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Interaction between COLREG-compliant collision avoidance systems in a multiple MASS scenario

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Abstract. The transportation systems are heading towards increasing autonomy in all domains, and the maritime field makes no exception. The International Maritime Organization has been working on releasing a regulatory framework for Maritime Autonomous Surface Ships (MASS) to keep pace with the technological developments in the field. Autonomous shipping forces the researcher and the designers to face a wide range of scientific challenges, such as navigation decision support systems, collision avoidance algorithms, path planning, navigation and control, sensor data processing and fusion, remote control, and communication, with the final intent of achieving a fully integrated and autonomous worldwide maritime transportation system, where a human-less collaborative conflict resolution could potentially retire the COLREGs. However, the maritime sector will first face a transition period where traditional ships will share the seas and interact with heterogeneous MASS with various autonomous capabilities featuring different and probably incompatible communication protocols. In such a scenario, the COLREGs will still play a primary role in helping the collision avoidance systems resolve conflicts and limiting the degrees of freedom. This paper aims to study the interaction among multiple vessels with autonomous collision avoidance capabilities operating in a close navigation scenario. The ships operate according to a COLREG-compliant collision avoidance algorithm. The paper relies on numerical simulation to systematically investigate different scenarios in which autonomous vessels operate and interact in the presence of fixed obstacles. Results are presented and critically discussed.

1. Introduction

Transportation systems are rapidly evolving, embracing increasing autonomy across all domains, and the maritime industry is no exception to this trend: The emergence of autonomous vehicles (AVs) has transformed the transportation landscape, offering immense potential for revolutionizing mobility, and the maritime world makes no exception. Recognizing the technological advancements in the marine sector, the International Maritime Organization (IMO) has been actively working on developing a regulatory framework for Maritime Autonomous Surface Ships (MASS). In particular, IMO defined four autonomy levels, from degree one, representing a crewed ship with automated processes and decision support, to degree four, i.e., a fully autonomous, uncrewed, and unsupervised ship. The emergence of autonomous shipping poses numerous scientific challenges for researchers and designers. These challenges span various domains, including navigation decision support systems, collision avoidance algorithms, path planning, navigation and control, sensor data processing and fusion, remote control, and communication.

This paper is positioned in the sight of establishing a fully integrated degree-four autonomous maritime transportation system on a global scale. In such a future, collaborative techniques [1, 2, 3, 4] will allow conflict resolution based on information sharing that could replace the existing International Regulations for Preventing Collisions at Sea (COLREGs). Furthermore, as automation and artificial intelligence take center stage, a human-centric set of rules may become obsolete in a human-less loop. Nevertheless, the transition to full autonomous navigation will feature the coexistence of traditional ships and MASSs with different IMO degrees. During this phase, seafarers will navigate alongside human-crewed vessels equipped with decision support systems capable of suggesting evasive actions to enhance their navigation capabilities [5, 6, 7], same remotely operated vessels and Degree-Four full-autonomous ships with full reactive motion planning capabilities [8].

The standardization process will be long and complex: it is reasonable to expect each vessel to feature proprietary systems and different and incompatible communication protocols and interfaces. In this complex scenario, the old-but-gold COLREGs [9] will continue to play a central role in facilitating collision avoidance systems and limiting the degrees of freedom at sea to make decision-making easier. Moreover, since both autonomous and human-operated vessels will share the sea, the “digital” masters should behave in compliance with the COLREGs to avoid conflicting with the “analogic” seafarers.

The primary objective of this paper is to study the interaction between autonomous vessels with collision avoidance capabilities to ensure safety at sea, develop and improve robust collision avoidance technologies, reduce the risk of collisions, and enhance overall safety for both autonomous and traditional vessels. The paper investigates the interaction among two autonomous ships featuring autonomous collision avoidance capabilities in different COLREG encounter situations to assess the effectiveness of collision avoidance systems in the most relevant COLREG cases. In particular, a custom implementation [10] of the rapidly exploring random tree (RRT*) algorithm [11, 12], including COLREGs [13] is used as the core of the collision avoidance system of both the vessels. The simulation results are statistically evaluated according to properly defined metrics.

