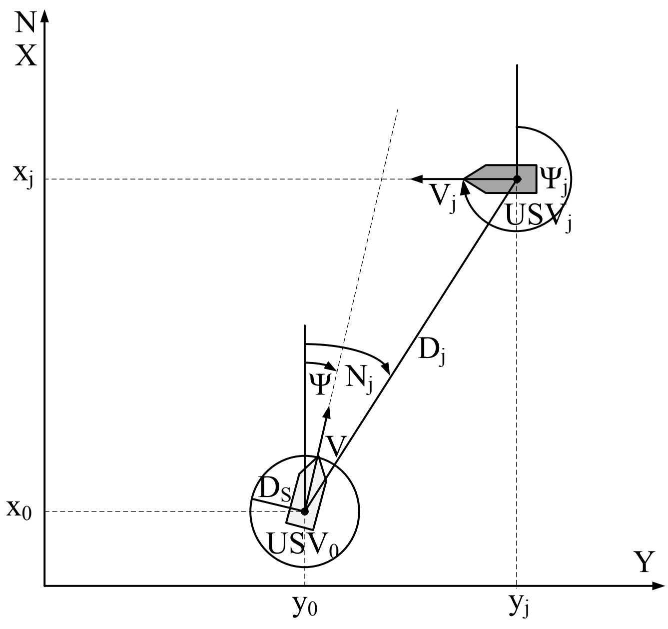

Figure 4. Parameters defining a navigational situation at sea.

Figure 5 presents a flowchart of the TBA. As mentioned above, input data are the courses, speeds, bearings and distances of all vessels taking part in an encounter. After the reception of input data describing the current navigational situation, the first candidate trajectory is retrieved from the database for the evaluation procedure. The evaluated candidate trajectory is divided into a number of steps. Afterwards, in every step, an own ship is moved into a new instantaneous position along the evaluated trajectory. Target ships are also moved into their next instantaneous positions, resulting from their motion parameters and a trajectory selected for the implementation. Then, the procedure of checking, whether the vessels positions do not lead to a collision, is carried out. When the whole trajectory is verified as a safe path, which means that it does not cause a collision with any of encountered ships during the vessel's movement along it, it becomes the final best solution. The optimization criterion applied in the collision avoidance algorithm, defined by Equation (1), is the minimal path length. It is calculated as a sum of the lengths of line segments composing the safe path, where $i = 1, \ldots, e$ are the waypoints composing the path:

$$f(t) = dist(t) = \sum_{i=1}^{e-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \rightarrow min \quad (1)$$

The information about the selected trajectory, as a part of cooperation activities between agents, is transferred to other agents in a multi-agent system to be used in their decision-making. Further calculations are terminated. A more detailed description of the TBA can be found in [41].

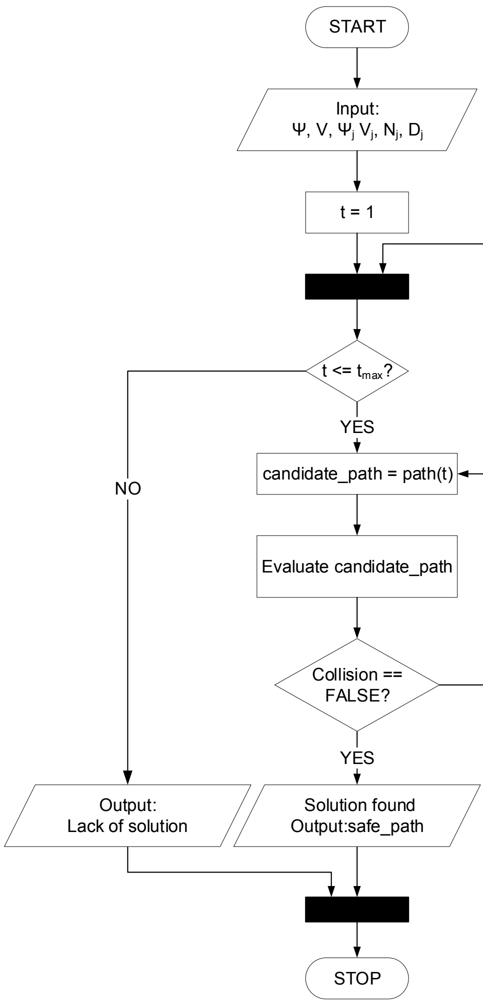

Figure 5. A flowchart of the Trajectory Base Algorithm.

