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A Conceptual COLREGs-based Obstacle Avoidance Algorithm Implementing Dynamic Path Planning and Collision Risk Assessment

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Abstract

This paper introduces an algorithm for collision avoidance systems intended for Maritime Autonomous Surface Ships. The algorithm takes into account the rules defined by the International Regulations for Preventing Collisions at Sea (COLREGs) and is tailored for real-world maritime environments. Analysis of collision accidents highlights human error and non-compliance with COLREGs as primary contributing factors. Employing the COLREGs as foundational design criteria can mitigate these factors. The algorithm also has the potential to serve as a decision support system on currently manned vessels, enhancing safe navigation. The study proposes a novel rule-based collision avoidance algorithm that adheres to COLREGs, utilizes the Collision Risk Index and ship domain for safety assessment, and combines dynamic path planning for collision-free navigation. Leveraging the Automatic Identification System, which is present on all ships navigating international waters, the algorithm achieves target detection. The algorithm was applied to simulate past ship-to-ship collision incidents, considering the ship kinematics, dynamics, and maneuverability resulting in successful prevention of such accidents through the proposed approach.

Keywords: Collision avoidance, Collision Risk Index (CRI), COLREGs, Dynamic path planning, Ship domain

1. Introduction

Human error has been recognized as a primary contributing factor in more than 75% of maritime accidents, according to the findings of [1]. In studies [2] and [3], the incidence of human error in marine accidents was identified as 78% and 80%, respectively. A recent comprehensive analysis of major collision accidents since 1977 has found that reduced crew numbers, the adoption of swift loading and unloading equipment, and the resultant increase in seafarers' workload and duty hours have contributed significantly to these incidents, with human error identified as the primary cause in 94.7% of cases [4]. A bridge watch entails a multifaceted process demanding simultaneous and continuous consideration and assessment of numerous elements. These encompass maintaining a lookout, coordinating with the bridge team, managing bridge resources, utilizing navigational equipment for observing maritime traffic, adhering to the International Regulations for Preventing Collisions at Sea (COLREGs) during maneuvering, and engaging in effective communication with other vessels. There is a requirement to develop algorithms and methods that can assist human operators in collision avoidance strategies, a pivotal component of ensuring ships' safe navigation. This need arises from the limitations of human operators as discussed earlier, compounded by commercial pressures [5]. These algorithms and methods will not only aid human operators but also serve as the foundation for future systems that are anticipated to replace human involvement.

The literature contains a plenty of techniques, algorithms, and applications for collision avoidance and path planning

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in autonomous surface vehicles. By excluding variations of these methods, the authors have identified a total of 37 distinct approaches (Table 1). However, in comparison to collision avoidance and path planning for aviation, land, and underwater vehicles, addressing these challenges for Maritime Autonomous Surface Ships (MASSs) presents a more intricate undertaking. The methods listed in Table 1 can be classified into two categories: those that offer vector-based visual solutions [6-14], and those that rely on numerical mathematical models [15-24]. While

Table 1. *Methods, algorithms, and functions used for ship collision avoidance and path planning in the literature*

Method	Purpose	Research
Artificial Potential Field (APF)	Collision avoidance	[6]
Velocity Obstacle (VO)	Path plan. + Collision avoidance	[7]
Dynamic Window (DW)	Collision avoidance	[8]
Voronoi Diagram	Path planning	[9]
Fast Marching Method	Path plan. + Collision avoidance	[10]
Swarm Intelligence	Path plan. + Collision avoidance	[11]
Dynamic Optimization Algorithm	Path plan. + Collision avoidance	[11]
Rapidly-Exploring Random Tree (RRT)	Path plan. + Collision avoidance	[12]
Branch and Bound Method	Collision avoidance	[13]
Grid-based Method	Path plan. + Collision avoidance	[14]
Fuzzy Logic	Collision avoidance	[15]
Model Predictive Control (MPC)	Path plan. + Collision avoidance	[16]
Neural Networks	Path plan. + Collision avoidance	[17]
Game Theory	Collision avoidance	[18]
Dijkstra Algorithm	Path plan. + Collision avoidance	[19]
Evolutionary Algorithm	Path plan. + Collision avoidance	[20]
Case-based Reasoning	Collision avoidance	[21]
Inevitable Collision State	Path plan. + Collision avoidance	[22]
Control Barrier Function	Collision avoidance	[23]
Barrier Lyapunov Function	Path plan. + Collision avoidance	[24]
Gauss Mix Model	Collision avoidance	[25]
Bayesian Networks	Collision avoidance	[26]
Deterministic Method	Path plan. + Collision avoidance	[27]
Line of Sight (LOS)	Path plan. + Collision avoidance	[28]
Interval Programming (IvP)	Collision avoidance	[29]
Non-linear Programming	Path planning	[30]
Constrained Convex Optimization	Collision avoidance	[31]
Danger Immune Algorithm	Collision avoidance	[32]
Distributed Search Algorithm (DSA)	Collision avoidance	[33]
Linear Extension Algorithm	Collision avoidance	[34]
Local Reactive Obstacle Avoidance Based on Region Analysis (LROABRA)	Collision avoidance	[35]
Local Normal Distributed Based Trajectory	Path plan. + Collision avoidance	[36]
Recursive Algorithm	Path plan. + Collision avoidance	[37]
Pseudospectral Optimal Control	Path planning	[38]
Probabilistic Approach	Collision avoidance	[39]
Observation Inference Prediction Decision Model	Collision avoidance	[40]
Pontryagin's Maximum Principle	Path plan. + Collision avoidance	[41]

visual solution methods are advantageous for their ease of calculation and interpretability, they are generally inadequate for providing safe recommendations in areas with heavy traffic. Conversely, methods based on mathematical models can yield safe outcomes under all conditions when accurately modeled, but they face challenges such as delayed results due to the complexities involved in modeling and numerous calculations. A limitation common to many algorithms for collision prevention is that they are restricted to the collision avoidance function alone [8,18,25,26] and cannot perform local route planning, which is essential for comprehensive collision prevention.

Despite the frequent use of methods like Artificial Potential Field (APF) [6], Velocity Obstacle (VO) [7], and Model Predictive Control (MPC) [16] in the literature, each has significant drawbacks concerning safe collision avoidance. APF can become trapped in local minimum regions; in the VO method, inaccurate trajectory prediction can result in unsafe recommendations; and in MPC, the approach cannot guarantee safe collision avoidance if the modeling is flawed or an unmodeled scenario arises. In comparison, the proposed method addresses both collision avoidance and local route planning, overcoming limitations such as the need for trajectory estimation and susceptibility to local minima. It operates independently of modeling assumptions by utilizing a rule-based system coupled with real-time risk analysis, thereby enhancing adaptability to unforeseen situations. The proposed method has certain limitations, primarily stemming from its exclusive reliance on Automatic Identification System (AIS) as the target detection sensor and its inability to detect obstacles, such as landmasses, due to the use of non-vectorized electronic charts. However, considering that the study introduces a conceptual system, it offers significant contributions to the literature. These include the incorporation of Rule 18, and the evaluation of interactions with other vessels on a case-by-case basis in compliance with COLREGs.

Collision risk must be identified to enable ships to recognize potential risks in various encountered situations and make suitable collision avoidance decisions. Once the collision risk is calculated during ship encounters, the decision of whether to maneuver or not becomes a crucial aspect that demands careful consideration. Not all ship encounters necessitate maneuvering, as some instances where ships approach each other closely (but still maintain a safe threshold) may not pose an immediate danger. Therefore, continuous monitoring of nearby vessels is essential, and avoidance maneuvers should be executed when deemed necessary based on the identification of collision risks.

This study represents the initial phase of a multi-stage project and within this phase, it has contributed the following advancements to the existing literature. The combination of the updated ship domain and the Collision Risk Index (CRI) serves to signal the initiation and termination points of collision avoidance maneuvers. As far as the available literature indicates, this study stands as the pioneering endeavor to encompass and adhere to all rules complying with COLREG Rules 5, 7, 8, and 13-18, which pertain to navigation and maneuvering aspects. Moreover, practical safety zones have been recommended, aligning with the guidance laid out in [42]. This study's innovation extends to enhancing the objectivity of regulations for autonomous vehicles. This is achieved by aggregating data from various studies that offer numerical interpretations of the COLREG Rules from diverse perspectives.