2. Collision avoidance

The collision avoidance system is built according to the flowchart shown in figure 1. The collision avoidance manager (red block) collects proprioceptive and exteroceptive data via sensors. Typical proprioceptive sensors include the GPS and the gyrocompass, while perception can be achieved via sensors such as AIS data, RADAR, LiDAR, and cameras. Based on the mission parameters, the collision avoidance manager calls the path planning algorithm, which computes the optimal evasive track. Eventually, the track keeping system is updated with the new track waypoints.

The path planning algorithm is the core part of the system: this paper relies on an RRT*-based COLREG-compliant optimal path planning algorithm. The authors have introduced the algorithm [10, 13] and tested it in simulation in the presence of obstacles [14]. The essential details are given in the following of this section.

2.1. Track parameterization

Track parameterization is crucial to building the computation framework. The planned track is represented by a set S of waypoints $\mathbf{x}_p$:

$$S = \{\mathbf{x}_p\},\, p = 0, ..., N \qquad (1)$$

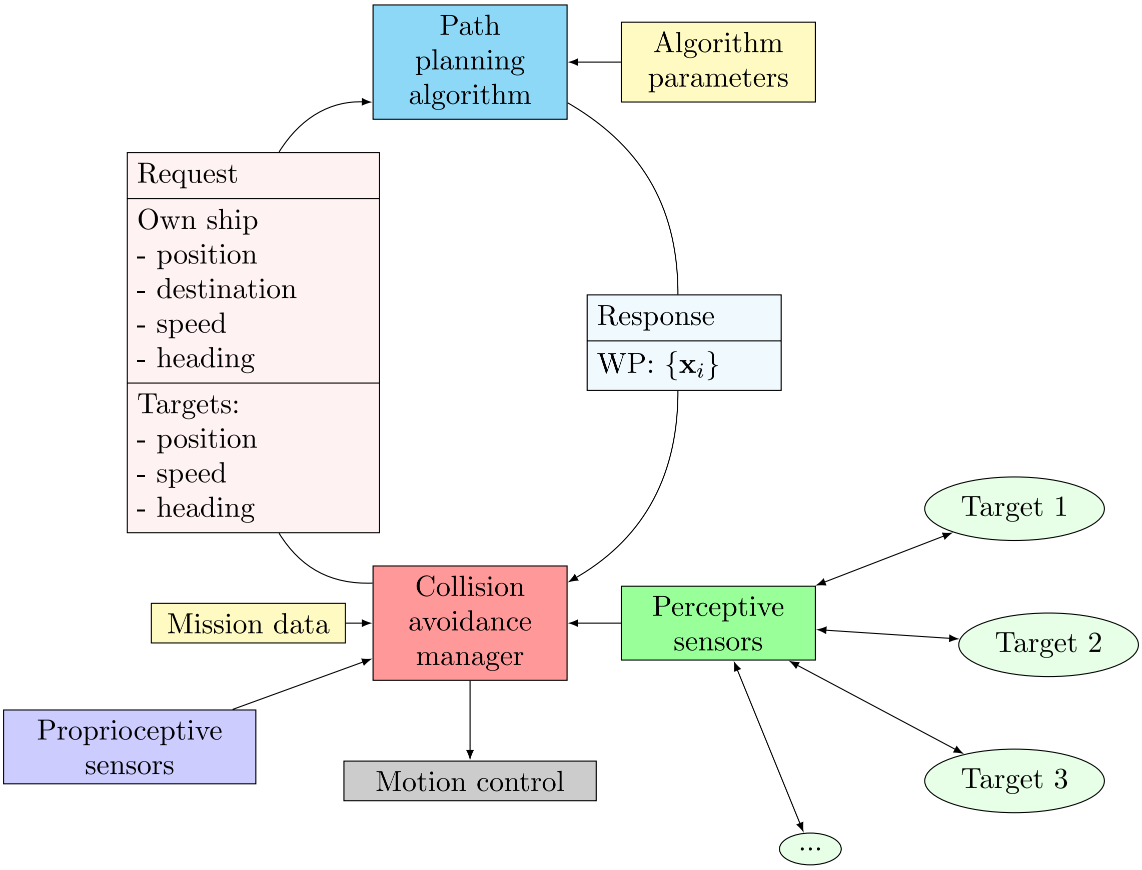


Figure 1: Conceptual architecture of the collision avoidance system

Two waypoints identify one route leg $\mathbf{l}_p$:

$$\mathbf{l}_p = \mathbf{x}_{p+1} - \mathbf{x}_p \tag{2}$$

The course change at waypoint $\mathbf{x}_p$, i.e. between legs $\mathbf{l}_{p-1}$ and $\mathbf{l}_p$ is denoted as θ_p. Two types of obstacles (also referred to as targets) can be identified: fixed (walls, buoys, shoals) and moving (other vessels). The current target positions are denoted $\mathbf{y}_i(t)$. The future motion of a target is approximated depending on its known position $\mathbf{y}_i(t)$ and its speed $\mathbf{w}_i(t)$ according to the following motion law:

$$\mathbf{y}_i(t + \Delta t) = \mathbf{y}_i(t) + \mathbf{w}_i(t)\Delta t \tag{3}$$

2.2. Constraints

The computed track must respect constraints, including collision avoidance constraints, kinematic constraints, and COLREG compliance. First, the evasive track must keep a distance from all the targets greater than a threshold value d_{safety} representing the distance below which the collision hazard is too high. If there are T targets:

$$|\mathbf{y}_i(t) - \mathbf{x}(t)| \geq d_{safety} \; i = 1, \ldots, T \tag{4}$$

Moreover, the maximum steering angle between two consecutive legs is limited by the vessel's maneuvering capabilities:

$$|\theta_k| \leq \theta_{max}, \; k = 0, \ldots, N-1 \tag{5}$$

In addition, the track must respect the COLREG rules. The authors introduced a mathematical framework to implement the COLREG rules for crossing, head-on, and overtaking between motor ships in the proposed model [13]. If $\mathbf{x}$ and $\mathbf{v}$ denote the own vessel's position and speed, $\mathbf{y}_i$ and $\mathbf{w}_i$ are the i^{th} target's position and speed, and $\mathbf{x}_c$ is the interception between their tracks, the following expression determines which vessel is engaging the point first:

$$\frac{|\mathbf{x}_c - \mathbf{x}|}{|\mathbf{v}|} - \frac{|\mathbf{x}_c - \mathbf{y}_i|}{|\mathbf{w}_i|} \begin{cases} > 0 \rightarrow \textit{target ship first at } \boldsymbol{x}_c \\ = 0 \rightarrow \textit{perfect collision} \\ < 0 \rightarrow \textit{own ship first at } \boldsymbol{x}_c \end{cases} \tag{6}$$

The relative orientation of the vessels can be identified by discussing the cross-product between $\mathbf{v}$ and $\mathbf{w}_i$, (positive downwards):

$$\mathbf{v} \wedge \mathbf{w}_i \cdot \mathbf{e}_D \begin{cases} > 0 \rightarrow \textit{own ship can see target's starboard} \\ = 0 \rightarrow \textit{parallel routes} \\ < 0 \rightarrow \textit{own ship can see target's portside} \end{cases} \tag{7}$$

According to the COLREGs, there is an overtaking scenario if the own ship is engaging the target ship from an angle θ_o of less than 22.5° from the own ship aft. According to this case, the own vessel must not cross the target's route, according to Equation 6.

In a crossing scenario, the ship that sees the other's port side (red light) must give way. The combination of Equations 7 and 6 gives condition for crossing:

$$(\mathbf{v} \wedge \mathbf{w}_i \cdot \mathbf{e}_D) \left(\frac{|\mathbf{x}_c - \mathbf{x}|}{|\mathbf{v}|} - \frac{|\mathbf{x}_c - \mathbf{y}_i|}{|\mathbf{w}_i|} \right) < 0 \tag{8}$$

The COLREGs prescribe a turn to starboard for both vessels in the head-on condition. Thus, the algorithm must ensure the target vessel is on the own ship's port side, according to Equation 7.