5. Results of Collision Avoidance Algorithm

The TBA proposed in this paper for USVs collision avoidance has been tested comprehensively in order to validate its reliability and robustness. Various tests of this algorithm have been carried out, including:

- Simple encounter situations with one target ship considered in The International Regulations for Preventing Collisions at Sea (COLREGs) (head-on, crossing and overtaking);
- Encounter situations with static obstacle (lands, shallows);
- Complex encounter situations with real navigational data.

The results of these test can be found in [42].

One of the methods to assure a proper distance between the USVs or other marine crafts in a collision avoidance algorithm is to model other USVs (target ships) with the use of a ship domain. A ship domain is defined as an area around a ship, which a navigator wants to keep free from static and dynamic obstacles. In the presented approach, a ship domain with a hexagon shape, as proposed in [43], has been applied. The dimensions of the target ship domain used in the tests were: distance towards the bow: 1.3 nm, distance of amidships: 0.6 nm, distance towards the stern: 0.5 nm, distance towards the starboard side: 0.6 nm and distance towards the port side: 0.5 nm.

For the purpose of the algorithm's application in the USV Autonomous Multi-Agent Navigation System, the evaluation of solutions consistency from different ships' perspectives has been carried out. The results of these experiments are presented here. The algorithm was implemented in the MATLAB programming language and tested on a PC with Intel Core i7-10750H CPU, 32 GB RAM, 64-bit Windows 10 operating system. Out of many test cases, four scenarios have been chosen for the presentation in this paper. These test cases have been chosen as standard scenarios, which present the solutions compliance with the COLREGs. Similar test scenarios were presented in the cooperative path planning approach proposed in [44]. Input data of USVs, including courses in degrees, speeds in knots, bearings in degrees and distances between the marine crafts in nautical miles, are given in Tables 6–9. Tables 10–13 present output data, such as USV courses in degrees at consecutive parts of the calculated safe path, path lengths in nautical miles and run time of the algorithm in seconds. Figures 6–9 show graphical solutions of test cases 1–4. Initial positions of USVs are marked by digits representing the number of an USV (USV No. in tables). The numbers given along the consecutive positions of the USVs show the time of the USV arrival at a given point in minutes. Presented results have been discussed in the following section.

Table 6. Input data of test case 1—head-on.

USV No.	Course [°]	Speed [kn]	Bearing [°]	Distance [nm]
0	0	10	-	-
1	180	14	0	4

Table 7. Input data of test case 2.

USV No.	Course [°]	Speed [kn]	Bearing [°]	Distance [nm]
0	0	10	-	-
1	270	16	45	3
2	180	9	0	4

Table 8. Input data of test case 3.

USV No.	Course [°]	Speed [kn]	Bearing [°]	Distance [nm]
0	0	14	-	-
1	270	10	45	4
2	90	10	315	4

Table 9. Input data of test case 4.

USV No.	Course [°]	Speed [kn]	Bearing [°]	Distance [nm]
0	0	14	-	-
1	270	8	45	6
2	180	12	0	8
3	90	8	315	6

