

COLREG Compliant Collision Avoidance System for an Unmanned Surface Vehicle

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COLREG Compliant Collision Avoidance System for an Unmanned Surface Vehicle

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Abstract

The increasing development of Unmanned Surface Vehicles (USV) for various applications in open and shallow waters has increased demand for more advanced USV with improved safety and navigation systems. This work introduces a collision avoidance system for USV that complies with the International Regulations for Preventing Collisions at Sea (COLREG) rules, particularly rules 13 to 18 from Part B - Steering and Sailing. The system utilizes a three-block architecture for risk assessment, situation identification, and path replanning. Practical testing and validation were conducted using the Stonefish simulator, demonstrating the system's effectiveness in ensuring compliance with COLREG rules and enabling safe navigation of USV.

Keywords: Collision avoidance, COLREG, USV, Stonefish

Resumo

A crescente evolução dos *Unmanned Surface Vehicles* (USV) para diversas aplicações em águas abertas e rasas tem aumentado a procura por USV mais avançados, com sistemas de segurança e navegação melhorados. Este trabalho consiste no desenvolvimento de um sistema de prevenção de colisões para USV que está em conformidade com as Regras Internacionais para Prevenir Colisões no Mar (COLREG), particularmente as regras 13 a 18 da Parte B - Regras de Manobra e Navegação. O sistema utiliza uma arquitetura de três blocos para avaliação de risco, identificação de situação marítima e replaneamento de rota. Foram efetuados testes práticos e a validação através do simulador Stonefish, evidenciando a eficiência do sistema em manter a conformidade com as regras do COLREG e em assegurar a navegação segura dos USV.

Palavras-Chave: *Collision avoidance*, COLREG, USV, Stonefish

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List of Acronyms

AIS	Automatic Identification System
APF	Artificial Potential Field
COLREG	International Regulations for Preventing Collisions at Sea
CPA	Closest Point of Approach
DRL	Deep Reinforcement Learning
IMO	International Maritime Organization
OS	Own Ship
ROS	Robot Operating System
TS	Target Ship
USV	Unmanned Surface Vehicles
VO	Velocity Obstacle

Chapter 1

Introduction

Scientific institutions, universities, and companies are currently focusing on developing Unmanned Surface Vehicles (USV) to address a broad spectrum of applications and services across various domains. The main advantage of USV is their ability to operate autonomously or teleoperated, with no presence of human operator needed. This autonomy enables the deployment of these vessels in hazardous environments [1], handling tasks that are too risky or, on the other hand, monotonous for humans. They are instrumental in military operations, providing critical capabilities for surveillance and security in territorial waters [2]. Environmental monitoring and marine research also benefit from USV, as they allow for persistent observation and data collection [3]. As highlighted in [4], the demand for USV is increasing, reflecting advancements in their capabilities, particularly in security systems and navigation efficiency. This evolution underscores the growing reliance on sophisticated USV technologies, marking a progressive path for this field.

As the capabilities and applications of USV expand, ensuring their safe operation in complex and dynamic marine environments becomes vital. One of the critical aspects of USV operation is collision avoidance, which is essential not only for the safety of the USV itself but also for protecting other vessels and property. Adherence to established maritime regulations, specifically the International Regulations for Preventing Collisions at Sea (COLREG), is crucial.

The COLREG, established by the International Maritime Organization (IMO), provides a set of rules to be followed by ships and other vessels at sea to prevent collisions between two or more vessels, [5]. However, applying these rules to USV

presents unique challenges, given their unmanned nature and the need for real-time autonomous decision-making.

This document details the development of a collision avoidance module for USV, designed to facilitate safe navigation in compliance with the COLREG. This innovative module was integrated into an existing robotic control system, enabling the evaluation of the USV capability to autonomously navigate and avoid obstacles while adhering to the critical safety standards essential for autonomous maritime operations.

1.1 Context

In recent years, the importance of studying and protecting water environments has grown in the fields of environmental science and engineering. There is a growing demand for new solutions to help map and keep these areas clean and safe. Automated technologies and advanced sensors are leading these efforts, providing new opportunities for caring for water environments and expanding the research. Within this context, the MARIMAR project emerged as an initiative to monitor and maintain aquatic ecosystems.

The MARIMAR is a project with the main objectives of creating and developing a system for mapping the seabed and supporting cleaning operations in restricted aquatic environments, such as ports, waterways, and other freshwater areas. The system requirements include using an unmanned electric vessel, which can be tele-operated or operated autonomously, equipped with specialized sensors to map the seabed and detect debris in the water.