2.3. Cost function

The total control energy is minimized to ensure a smooth track and reduce the demand for the track control system. In particular, the energy-optimal route is obtained by minimizing the total steering action c_s:

$$c_s(S) = \sum_{k=0}^{N} \theta_k^2 \tag{9}$$

2.4. Optimization algorithm

The framework described in this section is suitable for computing optimal tracks with gridded and scattered approaches, depending on how the waypoints are generated. This study uses the RRT* (Rapidly-exploring Random Tree) random sampling algorithm. The RRT* [11, 15, 12] is an optimized variation of the regular RRT algorithm: While the RRT algorithm aims to quickly generate feasible, collision-free trajectories, the RRT* adds a local optimization action to generate heuristically optimal trajectories.

3. Case study

The above-described approach was extensively tested in previous papers [14] in the presence of moving targets, considering straight-line targets and targets moving according to non-straight-line trajectories. This paper investigates if the proposed approach is robust enough to ensure collision-free navigation of two autonomous vessels in the same scenario, relying on their respective collision avoidance system instances and trying to reach their respective destinations. According to the COLREGs, there should be no communication between two encountering vessels, so each collision avoidance instance is not aware of the track planned by the other vessel, so the future target's motion is based on the current target's position, heading, and speed measured by the sensors.

The simulations have been carried out according to the following steps:

(i) The vessels' positions and destinations are initialized in the respective regions according to the scenario.
(ii) At the assigned replanning rate, each vessel performs its route planning based on the other's position, course, and speed.
(iii) Each vessel follows the planned route until the next replanning.

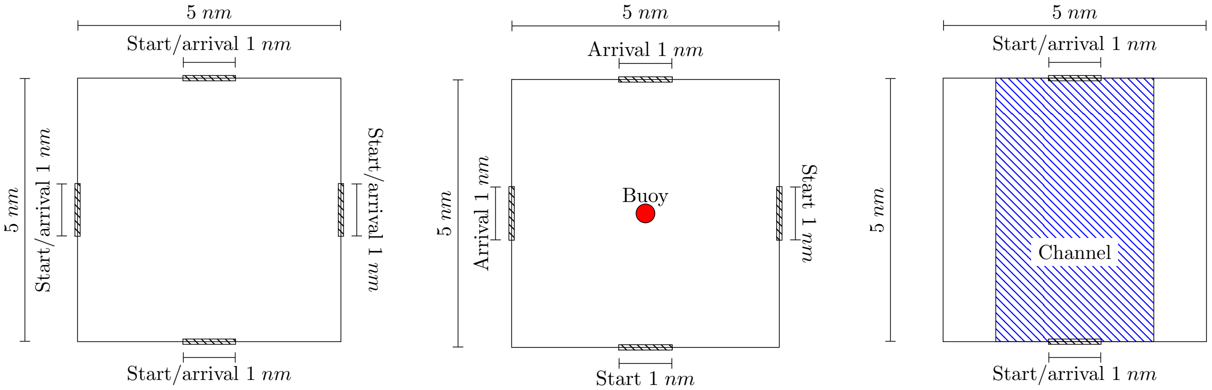
The algorithm was tested in three different COLREG cases (crossing, head-on, overtaking) and three test domains featuring the presence or absence of fixed obstacles, resulting in six combinations described below. In particular:

- The "OpenWater" test domain, shown in Figure 2a, is a square region of 5 nautical miles on a side. All three COLREG cases were tested in this domain.
- The "Buoy" domain features a fixed obstacle in the middle (e.g., a buoy marking a surfacing shoal), with a footprint of about 0.2 nautical miles, as shown in Figure 2b. The crossing COLREG case was tested in this domain.
- The "Channel" domain, in which overtaking and head-on were tested, features a three nautical miles wide channel, as shown in Figure 2c.

The three COLREG cases combined with the above-described test domains result in the following six scenarios:

- OpenWaterCrossing: The two vessels, starting from two successive sides to reach their respective target points, meet at an angle close to 90 degrees in entirely open water.
- OpenWaterHeadOn: The two vessels start from opposite sides of the square and meet with a bearing close to zero in fully open water.
- OpenWaterOvertaking: In this case, only the fast vessel crosses the square entirely and, in doing so, encounters ahead a slower vessel sailing along a similar course. The slow vessel is moving at half the speed in an identical square region shifted 2 miles forth.
- BuoyCrossing around a buoy: structured like the crossing scenario, but in the "Buoy" domain.
- ChannelHeadOn: The two vessels meet per the previously described OpenWaterHeadOn but in the "Channel" domain.
- ChannelOvertaking: The two vessels meet per the previously described OpenWaterOvertaking but in the "Channel" domain.