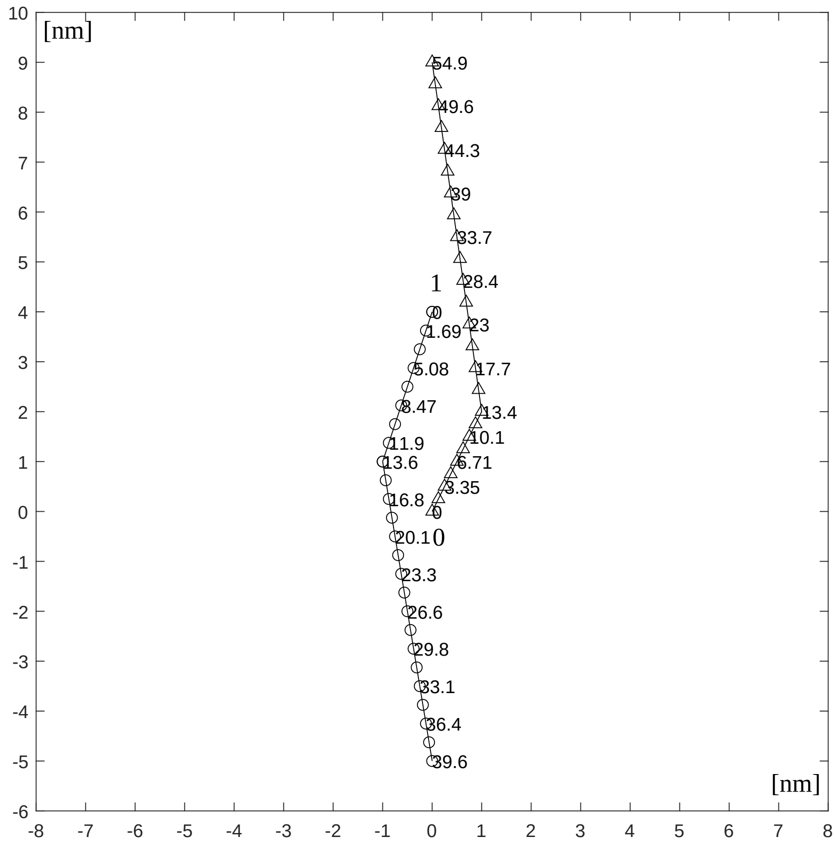

Figure 6. Solution of test case 1.

Table 10. Output data of test case 1.

USV No.	Course [°]	Path Length [nm]	Run Time [s]
0	27, 352	9.31	0.21
1	198, 171	9.25	0.12

Table 11. Output data of test case 2.

USV No.	Course [°]	Path Length [nm]	Run Time [s]
0	18, 351	9.25	0.16
1	315, 270, 262	9.49	0.39
2	198, 171	9.25	0.14

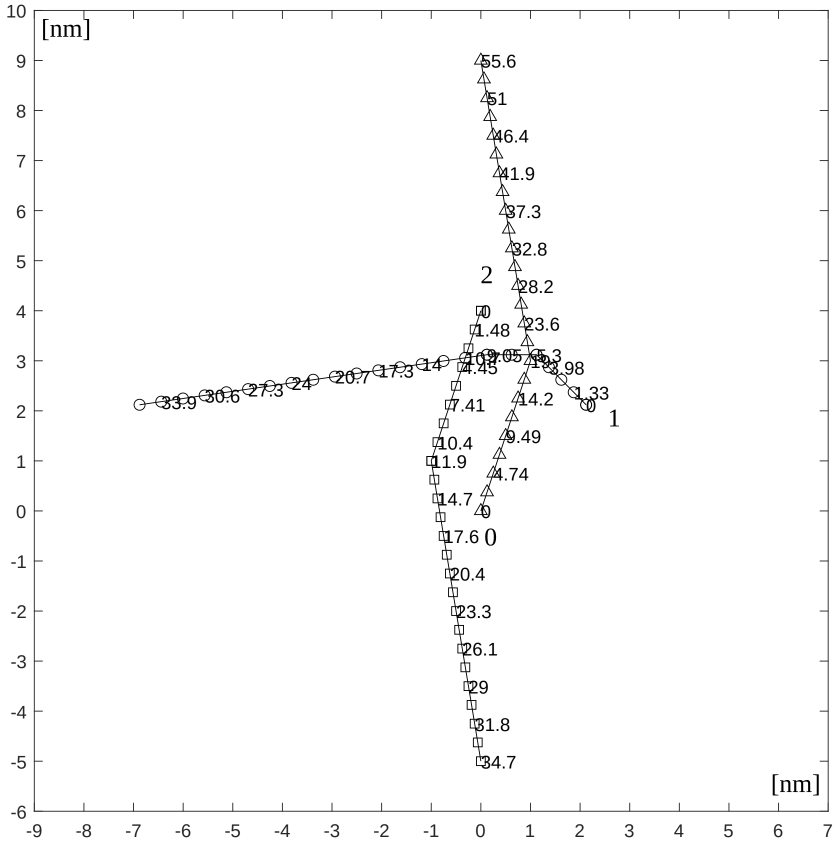

Figure 7. Solution of test case 2.