As a result, an autonomous vessel that meets these requirements was developed by CRAS-INESCTEC, see Fig 1.1. However, the operation context poses an extra challenge in the navigation component of this USV, which this work aims to solve.

1.2 Problem Definition

Autonomous maritime vessels rely on perception and navigation systems to ensure operational safety, avoid potential hazards, and fulfill predefined mission objectives. An USV perception system must also differentiate between static and dynamic obstacles, as this distinction must dictate the navigational strategy.

When a static obstacle, such as a buoy, is detected, the primary objective for the USV is to execute an avoidance maneuver to prevent collision. However, in the presence of dynamic obstacles, particularly human-operated vessels, the autonomous maneuver executed by an USV must be carefully deliberated. Such maneuver cannot be solely based on the USV convenience or algorithmic efficiency; instead, it must be predictable and comprehensible to human operators. Otherwise, this could result



Figure 1.1: USV from MARIMAR project in operational environment.

in misinterpretation by human operators, thereby escalating the risk of hazardous situations or collisions. Therefore, it is imperative that USV not only detect and classify obstacles accurately but also engage in transparent navigational strategies that align with the expectations set by maritime protocols.

In accordance with the navigational protocols mandated for human-operated vessels, USV must also adhere to the COLREG. These regulations delineate specific navigational and operational standards designed to extinct collision risks and ensure maritime safety. Such a collision module is indispensable for ensuring that the navigational actions of USV are autonomous and strictly compliant with COLREG.

1.3 Objectives

The work presented in this document focuses on developing a collision avoidance module for maritime navigation. The main distinction of this module compared to others lies in considering maritime navigation rules, namely COLREG. Thus, the main objectives outlined for this project are:

- COLREG rules: Analysis of the COLREG maritime navigation rules to determine the guidelines to be considered in the development process.
- Collision detection: Explore the current collision detection methods in the maritime context.
- COLREG rules identification: Analyse methods for rule identification based on the marine scenario in which vessels operate.

- **Trajectory Planning:** Research on maritime trajectory replanning techniques and algorithms that comply with COLREG.
- **Collision avoidance module:** Development of the collision avoidance module integrating detection and trajectory planning methods, respecting COLREG rules.
- **Module integration:** Include module into the existing navigation system of the USV.
- **Testing and validation:** Conducting tests on the simulator with the developed module to optimize and validate it.

1.4 Publications

The developed work of this thesis resulted in a publication at the IEEE OCEANS 2024 Singapore conference under the title *COLREG Compliant Collision Avoidance System for an Unmanned Surface Vehicle*.

1.5 Dissertation Organisation

This section outlines the structure of the dissertation, providing a clear roadmap for the sequence and purpose of each chapter. It begins with an introductory Chapter 1 that sets the context of this work, defines the problem being addressed, and outlines the work objectives.

Following the introduction, Chapter 2 presents a detailed examination of the relevant COLREG rules. This analysis is essential for ensuring the proposed collision avoidance system complies with international standards for preventing maritime collisions.

The subsequent literature review in Chapter 3 assesses existing research on collision avoidance systems. It identifies and analyzes the components of the commonly adopted architectural framework across different approaches.

In Chapter 4, the system architecture is presented, offering a comprehensive description of the proposed system's design.

Next, in Chapter A, the fundamental concepts and methodologies that support the work are detailed, focusing on crucial simulation tools and frameworks used in the development process.

Chapter 5 provides a detailed exploration of the implementation process, illustrating how the system design was executed and evaluated.

In the results chapter, the implementation outcomes and simulations' outcomes are analyzed, assessing the system's performance against the research objectives and COLREG compliance.

The final chapter synthesizes the work, critically analyzing the work outcomes and their implications. It also suggests potential routes for future work, emphasizing the dissertation's contribution to improving maritime safety through developed collision avoidance systems.

Chapter 2

Review of COLREG

All vessels navigating must obey rules that prevent any collision. Regardless of whether they are manned or unmanned, the rules must be followed since different and unpredictable behaviors can cause collisions [6]. This set of rules is called International Regulations for Preventing Collisions at Sea (COLREG), an abbreviation for “Convention on the International Regulations for Preventing Collisions at Sea”. It is a set of international rules and regulations that establish standards for safe navigation and collision prevention between vessels in international waters and the inland waterways of many countries [7].