In each scenario, each vessel starts from a randomly assigned point along the respective starting side and must reach a randomly assigned destination on the opposite side, sailing at 10 knots. The points of departure and destination are included in a region one nautical mile wide, straddling the middle of the pertinent side of the square. Moreover, the two vessels were expected to keep their closest distance above a threshold value $d_{safety} = 0.5\ nm$ based on seafarers' expert judgment to test the algorithm in critical conditions. Lastly, the replanning rate was set to once every 60 seconds for both vessels.



(a) OpenWater domain (b) Buoy domain (c) Channel domain

Figure 2: Test domains

4. Results

The algorithm was tested extensively in all the presented scenarios. The implementation in the Rust programming language was intended to maximize computational performance: a single call of the planning function takes place in a few milliseconds, opening the way to future real-time implementation in an experimental setup with fast, model-scale dynamics.

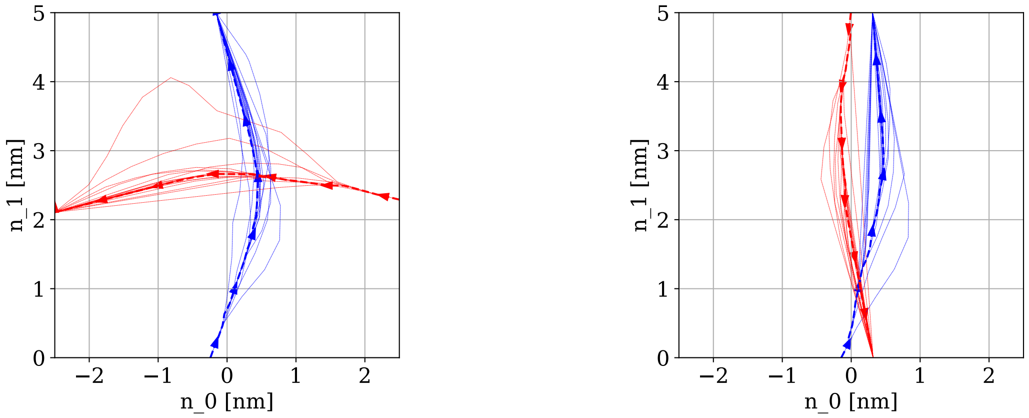
Figure 3 shows a simulated track for each scenario. The thick lines are the trajectories the vessels followed, while the thin lines represent the tracks each vessel planned at each replanning instant. The arrows represent corresponding time instants.

In particular, 2000 instances of each scenario were generated considering random start and arrival points. The following performance indicators were considered to analyze the results:

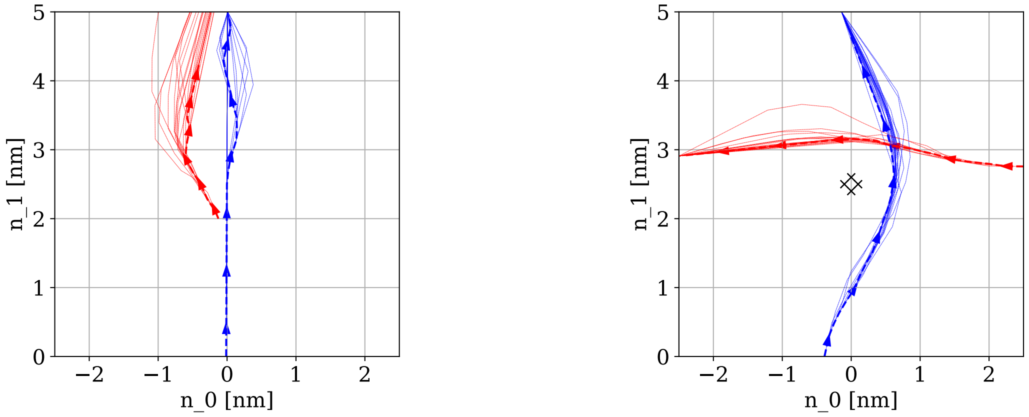
- CPA margin: the difference between the actual minimum distance (closest point of approach, CPA) during each simulation and the threshold safety distance ($d_safety = 0.5nm$).
- Percentage of successful simulations (OkRate): A simulation is successful when the CPA margin is positive.
- Minimum CPA (MinCPA): the worst achieved result regarding the CPA between the vessels.
- Percentage of failed replannings (RepFail): A fail happens when the algorithm cannot find a new feasible route, so the vessel keeps following the current set of waypoints until the next replanning.
- Average computation time (AvgCTime): the average time required to run the algorithm in the considered scenario.