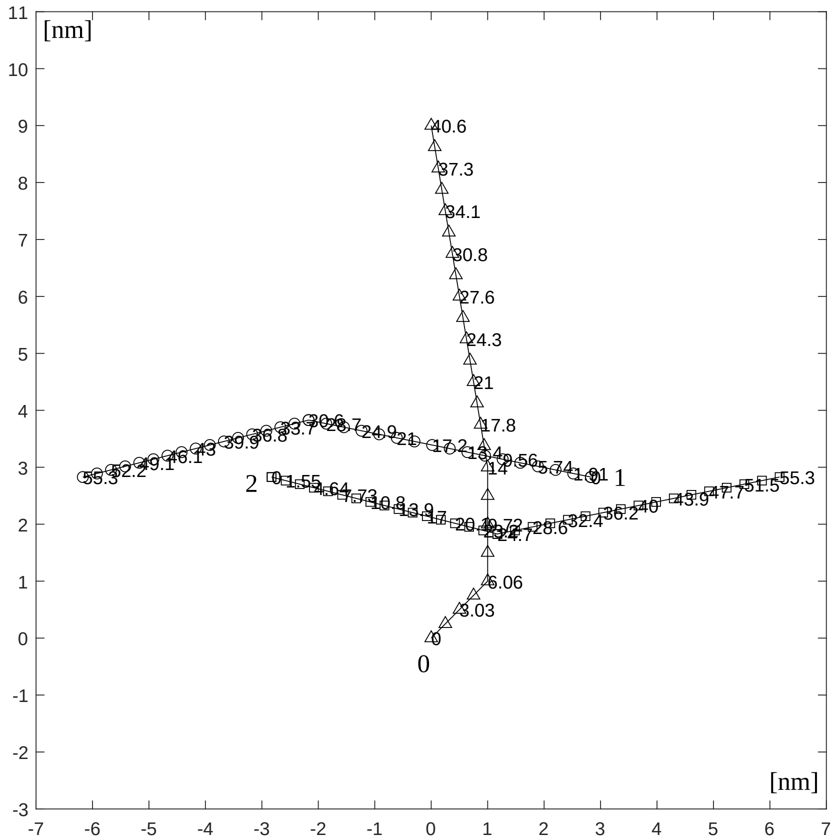

Figure 8. Solution of test case 3.

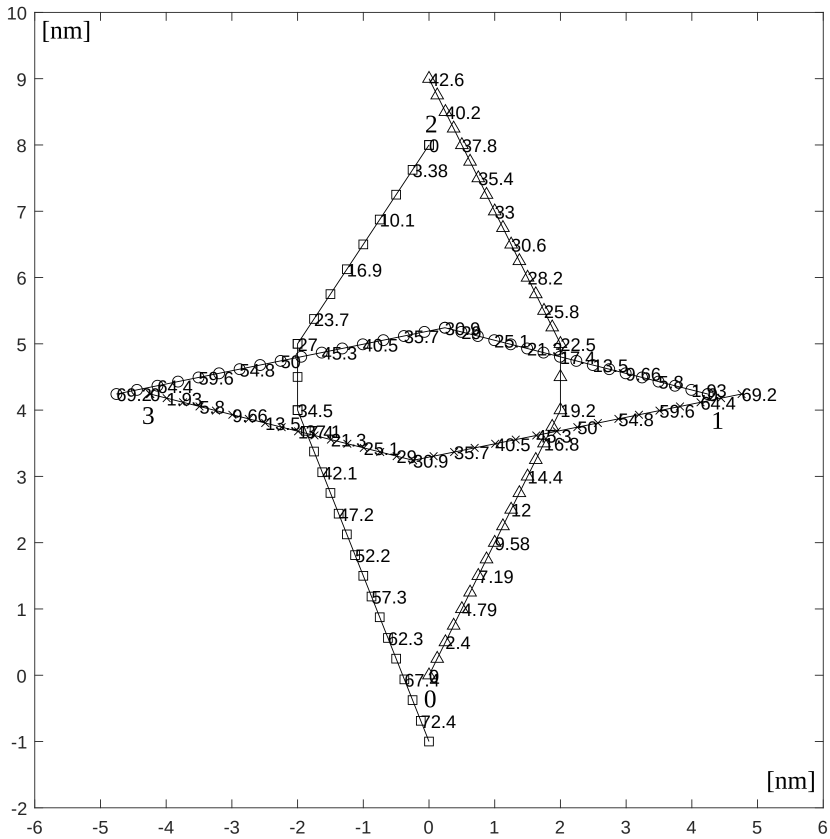

Figure 9. Solution of test case 4.