This regulation is essential to ensure maritime and river navigation safety, promoting standardization of vessel actions and reducing the risk of collisions and incidents at sea. It is crucial for organizing global maritime traffic and preventing accidents in aquatic environments. The regulation is divided into several parts [5]:

- Part A: General (Rules 1-3);
- Part B: Steering and Sailing (Rules 4-19);
- Part C: Lights and Shapes (Rules 20-31);
- Part D: Sound and Light Signals (Rules 32-37);
- Part E: Exemptions (Rule 38).

However, concerning the development of navigation algorithms, the most common rules to be implemented are Rules 13 to 17 [6, 8, 9], represented in Fig. 2.1. These

rules, referring to the steering and sailing part, specify the behaviors to take when two vessels approach each other, depending on each vessel's relative position.

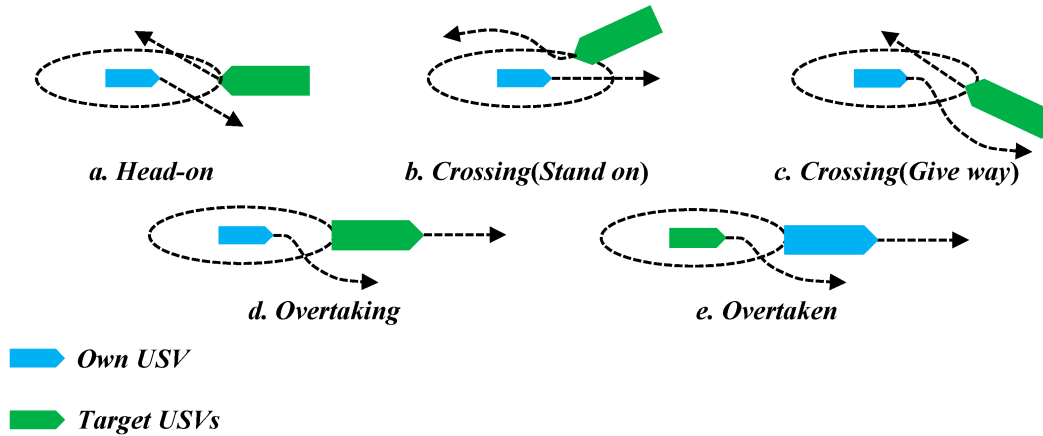


Figure 2.1: Rules 13 to 15 of COLREG [10].

In Fig. 2.1 (d, e), the “Overtaking” situation is represented. According to this rule, any vessel overtaking another must keep out of the way of the vessel being overtaken.

In Fig. 2.1 (a), the “Head-on” rule is depicted. When two mechanically propelled vessels approach each other head-on or nearly head-on in a way that creates a risk of collision, both shall alter their course to starboard so that they pass on the port side of each other.

In Fig. 2.1 (b, c), “Crossing situations” are shown. When two mechanically propelled vessels are crossing, and there is a risk of collision, the vessel that has the other on her starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

Rules 16 and 17, unlike the previous three, do not define a specific maneuver to take but rather the behavior to follow depending on priority or its absence, according to the previous rules, Fig. 2.1 (b, c). Rule 16 “Action by give-way vessel”: Every vessel directed to keep out of the way of another vessel shall, as far as possible, take early and substantial action to keep well clear. Rule 17 “Action by stand-on vessel”: Where one of two vessels is to keep out of the way, the other shall keep her course and speed. However, the latter vessel may take action to avoid collision by maneuvering alone as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules.

Besides these five rules, two additional ones are relevant to the work outlined in this document: rules eight and eighteen.

Rule 8, “Actions to Avoid Collision”, clearly states that if there is a collision risk, actions to take must follow the regulations and in enough time to prevent it. Any change in course or speed must be significant enough to be noticeable to another

vessel visually or via radar. Minor changes in course or speed should be avoided, and a simple course change should be desired whenever possible.

As a result, actions of and USV under Rule 8 should be proactive and, when possible, limited to course changes. Despite the capabilities of autonomous navigation systems to make minor adjustments, USV should opt for substantial changes that are clearly observable by human operators on other vessels.

Rule 18, “Responsibilities Between Vessels,” stipulates that assuming the USV is classified as a power-driven vessel and not under command or restricted in its ability to maneuver, it must give way to vessels not under command, vessels restricted in their ability to maneuver, vessels engaged in fishing, and sailing vessels. Therefore, the USV should act as the give-way vessel in encounters with any of these vessels.