The primary objective of this study is to introduce a system capable of adhering to the COLREGs, capable of autonomous decision-making that transcends human subjectivity, pre-evaluating collision risk, and executing avoidance actions. The overarching goal of this study is to enhance navigation safety and curtail the frequency of collision incidents leading to loss of life, substantial environmental damage, and property loss. Upon the completion of the project, the proposed system holds the potential for real-world implementation in actual maritime conditions. Additionally, the deployment of this system on manned vessels aims to alleviate the cognitive burden on bridge personnel, streamlining collision prevention measures. The forthcoming section delves into the methodology and approach applied for developing the collision avoidance algorithms. This narrative continues in Section 3, explaining the framework of the envisaged rule-based collision avoidance system. In Section 4, the kinematic and dynamic characteristics of the vessels are presented. The algorithms are exemplified through case studies in Section 5. Section 6 encapsulates the outcomes and fosters a discourse on the results, contextualizing their significance. Section 6 encapsulates the principal takeaways drawn from the study.

2. Preliminaries

In this section, an explanation is provided regarding the devices utilized in the application, as well as the rules and data that are taken into consideration.

2.1. Devices Used for Target Detection and Environment Sensing

The MASSs must be equipped with devices that can simply detect the target's location and acquire images and/or data of the vehicle's surrounding environment. Numerous device options are employed for target detection and environmental sensing on board ships. Alongside external detection sensors like radar [6], lidar [30], and cameras [43], transponder-based sensors like AIS [44], location-providing sensors such as GPS [45], and sensors supplying depth and underwater environmental images like sonar [46] are widely utilized. However, the harsh conditions at high sea pose significant challenges in using some of these devices. Especially cameras and lidars are not well-suited for the demanding sea conditions of MASSs [47].

AIS equipment is more cost-effective than radar and is widely employed as a sensor onboard ship, boasting a detection range greater than conventional shipboard radar. Particularly when combined with the Electronic Chart Display and Information System (ECDIS), AIS has the potential to supplant radar as the primary collision avoidance device for vessels equipped with AIS technology. This attribute positions AIS as an effective collision avoidance solution for ships [48]. AIS messages can be received from numerous ships, encompassing target vessels that might evade radar detection due to range limitations, obstruction, or other factors. Especially in areas with restricted visibility, like fjord-type regions, where radar and visual observers encounter obscured sections, AIS broadcasts generally demonstrate improved reception performance [49]. The direct usability of data from an AIS device, without the need for interpretation, enhances its appeal. However, AIS has limitations, such as data gaps and instances of not receiving data. To handle these limitations of AIS, the system we propose calculates the positions of target vessels using Dead Reckoning positions in place of missing or corrupted data from the moment it detects abnormal values in the data until the data returns to normal. Given these advantages, the AIS device was selected as the target detection sensor for this study. ECDIS, which synergizes well with the AIS device and offers reliable environmental information, played a crucial role.

2.2. COLREG Rules

Statheros et al. [50] demonstrated that 56% of marine accidents were attributed to violations of the COLREGs. Likewise, in the investigation conducted by [4], violation of the COLREG Rules emerged as the foremost contributing factor to ship-to-ship collisions. The outcomes derived from the implemented algorithm in this research underscore the imperative and critical significance of complying with the COLREGs to ensure the safety of ship navigation.

Studies purporting to account for the COLREG Rules commonly declare their adherence to COLREGs by focusing solely on three distinct encounter scenarios, as exemplified by [44] and [51]. However, COLREGs are not just about the situations specified by a few rules that delineate the encounters, i.e. by Rules 13, 14, and 15. The COLREGs also include regulations directly related to steering and sailing [52]. For instance, depending on the traffic-specific responsibilities of the ships, Rule 18 alone might be the predominant rule to apply, rendering other rules inapplicable. In this study, Rule 18 is recognized to exert a significant influence on collision avoidance. Nevertheless, the majority of the COLREG Rules related to navigation and maneuvering are incorporated into the algorithm development study, and they are itemized in Table 2.

2.3. Data Set

Recorded AIS data was utilized for both modeling and testing the algorithms. The data underwent sequential analysis with a focus on time and adherence to the COLREGs was established as the primary criteria. As a result, the same algorithm can be effectively applied in real-world scenarios, utilizing AIS-derived data.

For each collision accident, a simulation was created using the collision accident reports sourced from the Japan Transport Safety Board's (JTSB) database. The data extracted from the JTSB database included details such as the date, time, latitude, longitude, Speed Over Ground (SOG), Course Over Ground (COG), ship name, ship length, and the ship's navigational status. These data were employed in the simulation study. Additionally, parameters like Distance of Closest Point of Approach (DCPA), Time of Closest Point of Approach (TCPA), and Variation of Compass Degree (VCD) were computed using the formulas described in subsequent sections. The location data of the nearby ships was integrated and visually depicted on the map using the Webmap function of MATLAB/Simulink®, thereby facilitating the simulation

Table 2. *COLREG rules considered in the study*

Rule	Definition	Implementation status	Implementation method
5	Look-out	√	AIS data
6	Safe speed	X	-
7	Risk of collision	√	CRI and ship domain
8	Action to avoid collision	√	Developed algorithm
9	Narrow channels	X	-
10	Traffic separation schemes	X	-
13	Overtaking	√	Developed algorithm
14	Head-on situation	√	Developed algorithm
15	Crossing situation	√	Developed algorithm
16	Action by give-way vessel	√	Proposed rule-base
17	Action by stand-on vessel	√	Proposed rule-base
18	Responsibilities between vessels	√	Navigation status from AIS

COLREG: International Regulations for Preventing Collisions at Sea, AIS: Automatic Identification System, CRI: Collision Risk Index of the collision accidents. The accidents and the specific COLREG Rules violated in this study are displayed in Table 3.

3. Rule-Based Collision Avoidance

This section comprehensively elucidates various aspects, including the quantification of the COLREG Rules, the determination of ships' relative positions, the assignment of right-of-way between ships, and the calculation of the CRI.

3.1. Quantification of COLREG Rules

The algorithm developed in this study incorporated the following COLREGs, each accompanied by a concise outline of its collision avoidance requirements. The implementation of the COLREG Rules was carried out in specific stages within the framework of the study. These stages are illustrated in Figure 1.

Table 3. *Simulated collision accidents and COLREG rules violated in accidents*

Scenario no	Violated COLREG rule	Collision accident	Year
1	Rule 13	APL Pusan-Shoutokumaru	2019
2	Rule 14	Jia Hui-Eifuku Maru	2013
3	Rule 15	ACX Crystal-USS Fritzgerald	2017
4	Rule 15	Sulphur Garland-Wakomaru	2015
5	Rule 18	Aquamarin-Hirashin Maru	2011
COLREG: International Regulations for Preventing Collisions at Sea			

3.1.1. Receiving initial data of own ship and target ship

In this stage, the algorithm gathers the following input parameters from the target ships that are within the range of the AIS device:

- Date and time,
- Position as latitude and longitude,
- SOG,
- COG,
- Navigation status of target ships,
- Ship sizes,
- True bearing of the target ship (BRG_{TS}),
- Distance (range) of target ship (RNG_{TS}) and,
- CPA and TCPA.

3.1.2. Determination of the target ship's position relative to COLREGs

Sectors A, B, and D in Figure 2 are explicitly defined in Rules 13 and 15, respectively. However, Sector C is not precisely defined in Rule 14. In this study, an angular area of 12 degrees was adopted and applied for Rule 14.