The histograms in Figure 4 summarize the CPA margins achieved in the simulations, while the other results are reported in Table 1.

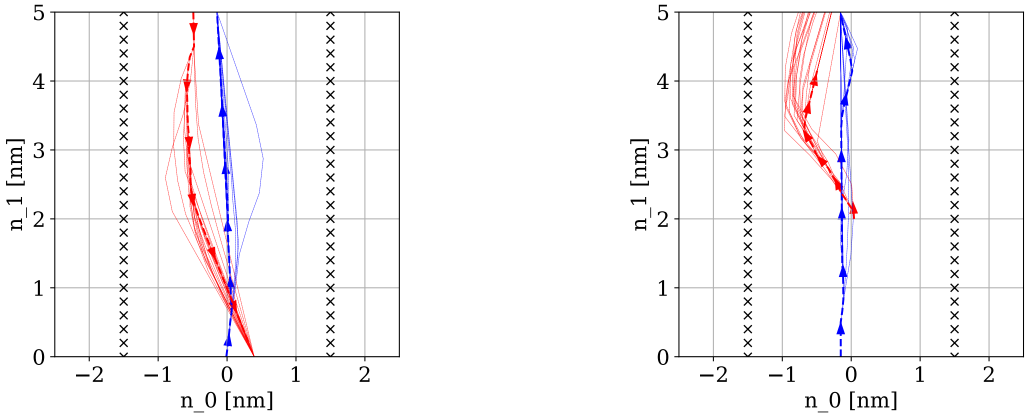
The success rate is between 91% and 99%. The crossing scenario shows the lowest success rate but a relatively high CPA margin. On the contrary, both the overtaking scenarios show very close CPA when failing, down to 0.02 nautical miles (about 40 meters). In other words, the failed simulations result in a near-miss or collision despite the higher success rate. Overtaking simulations appear to be the most critical scenario due to the long time the two vessels remain side by side with low relative speed, exposing themselves to a possible collision.