Overall, the rules defined in COLREG establish detailed guidelines for avoiding collisions at sea, but their interpretation can be challenging for autonomous systems. Written for human operators [11, 12], these rules require careful adaptation to be effectively implemented in USV, as they are open to interpretation and challenging to quantify [13]. It is essential to take extreme caution when adopting regulations. It is a challenging task because breaking the COLREG rules could put the USV and other vessels in danger.

Chapter 3

Literature Review

Navigating the marine environment presents a unique set of challenges for USV due to the unpredictable nature of the sea and the complexity of ensuring safe navigation while executing missions. Collision avoidance systems are vital in these settings, where USV must not only encounter fixed obstacles such as coastlines and rocks but also dynamically navigate around other vessels sharing the same maritime space. These systems play an essential role in maintaining safety and operational integrity by adhering to stringent regulatory standards. They identify potential hazards and execute strategic maneuvers to avert collisions, ensuring that USV can effectively respond to static obstacles and other vessels' potentially unpredictable behaviors. Adopting advanced collision avoidance technologies is crucial for improving navigational safety and ensuring compliance with the COLREG, which are fundamental to maintaining order and preventing accidents on water.

This chapter explores collision avoidance strategies designed to prevent collisions with other vessels. It begins with an overview of the sensors and perception systems that enable the detection of obstacle vessels, describing the information that can be obtained about these obstacles. A general architecture of the collision avoidance module is also presented, outlining the fundamental steps involved in implementing such systems. The discussion then shifts to collision avoidance, presenting various methods and algorithms that comply with the COLREG. These regulations apply to all vessels operating in international waters, whether autonomously or human-operated.

3.1 Obstacle Perception

A vessel at sea is subject to various forces, including environmental factors such as waves, wind, and currents, as well as additional forces exerted by the vessel's actuators to propel it in the desired direction. The kinematic model of a vessel encompasses six degrees of freedom: three linear motions—surge, sway, and heave—and three angular motions—roll, pitch, and yaw, as illustrated in Fig 3.1. The propulsion

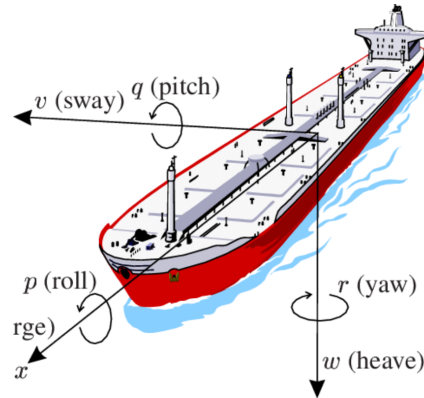


Figure 3.1: Marine vessel degrees of freedom [14].

system typically influences surge and yaw, while sea conditions primarily induce roll, pitch, and heave. Due to the uncontrollability of roll, pitch, and heave, the model is often simplified to three degrees of freedom—surge, sway, and yaw—corresponding to motion in a 2D plane [15]. This simplification reduces the observational variables required for detecting and perceiving obstacle vessels, focusing on essential information such as position, orientation, and velocity along each axis, which can be aggregated into a single velocity value and course direction. The size of the obstacle vessel is also crucial, as it helps establish boundaries for the collision avoidance system, ensuring the necessary deviation to avoid collisions. USV capable of detecting and tracking other vessels, generally combining Automatic Identification System (AIS) data with range sensors, [16, 17, 18, 19, 20]. Developed to enhance navigation safety and prevent collisions, AIS transmits static and dynamic information via radio [21]. Static information includes vessel characteristics, while dynamic information — reflecting the vessel's movement and status — updates periodically. However, the lower update rate of AIS data may not suffice for real-time autonomous navigation. To address this, AIS data is fused with range sensors like radar or lidar. Depending on the application, lidar is utilized for close-range applications due to its high resolution, [17, 20], whereas radar provides longer-range capabilities despite its lower resolution, [16, 18, 19]. Additional sensors, such as optical and acoustic devices, can also improve obstacle perception [22, 23]. These sensors are fused to provide a comprehensive sensory input, ensuring sufficient information is gathered to avoid obstacles safely.