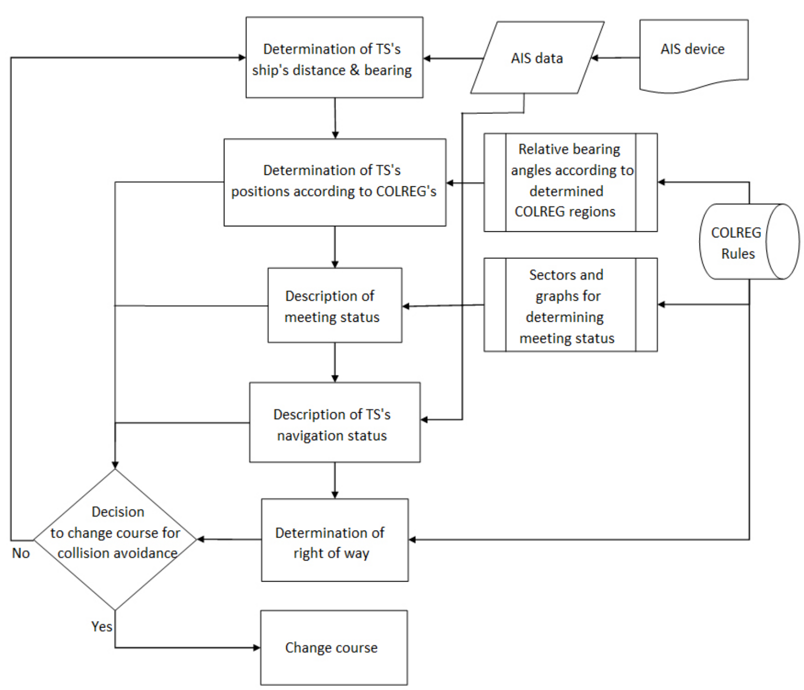

Figure 1. *Flowchart of the algorithm for quantifying COLREG rules*

COLREG: International Regulations for Preventing Collisions at Sea, TS: Target ship, AIS: Automatic Identification System

Sector A is defined in COLREG Rule 13/b as follows: “A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5° abaft her beam, that is, in such a position with reference to the vessel she is overtaking, that at night she would be able to see only the sternlight of that vessel but neither of her sidelights”. Sector C is defined in COLREG Rule 14/b as follows: “When a vessel sees the other ahead or nearly ahead and by night, she could see the masthead lights of the other in line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel”. Considering the definitions of Sector A and C, as well as the statement in COLREG Rule 15 regarding the responsibility of the Give-Way (GW) vessel, we can describe Sector B and D as depicted in Figure 2.

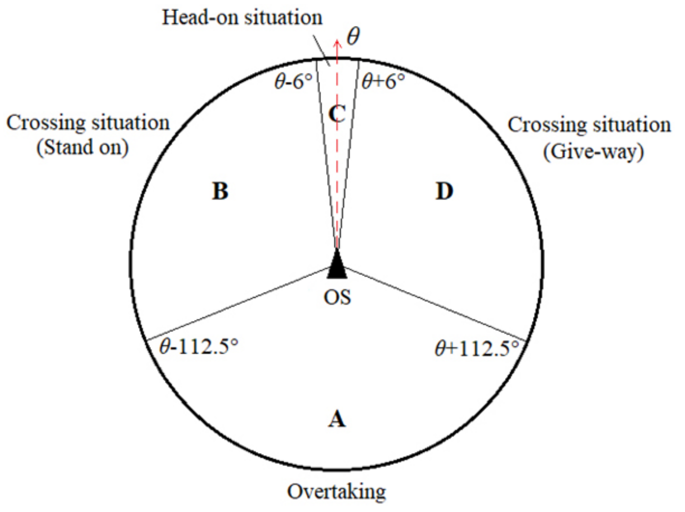

Figure 2. *Ship encounter situations according to COLREGs*

COLREG: International Regulations for Preventing Collisions at Sea

Sector A designates the region in which the TS is moving at a higher speed than the OS, signifying an overtaking situation. Sector A covers the relative bearing span ranging from 112.5° to 247.5°, considering the OS’s heading as 000°. This can be mathematically represented as follows (Equation 1):

$$\mathrm{P\ Sec_A} = \theta + 112.5° \leq \mathrm{BRG}_{TS} \leq \theta - 112.5° \tag{1}$$

In the provided equation, where: P represents the position of the TS, BRGTS denotes the true bearing of the TS, θ indicates the course of the OS relative to the ground. Sector B pertains to the situation where the OS is considered the Stand-On (SO) vessel during a crossing situation. Sector B covers the relative bearing range between 247.5° and 354° and can be expressed using the following relationship (Equation 2):

$$\mathrm{P\ Sec_B} = \theta - 112.5° < \mathrm{BRG}_{TS} < \theta - 6° \tag{2}$$

Sector C denotes the region where the OS and the TS are in a Head-On (HO) situation upon sighting the target ship. Sector C covers the relative bearing range from 354° to 006° [52] and can be represented using the following Equation 3:

$$\mathrm{P\ Sec_C} = \theta - 6° \leq \mathrm{BRG_{TS}} \leq \theta + 6° \tag{3}$$

Sector D covers the relative bearing region of the OS between 006° and 112.5°. If a collision risk arises, a TS within sector D is considered a SO vessel and should be avoided. The position of the TS within sector D can be described using the following Equation 4:

$$\mathrm{P\ Sec_D} = \theta + 6° < \mathrm{BRG_{TS}} < \theta + 112.5° \tag{4}$$

3.1.3. Determining the type of encounter

The subsequent conditional statements ascertain the type of the encounter situation, whether it corresponds to Rules 13, 14, or 15. These regulations are exclusively relevant when there is an imminent risk of collision. A comparable approach was adopted for identifying encounter types, as employed by [54].

Overtaking (Overtaken), Rule 13 (Algorithm Function Rule 13a):

IF $TS_{Posn} \subset$ Sec A,

THEN Execute Function Rule 13a.

In the formula TS_{Posn} signifies the position of the TS, and Sec A denotes the sector labeled as A in Figure 2.

When the TS is positioned within sector A, it indicates that the TS is moving at a higher speed than the OS. In such a situation, the TS is considered the GW vessel. An interesting aspect of this rule is that it remains applicable irrespective of the ship’s type or the navigational area.

Overtaking (Overtaking), Rule 13 (Algorithm Function Rule 13b):

IF $TS_{Posn} \subset$ Sec B, C or D,

THEN Execute Function Rule 13b.

COLREG Rule 13 applies if the TS is in sectors B, C, or D and the OS is faster than the TS. In this case, OS is in the status of a GW vessel. COLREG Rule 13 comes into effect when the TS is located within sectors B, C, or D, while the OS has a higher speed than the TS. In this situation, the OS assumes the role of the GW vessel.

HO situation, Rule 14 (Algorithm Function Rule 14):

IF $TS_{Posn} \subset$ Sec C,

AND $COG_{OS} - COG_{TS} \approx 180°$,

THEN Execute Function Rule 14.

If the TS is situated within sector C, COLREG Rule 14 will be applicable when both ships are on reciprocal or nearly reciprocal courses.

Crossing situation (GW), Rule 15, 16 (Algorithm Function Rule 15a):

IF $TS_{Posn} \subset$ Sec D,

THEN Execute Function Rule 15a.

COLREG Rule 15 is applied when the TS is located within sector D. This rule dictates that the OS must take evasive action, while the TS should maintain its course and speed.

Crossing situation (SO), Rule 15, 17 (Algorithm Function Rule 15b):

IF $TS_{Posn} \subset$ Sec B,

THEN Execute Function Rule 15b.

When the TS is situated in sector B and both vessels are power-driven, COLREG Rule 15 comes into effect, designating the OS as the SO vessel. However, if the TS is not a power-driven vessel underway, Rule 18, which addresses responsibilities between vessels, should be applied.

The preceding paragraphs explain the occurrence of encounter situations. The following section provides graphical illustrations that highlight possible situations and their corresponding occurrence times. The identified areas presented here are modeled after the delineations in the work conducted by [55]. The classification process commences by categorizing targets according to the instantaneous heading of the OS and its relative position within the zones identified in Figure 3.

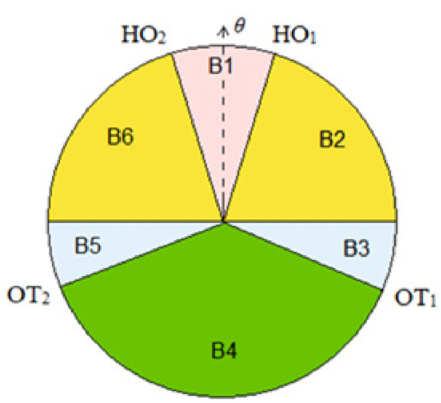

***Figure 3.** Zones used to classify the TS's location where the OS is in the center [55]*

OT: Overtaking, HO: Head-On, TS: Target ship, OS: Own ship

Zones B1 to B6 are the zones we designate created according to the COLREG Rules, where $\{HO_1, HO_2, OT_1, OT_2\} = \{\theta+6°, \theta-6°, \theta+112.5°, \theta-112.5°\}$. The angular expression of the regions according to the heading of the OS: B1 = (θ-6°_ θ+6°), B2 = (θ+6°_ θ+90°), B3 = (θ+90°_ θ+112.5°), B3 = (θ+112.5°_ θ-112.5°), B5 = (θ-112.5°_ θ-90°), B6 = (θ-90°_ θ-6°).