(a) OpenWaterCrossing (b) OpenWaterHeadOn

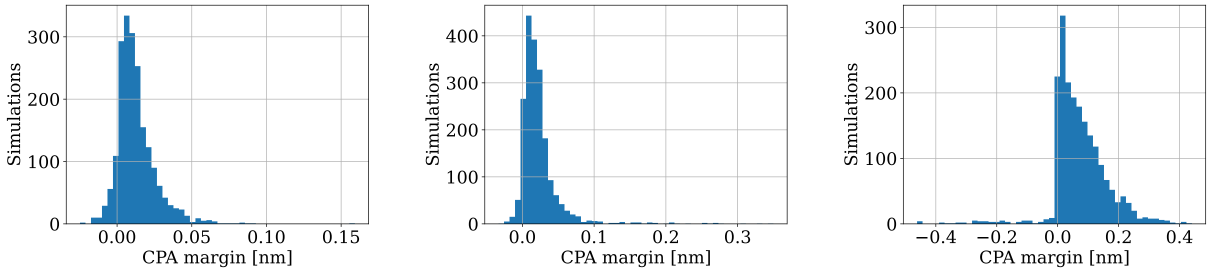


(c) OpenWaterOvertaking (d) BuoyCrossing

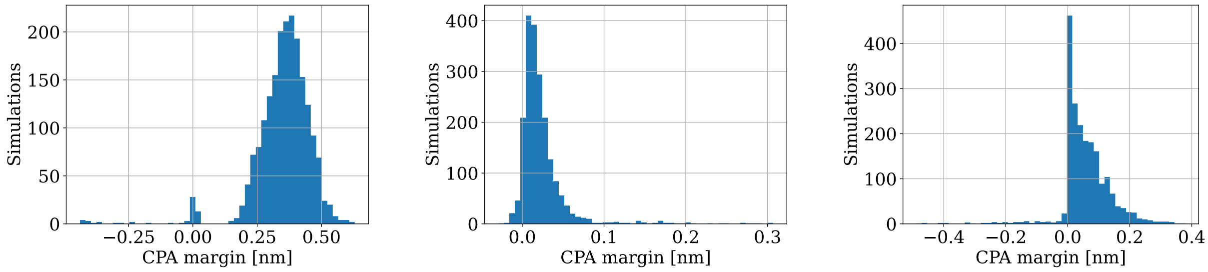


(e) ChannelHeadOn (f) ChannelOvertaking

Figure 3: Examples of simulated scenarios



(a) OpenWaterCrossing (b) OpenWaterHeadOn (c) OpenWaterOvertaking



(d) BuoyCrossing (e) ChannelHeadOn (f) ChannelOvertaking

Figure 4: Per-scenario aggregated data of the CPA margin

Table 1: Performance indicators for 2000 randomized simulations per scenario

Scenario	OkRate	MinCPA	RepFail	AvgCT*
OpenWaterCrossing	91.7 %	0.48 nm	0.5 %	9 ms
OpenWaterHeadOn	94.2 %	0.47 nm	0.7 %	7 ms
OpenWaterOvertaking	95.0 %	0.04 nm	9.2 %	3 ms
BuoyCrossing	98.8 %	0.06 nm	1.2 %	15 ms
ChannelHeadOn	94.8 %	0.47 nm	0.8 %	15 ms
ChannelOvertaking	94.9 %	0.01 nm	10.2 %	4 ms

(*) Hardware: AMD Ryzen 9 5900HS CPU (8 × 3.3Hz - 4.6Hz boost), 32GB DDR

Since the results suggest a higher risk (more severe consequences in case of failure) during overtaking, it would be desirable to modulate the safety distance according to the type of COLREG encounter the vessels face, increasing the safety distance in higher-risk cases. It is worth noticing that the threshold safety distance was set at the lower limit of the acceptable range in the real world, based on the expert judgment of seafarers, to stress the algorithm under a realistic but challenging condition. In a real-world application, safety distance should be enough to include an additional margin to account for sensor and track errors, delays in the decision-making process, vessel dynamics, and other uncertainties.

The proposed algorithm implementation presented a very low failure rate (lower than 1%) in most cases. From the results obtained, simulated overtaking scenarios show a decade higher failure rate than the others, explaining why the simulation success rate is lower in overtaking scenarios. Eventually, note that the proposed algorithm required a negligible computation time compared to previous implementations [10], opening the way to real-time and experimental tests.

5. Conclusions

This paper studied the interaction between multiple vessels with autonomous collision avoidance capabilities operating in a close navigation scenario. The behavior of two autonomous vessels operating according to a COLREG-compliant collision avoidance algorithm was simulated.

Before establishing an entirely autonomous framework where collaborative conflict resolution will retire the COLREGs, the transition to full autonomous navigation will face the coexistence of traditional and autonomous vessels, where compatibility and communication issues are expected. The authors believe that COLREGs will still help make decisions and resolve conflicts between human-crewed and human-less vessels.

The tests reported include randomly generated crossing, head-on, and overtaking scenarios, both with and without fixed obstacles, where both vessels had to reach their respective destination without colliding. The algorithm was tested extensively in all the presented scenarios, performing 2000 randomly initialized simulations for each scenario and analyzing performance indicators, including the percentage of successful simulations, the CPA margin, the percentage of failed path replannings, and the average replanning computation time.

The percentage of success was higher than 91% in all the considered scenarios. The overtaking encounter presented a very close CPA when failing, showing a higher collision risk. This result suggests that the safety distance might be modulated according to the type of COLREG encounter the vessels face, increasing the safety distance in higher-risk cases. Eventually, the proposed algorithm showed a very low failure rate and computation time, opening the way to real-time and experimental tests.

It is worth noticing that while the interaction among autonomous vessels and humanly operated ships with pre-planned trajectories has been studied in the past, the present paper discussed the real-time interaction between two autonomous vessels. Future work will feature vessels with different levels of autonomy, including human-in-the-loop, sharing the same navigation area.

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