3.2 General Architecture

Collision avoidance modules may vary in design, but they all must start with the essential procedure of detecting the possibility of a collision. This initial step is crucial, as the risk assessment based on the input data from the perception systems of both the obstacle vessels and the USV determines whether a collision avoidance maneuver is necessary. Without a perceived risk, no further action would be required. As outlined in [24], collision avoidance modules that adhere to the COLREG community share a typical architectural structure. The first step, as mentioned, involves risk assessment. Following the detection of a potential risk, the USV under COLREG which all vessels must obey, determine whether a collision prevention maneuver is necessary and, if so, determine the appropriate direction for the maneuver following COLREG. The final component of the architecture is path replanning. Once the appropriate COLREG rule has been identified, this block is responsible for tracing a new trajectory, if necessary, to avoid the collision. The following sections will delve deeper into each block, presenting the algorithms and methods employed to ensure effective collision avoidance.

3.3 Risk Assessment

Risk assessment is an initial stage that involves evaluating the potential risks in the USV's environment, which could lead to collisions or navigational challenges. Some of the commonly used approaches will be presented in this subsection. For clarity, in the field of marine collision avoidance, the notation of Target Ship (TS) is used for an obstacle vessel, and Own Ship (OS) is used for the USV.

One of the methods employed to detect the risk of collision is the ship domain approach, initially introduced by Fujii in 1971 [25]. This methodology involves establishing a buffer zone around the vessel, which serves as a protective area enabling safe maneuvering to prevent collisions [26]. Across various studies, the size and shape of this area change, reflecting the diversity of approaches and emphasizing the method's adaptability to different vessel types and navigational contexts [27]. Fig. 3.2 showcases a variant of the ship domain method, where the safety buffer around the OS is dynamic, adjusting to each specific rule of COLREG scenario.

Another popular method employed to detect potential collisions is the Closest Point of Approach (CPA) [28, 29, 30]. This approach identifies the point on the trajectories of two vessels where the distance between them is minimal. It estimates the risk of collision by calculating two key parameters [31]:

- d_{cpa} : the distance between the vessels at the closest points of their trajectories;
- t_{cpa} : the time until reaching that point.

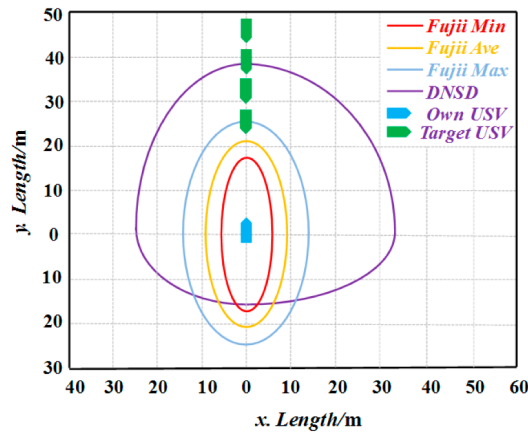


Figure 3.2: Ship domain variant method proposed by Zhou et al. for head-on situation [10].

This method assumes that both vessels will maintain their current course and speed. The risk of collision is evaluated based on safe minimum values assigned to d_{cpa} and t_{cpa} . A potential collision is assumed if these thresholds are exceeded [32]. Thereby, collision prevention actions are needed to guarantee the safe passage of the vessels.

3.4 COLREG Rule Identification

As soon as the risk of collision is identified, it is imperative to ascertain which COLREG rules are applicable. Compliance with these rules transcends mere legal obligation. It is crucial for mitigating potential risks and ensuring the safety of all vessels involved. A fundamental element of this process is the application of specific COLREG rules to varied navigational contexts. For instance, the definition of overtaking is explicitly stated in the COLREG: “A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5° abaft her beam...”. This rule utilizes relative bearing to determine adherence during an overtaking maneuver. Consequently, the relative bearing is commonly employed to identify other COLREG situations [28]. Figure 3.3 presents an example of a rule decision graph based on the relative bearing between the OS and the TS.