TSs are also classified according to their relative directions determined by the direction of the OS. Figure 4 identifies the categorized regions HGB1 and HGB6, where $\{HO_1, HO_2, OT_1, OT2\} = \{\theta+67.5°, \theta-67.5°, \theta+174°, \theta-174°\}$ (HGB: Target Ship Region).

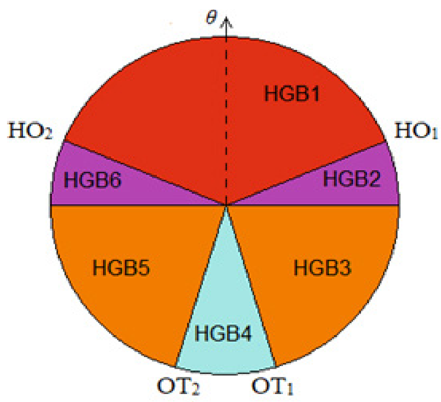

***Figure 4.** Zones used to classify the direction of the TS [55]*

TS: Target ship, OT: Overtaking

Targets detected within the yellow zone in Figure 3 are assigned abbreviated encounter statuses: Overtaking (OT), Crossing SO, Crossing GW, HO, and Safe (SF). In regions

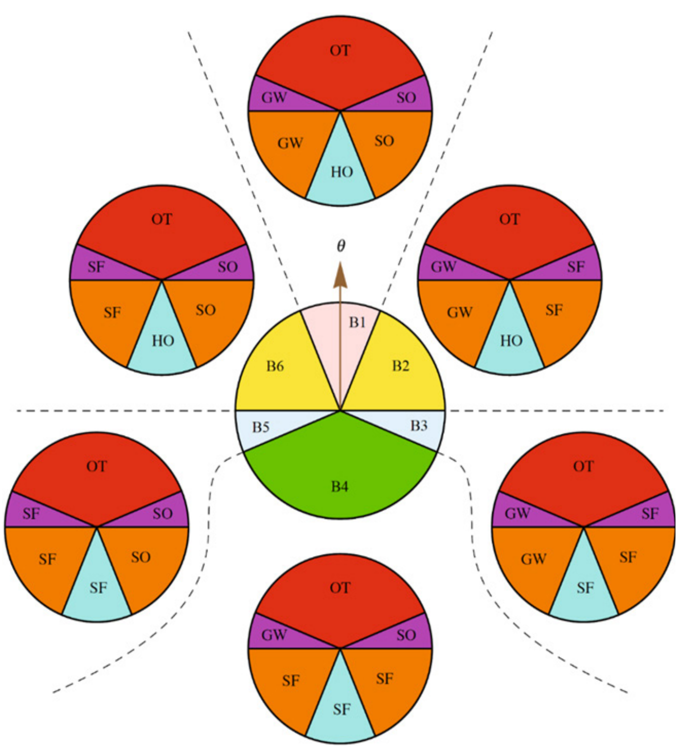

***Figure 5.** Determining the type of encounter [55]*

OT: Overtaking, GW: Give-Way, HO: Head-On, SF: Safe designated as SF, the OS is not required to take immediate action. Each target ship is categorized into an encounter type based on its bearing and relative position to the OS. To illustrate, if the TS is situated in zone B2 (as depicted in Figure 5) and its heading falls within zone HGB1, indicating a course between 292.5° and 67.5°, the resultant encounter type would be Overtaking (OT) as per the graph, considering the OS's course of 000°. The depicted encounter situations on the graph are determined by the OS's location.

3.1.4. Determination of the navigational status of the target ship

At sea, determining the right of way is not solely governed by COLREG Rules 13, 14, and 15, as the ship's navigational status derived from the AIS plays a crucial role. Navigational status is a piece of information accessible to all nearby ships equipped with AIS. According to COLREGs, AIS provides the navigation statuses for ships:

According to COLREG Rule 18, ships are assigned distinct priorities over other vessels based on their navigational status. This rule supersedes Rules 14 and 15, which are only applicable in situations where there is a potential collision involving power-driven vessels. The ship identification process outlined in this study establishes the respective responsibilities between the ships, as described in the subsequent sections.

3.1.5. Determination of the navigational status of the target ship

In accordance with the COLREGs, the SO vessel is required to maintain its current course and speed, while the GW vessel is responsible for executing the necessary evasive maneuver. The obligations of the OS differ across various navigational circumstances. The algorithm produces one of two potential outcomes: the right of way assigned to either the TS or the OS.

In the case of Rule 13 ($\theta \approx COG_{TS}$ and $SOG_{OS} > SOG_{TS}$), the right-of-way (SO) vessel is the overtaken vessel. If the OS intends to overtake another vessel, it must do so without impeding the course of that vessel and ensuring a safe clearance during the overtaking maneuver.

In the case of Rule 14 (θ - $COG_{TS} \approx 180°$) there is no right of way between vessels. Both vessels are obliged to pass clear from each other.

In the case of Rule 14 (θ - $COG_{TS} \approx 180°$), there is no established right of way between the vessels. Both vessels are obligated to navigate in a manner that ensures they pass clear of each other.

In the case of Rule 15, if the OS detects the TS on its starboard side, the TS has the right of way, meaning the OS is obligated to give way to the TS. Conversely, if the OS detects the TS on its port side, the right of way belongs to the OS, and the TS is then obligated to give way.

Under Rule 18, when dealing with a power-driven vessel underway, the obligation to give way falls upon that vessel, irrespective of the zone in which the TS is detected. In this case, the right of way is granted to the TS, which is considered a vessel restricted in her ability to maneuver.

3.1.6. Determination of the action to be made by the own ship

In this section, we will discuss the movement of the OS based on the data obtained in the previous stages. The areas identified in this study, as illustrated in Figure 6, conform to [17]. According to International Maritime Organization's (IMO) recommendation [42], the yellow, orange, and red areas correspond to "caution", "warning", and "alarm", respectively. The region outside the yellow area is considered the "safe" zone.

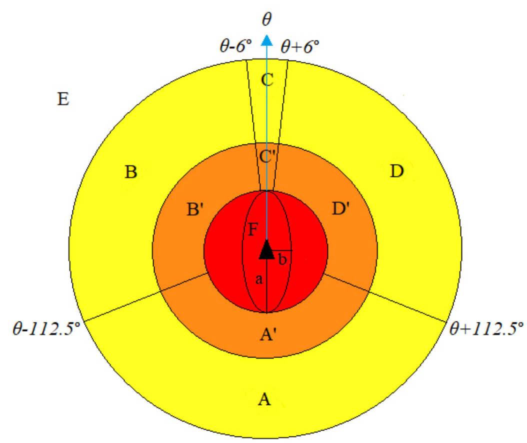

Figure 6. *Zones determined according to the COLREGs and the action to be taken by the OS*

COLREG: International Regulations for Preventing Collisions at Sea, OS: Own ship

Among the regions specified by IMO, the red/alarm area in our study has been designated as a "restricted zone", and the measurement of this area has been determined considering the maneuvering characteristics, including the maximum turning radius of a commercial vessel. It's important to note that merchant ships typically require a turning circle with a maximum diameter of 4.5 times their length when they are navigating at full ahead speed [56].

The orange/warning area has been designated as the "close-quarters situation zone". In navigation practice and theoretical calculations, the term "point of the latest minute action" [17] or "last moment maneuver" [57] typically refers to the distance at which two vessels in a close-quarters situation at sea are positioned, which is usually between two to three nautical miles (NM). This point represents the latest possible moment at which the vessel responsible for avoiding a collision can initiate a maneuver, taking into account the maneuverability of the vessel. If the maneuver is executed later than this critical point, there is a risk that the vessels may not have enough distance to pass each other safely [58].

In the algorithm developed, since the regions in Figure 6 are calculated separately for each of the two vessels, taking a reference of an average merchant vessel length of 185 m, a warning zone of three NM in total has been established. In addition, the values explained and evidenced by [59] in their study were also taken into account in determining the diameter of the orange zone.

The yellow zone, where the monitoring of surrounding vessels will begin, has been set at three NM or 30 ship lengths, considering an average commercial vessel length, especially in regions with heavy traffic. Since this zone will be created for each vessel, a total warning area of 12 NM will be obtained. This measure is taken to ensure that the computer and algorithm's performance is not significantly affected, particularly in busy traffic areas.

The radius of color-coded circular zones relative to the length of the ship, "L":

The radius of the red ellipse ⇒ a = min (4.5L) and b = 1.5L,

The radius of the orange circle ⇒ 30L – min 4.5L,

The radius of the yellow circle ⇒ 30L – 60L.