Table 12. Output data of test case 3.

USV No.	Course [°]	Path Length [nm]	Run Time [s]
0	45, 0, 351	9.5	0.47
1	281, 256	9.22	0.12
2	104, 79	9.22	0.11

Table 13. Output data of test case 4.

USV No.	Course [°]	Path Length [nm]	Run Time [s]
0	27, 0, 333	9.94	0.7
1	284, 259	9.22	0.09
2	214, 180, 158	9.99	0.8
3	104, 79	9.22	0.09

6. Discussion

6.1. Analysis of Results

Results of TBA applied in the presented concept for USV collision avoidance allow to state the following remarks:

- Safe paths calculated by the algorithm are compliant with COLREGs (especially rules 8b, 14 and 15);
- Paths calculated by the algorithm from the perspectives of different USVs taking part in the considered test case are consistent (do not lead to a collision between the crafts);
- The run time of the algorithms (less than a second) is acceptable for real-time path planning purposes.

It should be underlined here that results of collision avoidance algorithms, regarding calculation of multiple trajectories, are very rare in the literature on that topic. Examples of approaches other that the one presented in this paper can be found in [44,45].

Test case 1 presents a head-on situation. In this encounter situation, according to rule 14 of COLREGs, both vessels should alter her course to starboard side in order to pass on the port side of the other vessel. Figure 1 presents paths calculated by the algorithm for both vessels. As can be observed there, both USVs execute maneuvers to their starboard sides. Maneuvers are also compliant with rule 8b of COLREGs—they are large enough to be easily noticed and interpreted by the other vessel.

Test case 2 presents an encounter of three USVs and is composed of head-on (between vessels 0–2) and crossing situations (between vessels 0–1 and 1–2) between the different pairs of vessels. The behavior of vessels in a crossing situation is defined by rule 15 of COLREGs. According to this rule, the vessel that has the other vessel on her starboard side should keep out of the way and avoid crossing ahead of the other vessel. As can be observed in Figure 2, the USV no. 0 keeps out of the way of the USV no. 1 and does not cross ahead on the other vessel. In the same manner, the USV no. 1 keeps out of the way of the USV no. 2. The solution is also compliant with rule 14 of COLREGs—both USVs no. 0 and no. 2 alter their course to starboard, passing on the port side of the other vessel. Similarly, as in test case 1, maneuvers of all USVs also fulfill rule 8b.

In test case 3, a crossing situation occurs between vessels 0–1 and 0–2, whereas a head-on encounter takes place between vessels 1–2. Likewise, in test case 2, solutions are calculated by the TBA for all of the USVs fulfill rules 8b, 14 and 15.

Test case 4 is an encounter between four USVs, where crossing situations occur between the vessels 0–1, 1–2, 2–3 and 3–0, and head-on situations take place between vessels 0–2 and 1–3. Analyses of safe paths returned by the TBA enable to state that the solutions are compliant with COLREGs rules 8b, 14 and 15.

The obtained results confirm the prospect to apply the proposed collision avoidance algorithm in the Autonomous Multi-Agent Navigation System for Unmanned Surface Vessels, as it has been proven that the solutions calculated for different vessels in the same encounter situation constitute safe paths (do not lead to a collision between the marine crafts). Therefore, they can constitute a solution of maneuver auto-negotiation procedure.

6.2. Comparison with Other Collision Avoidance Algorithms

The collision avoidance algorithm has been compared with other approaches proposed for the application in maneuver auto-negotiation systems or presenting results from different ships' perspectives. The results of this analysis are shown in Tables 14 and 15. The comparison includes: applied method, type of the method, i.e., deterministic or non-deterministic, consideration of static navigational restrictions, dynamic obstacles and COLREGs, applied optimization criterion. The run time of the algorithm and repeatability of a solution for every run of calculations with the same input data are also specified in the tables. The adopted calculation approach has also been defined for every algorithm, whether the trajectories are calculated by only one vessel: the leader ship or by all of marine crafts taking part in the encounter. The main advantages of the approach proposed in this paper, in relation to other existing methods, are as follows:

- Deterministic nature of the algorithm, which guarantees repeatable solutions, similarly to [28,44];
- Near-real run time: up to a second, making it applicable for USVs;
- COLREGs compliant solution (rules 8b, 13–15);
- Consideration of static constraints (lands, shallows, buoys), as in [45];
- Possibility to calculate the solution from the leader USV perspective as well as all ships' perspectives.