However, some COLREG rules do not have such precise quantification, leading to diverse interpretations among various studies. This is particularly evident with the head-on situation, where the author of Fig. 3.3 considers a head-on approach within 10° of vessel heading, whereas in [34], it is considered at 45°. This discrepancy highlights the complexities of applying COLREG rules in practical scenarios. Additionally, reliance solely on relative bearing might not be adequate, as vessels with identical relative bearings can be in entirely different circumstances [11]. To address these challenges and also the uncertainties associated with vessel positioning, the application of fuzzy logic [35] [36] [37] or neural networks [38] can be beneficial. In

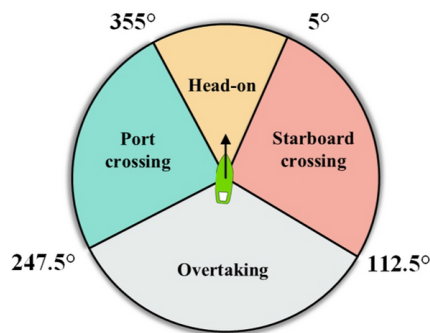


Figure 3.3: Example of rule decision graph base on relative bearing [33].

summary, for a thorough and precise implementation of COLREG rules, a vessel’s bearing, course, and other contextual factors must be considered [39].

3.5 Path Replanning

The collision avoidance field features various approaches adapted to different navigational challenges and operational contexts. Many of these approaches are grounded in well-known methods, which in [24] were classified as behavior-based, hybrid, reactive, optimization-based, and Deep Reinforcement Learning (DRL). Examples of each type will be presented below.

It is important to note that the path replanning presented here differs from path planning. Path replanning requires real-time, online adjustments to create an immediate evasive trajectory once a decision to avoid collision is made. It temporarily alters the route locally, intending to return to the pre-planned global path after the collision risk disappears, and in this case, ensuring that the vessel’s trajectory remains safe and complies with COLREG rules.

Initial studies on USV collision avoidance predominantly used rule or behavior-based approaches to incorporate COLREG rules into path adjustment, typically custom-made for straightforward encounters. The approach presented in [29] generates waypoints for the line-of-sight algorithm. Meanwhile, [40] proposes a behavior-based local planner, an example of the output of which can be seen in Fig. 3.4. In this figure, each position on the circle represents a heading and various velocities (the larger the radius, the bigger the velocity), where the brighter spaces indicate a higher probability of collision with an obstacle.

Hybrid methods are advanced path replanning approaches that improve traditional route planning by adapting them for real-time scenarios and integrating COLREG compliance into the path replanning process. Some notable examples include algorithmic approaches like A*-variants. Specifically, in [30], the R-RA* is introduced, see Fig. 3.5, focusing only on local replanning.

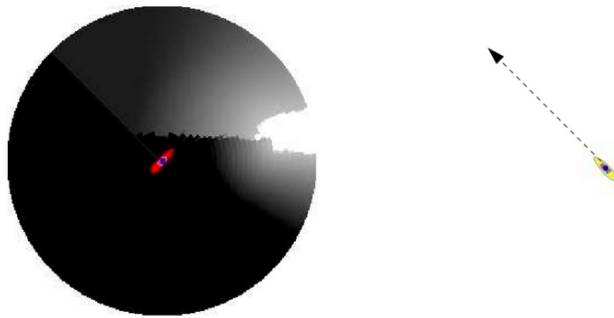


Figure 3.4: Output of the behaviors base objective function proposed by Benjamin et al. [40].

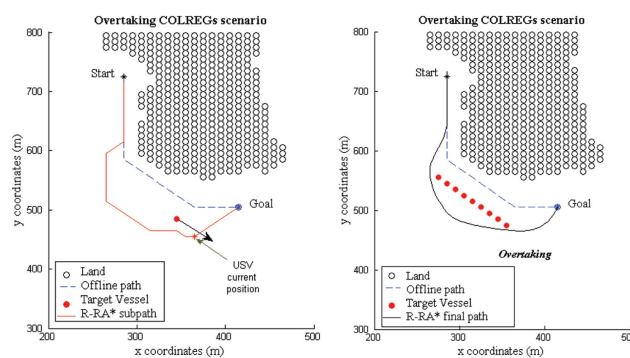


Figure 3.5: Example of A*-variant local replanner [30].

In [41], A* is merged with the dynamic window algorithm; [42] integrates it with θ^* ; and [43] combines A* with the fuzzy algorithm. These variations of A* demonstrate the versatility and efficiency of hybrid methods in addressing the challenges of path replanning. Furthermore, introducing an RRT*-based optimal algorithm for autonomous ships, like in [44], enhances hybrid methods focusing on path feasibility, optimality, collision avoidance, and COLREG compliance. As discussed in [45], RRT variants further underscore these methods' efficiency in dynamic environments, showcasing their comprehensive application in navigational and path-planning advancements.