In maritime collision avoidance, two primary methods are employed: altering course and/or changing speed. This study focuses exclusively on course alterations as the preferred strategy for collision avoidance in open sea, given the impracticality of relying on speed changes.

To assess collision risks, we establish a specific area called the "ship domain", which is determined based on the turning circle's diameter, representing the ship's maneuvering capabilities. The calculation method for determining the ship domain is elaborated in detail in Section Referring to Figure 6, the tracking process begins with targets detected within the yellow zone. When these targets enter the orange zone, the relevant COLREGs come into play to avoid potential collisions. If the OS maintains the SO position and the TS does not yield as they approach the red zone, the OS will initiate the necessary maneuver to prevent a collision, even if it means deviating from strict COLREGs compliance. The goal is to prevent the TS from entering the red zone. The OS executes turns with a rudder angle of 30° to ensure a clear course while adhering to COLREGs Rule 8/b.

Table 4 identified the OS's behavior when detecting TSs within the zones illustrates in Figure 6. According to the rule-based collision avoidance method, the appropriate action is

Table 4. *The action is to be taken by OS according to the area where the TS was detected*

Zone of the TS	Navigation status of TS	Speed of TS as per OS	Course of TS as per OS	Position of TS as per OS	COLREG rule(s) to comply with	Action to be taken by OS
A	Underway	Faster	Parallel	-	Rule 13	Keep speed & course
A'	Underway	Faster	Parallel	Port	Rule 13 + Rule17-a-ii/b	Change course to starboard
A'	Underway	Faster	Parallel	Starboard	Rule 13 + Rule17-a-ii/b	Change course to port
B	Underway	-	Crossing	Port	Rule 15 + Rule17-a-i	Keep speed & course
B	Restricted maneuver	-	Crossing	Port	Rule 16 + Rule 18	Change course to safe side*
B'	Underway	-	Crossing	Port	Rule 15 + Rule17-a-ii/b	Change course to safe side*
C	Underway	-	Reciprocal	-	Rule 14 + Rule 16	Change course to starboard
C	Restricted maneuver	-	Reciprocal	-	Rule 16 + Rule 18	Change course to safe side*
C'	Underway	-	Reciprocal	-	Rule 14	Change course to safe side*
D	Underway	-	Crossing	Starboard	Rule 15 + Rule 16	Change course to safe side* (do not pass ahead)
D'	Underway	-	Crossing	Starboard	Rule 13 + Rule17-a-ii/b	Change course to safe side* (do not pass ahead)
E	-	-	-	-	-	-
E	-	-	-	-	-	Change course to safe side*

*CRI and ship domain determine the safe side

CRI: Collision Risk Index, TS: Target ship, OS: Own ship, COLREG: International Regulations for Preventing Collisions at Sea determined based on the zone where the target is detected and the corresponding action specified in Table 4. For instance, if a target moves from zone A to zone B' in Figure 6, the OS will continue to adhere to the rules applicable in zone A but will not follow the rules for zone B'.

3.2. Identifying the Risk of Collision

To facilitate ships' ability to recognize the risk and make appropriate collision avoidance decisions when encountering different collision scenarios, it is essential to assess collision risk. The determination of when and how to execute evasive maneuvers is typically guided by collision risk assessment methods. Despite the presence of these promising methods, classical parameters like DCPA and TCPA continue to serve as industry standards for collision avoidance and decision support systems. The ship domain, which is widely used, is mainly employed in warning-based collision avoidance decision-making applications. On the other hand, CPA-based methods may not always ensure collision avoidance with certainty, but they have their own advantages.

In this study, we aimed to address the limitations of these methods by incorporating CPA and TCPA, along with VCD, as proposed by [60]. Additionally, we introduced the concept of CRI, which takes into account various factors influencing collision risk, such as the distance between ships.

3.2.1. Calculation of the CRI

CRI is among the most commonly employed methods for assessing collision risk in land, marine, and air vehicles [48]. CRI quantifies the probability of collision for each ship in the vicinity with respect to the OS. This calculation takes into account various parameters, including the ship's length, maneuvering characteristics, environmental factors like current and wind, ship domain, safe area diameters, ship speed, VCD between ships, DCPA, and TCPA (Equation 5). An advantage of determining the CRI is that it identifies ships that do not pose a collision risk, even when they are in close proximity to the OS. In such cases, no avoidance maneuver is required, which can result in savings in both fuel and time [61]. What sets CRI apart from other collision risk assessment methods is its ability to provide a quantitative and real-time view of the risk associated with each ship, without necessitating immediate action.

Because the COLREGs are designed for ship-to-ship encounters, calculating the collision risk for multiple ships within a specific sea area or zone, as well as grouping ships together, can create challenges in adhering to COLREG Rules [62]. Therefore, in this study, the CRI is computed individually for each target, and collision avoidance maneuvers are executed based on ship-to-ship encounter situations as defined by the COLREGs.

The significance of the CRI obtained in this study, in accordance with COLREG Rules, aligns with Rule 7/d/i, which addresses the risk of collision. Specifically, it refers to "the risk deemed to exist if the compass bearing of an approaching vessel does not appreciably change" and takes into account the change of bearing between ships. While there are fundamental differences, such as the consideration of VCD and the use of different coefficients depending on encounter situations, the CRI calculation technique outlined in the study by [63] was adopted. However, in contrast to this study, elliptical ship domains were defined instead of the quadrilateral ship domain. The CRI proposed in this study assesses real-time collision risk and is dynamically updated based on changes in the parameters involved in its computation.

$$VCD = |Bearing_{i-1} - Bearing_i| \tag{5}$$

The asymmetric Gaussian function was employed to calculate the collision risk using the following Equation 6:

$$\sigma_a = \frac{r_a}{\log(\frac{1}{r_0}) \times (\frac{1}{r})^2} \tag{6}$$

In the Equation, σ_a is the longitudinal collision risk, r_a is the long side of the ellipse ship domain, r is the collision risk coefficient according to the distance between the ships, r_0 is the coefficient of the point where the risk will start to be calculated, and it is accepted as 0.6 in this study. The transverse collision risk is calculated with the asymmetric Gaussian function as follows (Equation 7):

$$\sigma_b = \frac{r_b}{\log(\frac{1}{r_0}) \times (\frac{1}{r})^2} \tag{7}$$

where σ_b is the longitudinal collision risk and r_b is the short side of the elliptical ship domain.

Transverse and longitudinal collision risks obtained from Equations 6 and 7 are substituted in Equation 8 and collision risk is calculated for a single ship:

$$R = exp\left(-\left(\frac{x}{\sigma_a}\right)^2 + \left(\frac{y}{\sigma_b}\right)^2\right) \tag{8}$$

Since DCPA and TCPA are important parameters in the determination of collision, the effects of the risks created by these values in the calculation of the collision risk were also calculated with the following Equations 9 and 10:

$$R_{DCPA} = exp^{-|DCPA|} \tag{9}$$

$$R_{TCPA} = exp^{\frac{-TCPA}{10}} \tag{10}$$

In this study, the following Equation 11 is proposed as an additional condition to obtain the collision risk value more effectively:

$$If\ TCPA < 0\ then\ R_{TCPA} = 0 \quad (11)$$

Instead of using a summation of product approach, the preferred method involved multiplying factors, specifically those related to DCPA, TCPA, and degrees of danger as a function of the type of encounter [64]. The CRI value was calculated by applying the CR, RDCPA, RTCPA, and VCD values as follows (Equation 12):

$$CRI = CR \,.\, R_{DCPA} \,.\, R_{TCPA} \,.\, VCD \quad (12)$$

The CRI is calculated for ships when they enter the yellow zone, as depicted in Figure 6. COLREG Rules come into effect to avoid the TSs detected in the orange zone. If the OS is the SO vessel and the TS fails to give way within the orange zone, attempting to enter the red zone while surpassing a CRI threshold of 0.6, the OS must execute the necessary maneuver to avoid collision and strictly prevent the TS from entering the red zone. In this study, the CRI parameter is set to one at the boundary of the ship domain and assigned a smaller value (with a minimum of 0) as the distance from the OS increases. The CRI value range is predetermined, with its maximum value indicating a collision situation. Consequently, the CRI can be easily correlated with the actual probability of collision, facilitating the quantification of collision risk.