Table 14. Comparison of collision avoidance algorithms applicable in maneuver auto-negotiation systems—part 1.

Authors	Year	Method	Type	Static Obstacles	Dynamic Obstacles	COLREGs
Tam and Bucknall [44]	2013	Cooperative Path Planning (CPP)	deterministic	static point-based obstructions (buoys)	simple and complex encounters	determined priority based on COLREGs
Szapczynski and Szlapczynska [45]	2012	Evolutionary Sets of Safe Ship Trajectories (ESoSST)	non-deterministic	shorelines, shallows	simple and complex encounters	COLREGs-violation penalties
Tam and Bucknall [46]	2010	evolutionary algorithm	non-deterministic	ship with 0 speed	simple and complex encounters	COLREGs-influenced area (CA)
Hu et al. [28]	2008	Collision-Avoidance Negotiation FrameWork (CANFO)	deterministic	not considered	two ship encounters	might not be COLREGs compliant
This approach	2022	Trajectory Base Algorithm (TBA)	deterministic	shorelines, shallows, point-based	simple and complex encounters	COLREGs enforced by ship domain shape and size

Table 15. Comparison of collision avoidance algorithms applicable in maneuver auto-negotiation systems—part 2.

Authors	Year	Optimization Criteria	Run Time	Repeatability	Perspective
Tam and Bucknall [44]	2013	course change of 30 degrees)	7 s for complex test cases	yes	consistency from all ships' perspectives
Szapczynski and Szlapczynska [45]	2012	min. way losses of trajectories in a set;	maximum 1 min	no—small differences possible	leader ship perspective
Tam and Bucknall [46]	2010	path length, avg. speed, travelling time, engine adjustment;	200–800 s	no	consistency from all ships' perspectives
Hu et al. [28]	2008	details not given	not given	yes	both ships' perspectives
This approach	2022	minimal path length	less than 1 s	yes	leader ship/all ships perspectives

7. Conclusions

The main contributions of the research presented in this paper in relation to the previous works of the authors are the application of the developed deterministic collision avoidance algorithm within the framework of a multi-agent system for the purpose of USV maneuver auto-negotiation and also the carried out tests of the algorithm in order to assess the possibility to apply collaborative strategies to avoid collisions with other agents in the proposed multi-agent system by the calculation of multiple trajectories for all USVs taking part in the considered navigational scenario.

A concept of the Autonomous Navigation System for Unmanned Surface Vessels, with a special emphasis on the task of collision avoidance, was presented first. A general structure of the ANS system was developed, based on the idea of multi-agent systems. An agent is an autonomous entity that perceives the environment using sensors and acts on the environment through effectors (actuators). The agent's interaction can be based on cooperation or competition. The goal of the USV, modeled as an agent, is to reach the end point of the trajectory. However, in order to achieve this objective, it has to apply collaborative strategies to avoid collisions with other agents. For this purpose, agents exchange information on planned actions. Proposed collision avoidance algorithm was validated by simulation experiments with a special emphasis on the verification of its applicability for the purpose of maneuver auto-negotiation. The achieved results prove that the trajectories obtained for different agents do not lead to a collision; therefore, the algorithm is suitable for the application in the Autonomous Multi-Agent Navigation System for the USV.

Further research include the development of the communication protocol between agents, allowing them to exchange the information efficiently. After that, experiments in real operating conditions are planned to be carried out.

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Abbreviations

The following abbreviations are used in this manuscript:

AIS	Automatic Identification System
ANS	Autonomous Navigation System
ARPA	Automatic Radar Plotting Aid
ASM	Advanced Sensor Module
CA	Collision Avoidance module
COLREGs	The International Regulations for Preventing Collisions at Sea
DAI	Distributed Artificial Intelligence
GPS	Global Positioning System
IMO	The International Maritime Organization
MASS	Maritime Autonomous Surface Ship
MPC	Model Predictive Control
SA	Situation Awareness module
SF	Sensor Fusion module
TBA	Trajectory Base Algorithm
UAV	Unmanned Aerial Vehicle
USV	Unmanned Surface Vessel (Vehicle)
UUV	Unmanned Underwater Vehicle
VO	Velocity Obstacles method

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