The threshold value of 0.6 established for the CRI was determined through the formulation of scenarios involving target vessels across each region corresponding to the columns in Table 4 and within six distinct regions depicted in Figure 5. To assess the robustness of the proposed methodology, scenarios necessitating adherence to multiple COLREG Rules and encounter situations concurrently, including those involving multiple target vessels, were incorporated. Totally 22 analyses/scenario practice performed according to Imazu Problem [65]. The primary objective is to prioritize collision risk and thereby ascertain the collision avoidance risk for each target vessel. Upon comprehensive evaluation of all devised and tested scenarios, it was found that the safer outcomes, which effectively mitigate the overlap of red/alarm zones, were achieved with a CRI coefficient of 0.6.

3.2.2. Calculation of ship domain

When determining the elliptical ship domain [66], various criteria were taken into consideration in this study. To determine the long diameter of the ellipse, the "advance" distance, which reflects a ship's turning maneuver characteristic, was used as a reference. The maximum value recommended by the IMO for ships, which is 4.5 times the ship's length, was adopted as the long radius of the ellipse. Reference [67] have noted that the distance between ships passing side by side in narrow channels should be at least one ship length to mitigate their adverse hydrodynamic effects. In this study, a short radius of 1.5 times the ship's length was chosen for added safety. The radii of the elliptical ship domain are determined using the following Equations 13 and 14:

$$\begin{cases} (SOG_{OS} + SOG_{TS}) \times 28sec & if\ (SOG_{OS} + SOG_{TS}) \times 28sec \geq 4.5\, L_{OS} \\ 4.5\, L_{OS} & otherwise \end{cases} \quad (13)$$

$$b = 1.5 L_{OS} \quad (14)$$

SOG_{OS} represents the speed of the OS, SOG_{TS} is the speed of the TS, and L_{OS} is the length of the OS. The reason for choosing 28 seconds in Equation 13 is because it is the average maximum time that merchant ships can perform a hard to starboard to port, or vice versa, with a single rudder engine. The flow chart of the proposed rule-based collision avoidance system is shown in Figure 7.

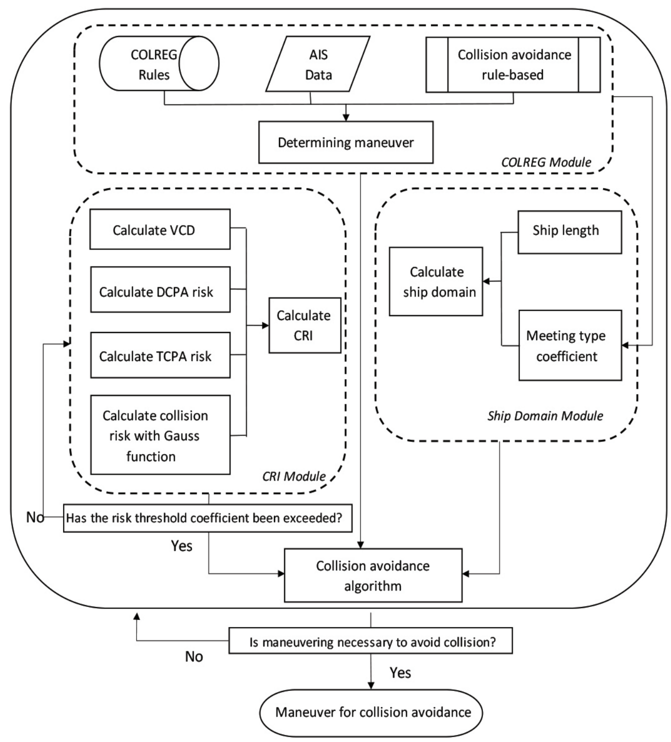

Figure 7. *Rule-based collision avoidance system flowchart*

CRI: Collision Risk Index, COLREG: International Regulations for Preventing Collisions at Sea, AIS: Automatic Identification System, DCPA: Distance of Closest Point of Approach, TCPA: Time of Closest Point of Approach, VCD: Variation of Compass Degree

4. Case Studies

The MATLAB/Simulink® software was employed to code the equations, data, and calculation process in a structured manner, following the flow diagram depicted in Figure

Figure 8. *Legend for the collision avoidance scenarios*

8. A simulation study was conducted to demonstrate the execution of COLREG Rules 13, 14, 15, and 18 for accident scenarios, as detailed in the subsequent subsections. The magenta, green, yellow, and light blue colors in the depicted ship routes within the scenarios signify their trajectories leading up to the moment of collision. In the context of the study, it is presumed that other vessels failed to adhere to their responsibilities outlined in the COLREG Rules. Consequently, the own ship avoids the potential collision accident by proactively implementing avoidance measures in adherence to the COLREG Rules. Figure 9 illustrates representative lines and areas delineating the simulated routes of ships, ship domains, as well as monitoring and avoidance zones.

4.1. HO Situation

In event scenario 2, as outlined in Table 3, the OS is the vessel navigating along a magenta-colored course. When the TS enters the orange circle and reaches a CRI of 0.6 or higher (as shown in Figure 9), the OS promptly alters its course following the established rules. To ensure clarity, the course change is executed with a 30° rudder angle, in accordance with Rule 8(b) of the COLREGs. After successfully completing the collision avoidance maneuver and confirming that there is no longer a risk of collision CRI <0.6 and keep clear of TS TCPA <0, the OS resumes its course along the new route leg, determined through dynamic path planning, toward the designated waypoint that should have been reached prior to the avoidance maneuver.

4.2. Overtaking

The rule-based collision avoidance algorithm faced a challenge when identifying land areas in the Webmap function of MATLAB/Simulink®. Consequently, in the simulation for Scenario 1 from Table 3, the ship following the magenta course was designated as the OS. As depicted in Figure 10, at the outset of the simulation, the vessel following the green trajectory came under observation due to the ships' current positions. This led to the initiation of a collision avoidance maneuver in accordance with COLREG Rule 13 and the process outlined in Figure 8. The black line represents the new course determined as a result of the dynamic path planning process.

4.3. Crossing Situation

Two distinct simulations have been generated for Rule 15 because the crossing situation rule encompasses two separate scenarios: GW and SO.

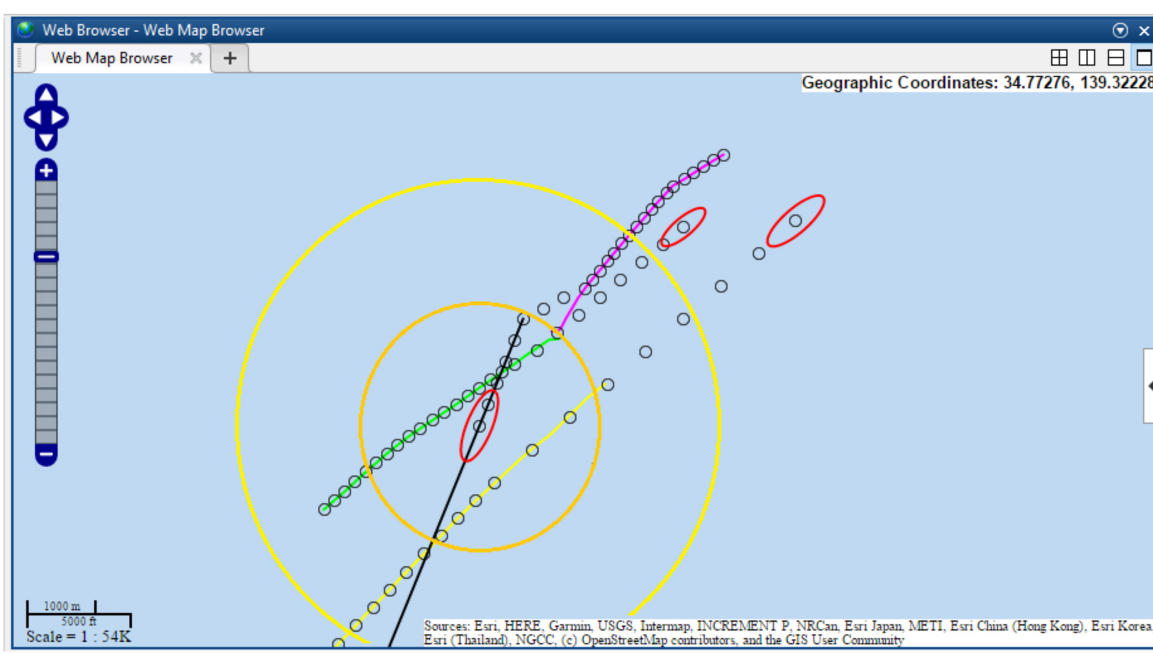

Figure 9. *A collision avoidance maneuver with a rule-based method for Head-On situation (Rule 14)*

4.3.1. Behavior of the GW vessel

As depicted in Figure 11, the simulation for Scenario 3 in Table 3 involves three distinct ships. The vessel following the magenta-colored route is designated as the OS, while the ships entering the yellow circle are being monitored as TSs.

Figure 11 presents a simulation image depicting the OS taking evasive action when there was a risk of collision with the TS proceeding on the green course and the CRI reached 0.6. To avoid a collision, the OS altered its course to port, ensuring it did not cross in front of the other two vessels. This collision avoidance maneuver involved a rudder angle of 30° in accordance with COLREG Rule 16.

4.3.2. Behavior of the GW vessel

In the simulation generated for Scenario 4 in Table 3, a total of four vessels were involved at the time of the accident. The magenta-colored vessel was designated as the OS. Once the

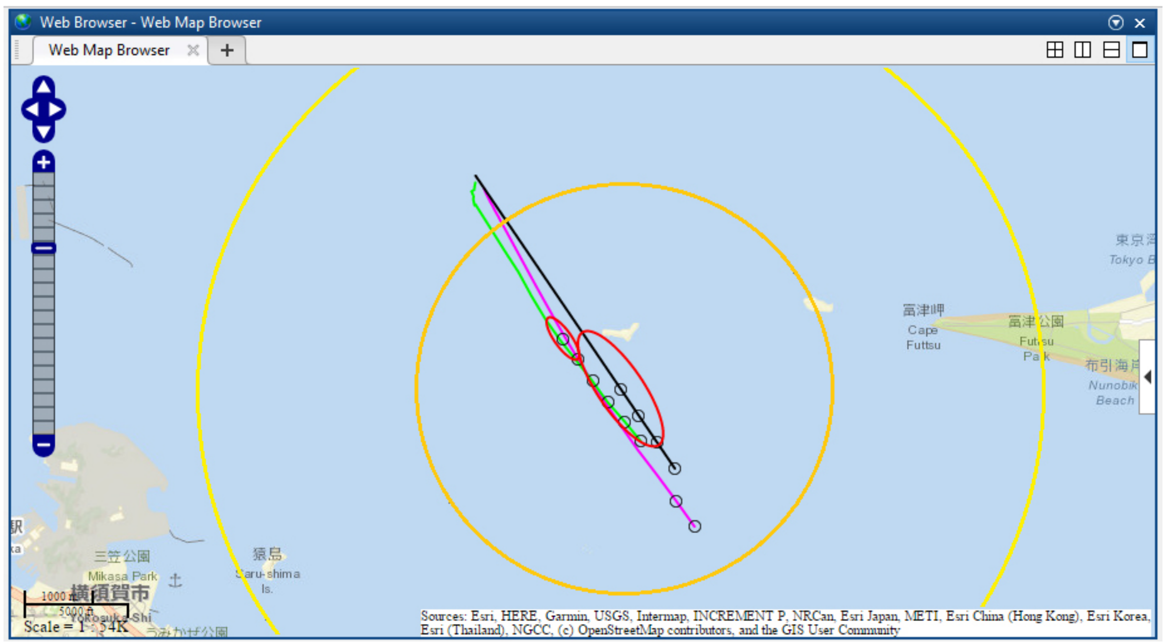

Figure 10. *Collision avoidance maneuver with rule-based method for overtaking (Rule 13)*

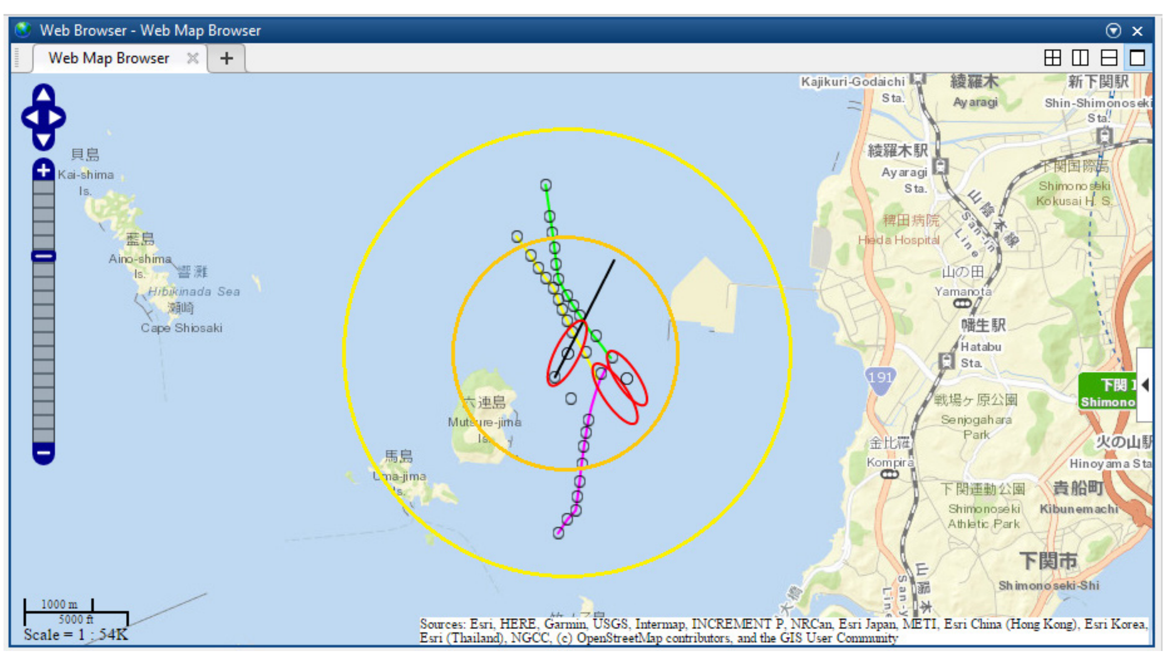

Figure 11. *Rule-based collision avoidance maneuver for a vessel crossing Give-Way (Rule 15)*

surrounding vessels entered the yellow circle, they began to be monitored, and their courses were plotted as shown in Figure 12.

In this scenario, a TS specified in COLREG Rules 15 and 17 did not give way when it was supposed to. As soon as it entered the orange circle, its CRI value exceeded 0.6. Consequently, the OS had to change its course to avoid a collision, even though it was the SO vessel. This situation is visualized in Figure 12. After the TS became clear and its CRI value decreased to 0, the OS resumed its original route. The ships following the yellow and blue trajectories did not pose a collision risk to the OS, with CRI values below 0.6, so the OS did not need to change course for these vessels' positions and courses.

4.4. Responsibilities Between Vessels

In the scenario described in Table 3, a magenta-colored vessel was selected as the OS. According to AIS information, the vessel following the green trajectory was identified as a fishing vessel. The rule-based algorithm determined that Rule 18 applied, requiring the OS to maneuver and give way. Figure 13 illustrates that the OS executed a collision avoidance maneuver by altering her course to the port side to avoid crossing the path of the fishing vessel.

5. Results and Discussions

While COLREG Rules are typically designed for single-ship encounters, this study addresses the behavior of OS in multi-ship encounters through the calculated CRI. The

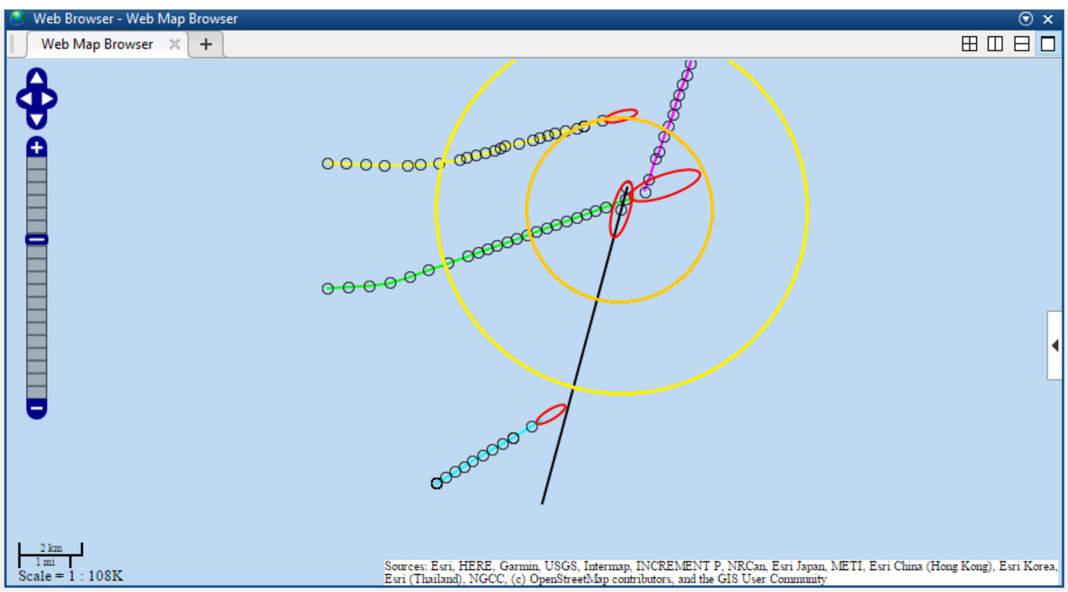

***Figure 12**. The path followed by own ship for the vessel crossing Stand-On (Rule 15)*

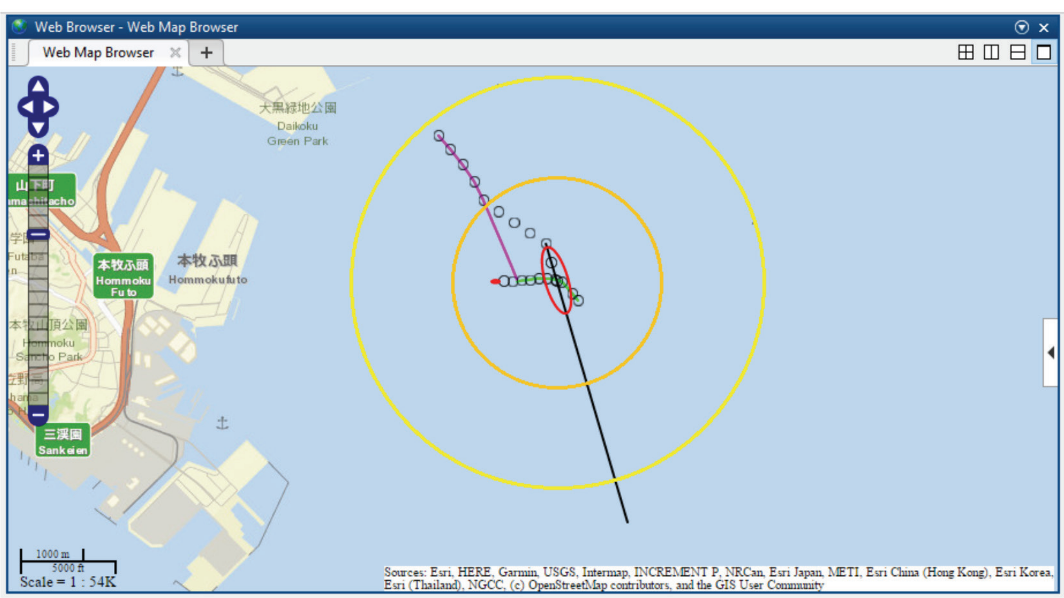

***Figure 13**. Rule-based collision avoidance maneuver for responsibilities between vessels (Rule 18)*

TS is identified as the highest collision risk and is the primary focus of avoidance actions. However, real-world efficiency necessitates monitoring and evaluating CRIs continuously, rather than relying solely on route changes. Despite limited rule-based data, the study successfully provides collision-free paths based on the OS's CRI value and computes the dynamic ship domain for both the OS and TS. The rules determine the turning direction for the OS, which, once executed, proceeds along the avoidance course while continually assessing collision risk criteria. The deviation caused by the avoidance maneuver prompts the creation of a new route to reach the next waypoint. These rules encompass the entire process of determining and monitoring collision risk criteria, acting as objective functions to ensure flexibility and guarantee the optimal collision-free path.

While the primary goal of this study is to prevent collisions in open waters, it is worth noting that most of the accident scenarios presented in the research occurred in restricted waters and congested sea lanes. This observation indicates that the algorithm developed in this study has applicability in both open seas and confined waterways (in areas without traffic separation schemes and narrow waterways). The algorithm focuses its monitoring efforts on vessels within the specified COLREGs region, thereby reducing the unnecessary processing of extensive data sets that could otherwise lead to confusion and sluggish computations.

This study has genuine outcomes with the following important aspects:

a) Unlike similar studies [29,36], Rule 18 under the COLREGs (responsibilities between vessels) has been used in the algorithm set. The following example depicts the importance of Rule 18. A TS that is detected on the port side of the OS and that is at risk of collision must give way to the OS under Rule 15. However, if the navigation status of the vessel is a "fishing vessel", then Rule 18 becomes the rule to follow and the OS is obliged to give way to this TS. That is, the detected ship at the port side being a fishing vessel invalidates Rule 15.

b) To test the effectiveness of the outcomes of this study, real-world accident events were simulated by creating scenarios with data recorded during these accidents. These accidents were selected to test each of the developed algorithms that coincide with each COLREG Rule considered for maneuvering. Scenarios demonstrated that all four accidents would be prevented.

c) Demonstrations also prove that the CRIs are monitored after the primary route change actions.

d) To increase the efficiency, an index different from the existing CRIs [62,63] in the literature was calculated with the help of criteria that are effective in preventing collision to determine only the targets posing collision risk, not every determined target.

e) Different from the ship domains in the literature [66,68], improved dynamic mutual ship domains have been obtained and applied, taking into account the COLREGs.

f) Risk calculations can be made for all of the many ships in the vicinity and it does not require manual plotting.

6. Study Limitations

There are also limitations of the study. The biggest shortcoming of the study is that it can only detect targets with AIS devices. In this conceptual study, the authors acknowledge that AIS alone may not fulfill the "Lookout" requirements. Nevertheless, due to its capability to detect all ships equipped with AIS, the study exclusively employed AIS as the target detection sensor. It cannot interpret when faced with a situation outside the suggested rule base. Such situations often occur in narrow waterways and areas with heavy traffic. However, these regions are not the areas intended for the study. Finally, since the primary purpose of the route changes is to ensure the safe passage of the ships, the route change optimization that will increase the efficiency of the turns is not discussed in the study. An elliptical ship domain was preferred over a quaternion ship domain to improve the algorithm's processing speed, even though the quaternion ship domain provides more accurate results. The last constraint arises from the limitations of the electronic chart function, which does not allow for the detection of land areas and depths, leading to the disregard of this data.

7. Conclusion

Maritime operations being human-centric systems, with human error being the dominant factor in maritime accidents despite precautions, highlights the need for fundamental changes in the maritime industry. The introduction of autonomous ships is a key element of this transformation. While autonomous ships involve many systems, collision avoidance stands out as one of the most critical and challenging tasks. To address this, a set of rule-based collision avoidance algorithms, considering relevant COLREG Rules, has been proposed. The scenarios demonstrated in this study have shown the effectiveness of these algorithms in preventing collisions in real-world accident events. The research suggests that the algorithm can also serve as a decision support system for collision avoidance on manned ships. Implementation of this algorithm helps reduce collision risks.

Every ship equipped with an AIS device becomes a data source for maritime authorities, but processing this data is essential as it can be overwhelming. The proposed system not only acts as a collision prevention system but also provides valuable real-time data to shore authorities. Ships equipped with this system calculate dynamic CRI using collected data, enhancing collision avoidance and safe navigation. This advancement marks a significant step in improving safety and efficiency in maritime transportation.

This study is expected to offer valuable insights and a fresh perspective to researchers, shipyards, classification societies, IMO's navigators and the broader maritime community involved in autonomous ships.

Despite the various limitations, the proposed study has managed to achieve the intended results in terms of collision accidents. This study represents the initial phase of a multi-stage project. As the project progresses, the subsequent phase will incorporate a route optimization feature into the algorithm, utilizing electronic maps that account for bathymetry in relation to static target data. Radar will then complement AIS for both target and environment detection. Furthermore, grounding prevention will be encompassed in the study's scope. In the project's final stage, the accumulation of knowledge will culminate in field tests and research regarding helm commands, conducted with an unmanned surface vehicle. This will bring the project to its ultimate completion, offering comprehensive insights and advancements in the field.

Footnotes

Authorship Contributions

Concept design: H. Uğurlu, Data Collection or Processing: H. Uğurlu, and İ. Çiçek, Analysis or Interpretation: H. Uğurlu, Literature Review: H. Uğurlu, Writing, Reviewing and Editing: H. Uğurlu, and O. Djecevic.

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