Reactive approaches, in which Velocity Obstacle (VO) and Artificial Potential Field (APF) are predominant, are the rapid and reactive response path planning algorithms.

Collision avoidance systems for USV based on VO are proposed in [46, 47, 48, 49]. The general method involves generating a cone-shaped obstacle in the velocity space to avoid moving threats and incorporating COLREG compliance by imposing additional constraints within this space. In Fig. 3.6, an example of this method is presented, where the yellow area is added to a cone-shaped obstacle to consider the obstacle vessel's velocity uncertainty.

APF methods, variants of which were used in [50, 51, 52], generates virtual

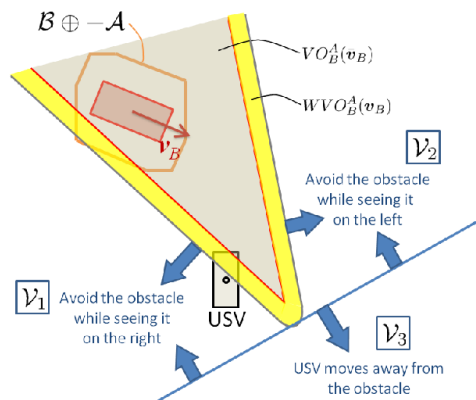


Figure 3.6: VO-base collision avoidance with uncertainties in the velocity of the moving obstacle [47].

forces for path guidance, repulsive around the obstacles and an attractive around the destination, and to make it compliant with COLREG, additional repulsive forces are created around obstacle vessel.

Optimization-based methods aim to find the optimal solution for a function, which varies depending on the specific task. For instance, the goal might be determining the optimal path length, constituting a single-objective optimization problem. Contrarily, if both the path's length and time are considered, it becomes a multi-objective optimization problem. The single-objective optimization problem can be addressed using methodologies described in [53], [54], or [55]. Meanwhile, solutions for the multi-objective optimization problem are presented in [56], [32], and [57].

Finally, there is DRL, a relatively modern approach that has seen significant advancements in recent years, as evidenced by numerous achievements [58, 59]. This progress has led to the application of DRL in USV navigation, where DRL-based methods learn an end-to-end policy that directly maps perception to action for USV navigation [60]. The DRL approach in USV navigation is highlighted by its capability to ensure COLREG compliance and perform collision avoidance. This dual functionality emphasizes DRL's role in addressing navigational challenges within autonomous maritime systems. Supported by studies [61, 62, 63, 64], DRL's application is shown to advance USV navigation by integrating regulation conformity and safety improvements.

Overall, the choice of method depends on the maritime context, USV constraints, and environmental complexity, highlighting the advanced adaptability required in autonomous maritime systems.

Chapter 4

System Architecture

The structure of an efficient collision avoidance system for USV, compliant with COLREG rules, requires a robust and clearly defined architecture. The architecture proposed in this work arises from the literature review presented in Chapter 3. Fig. 4.1 illustrates the proposed architecture, consisting of three main blocks: risk assessment, rule identification, and path replanning.

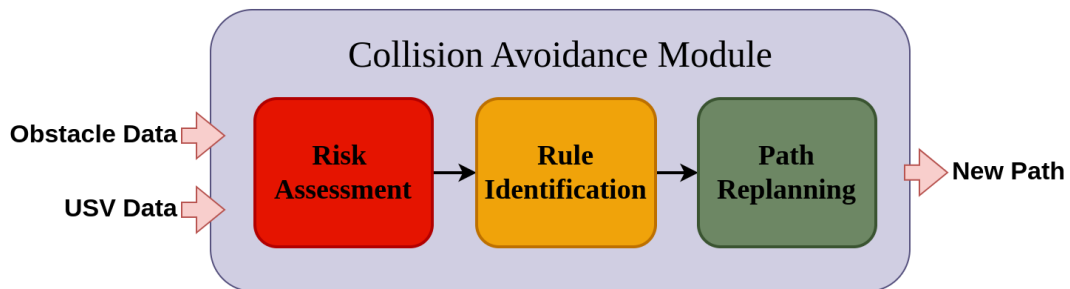


Figure 4.1: Architecture of proposed collision avoidance module

From the figure, it is evident that the module receives two inputs. The first input, labeled as obstacle data, includes the TS position and orientation, vessel priority, its linear velocity, and the vessel's dimensions (beam width and overall length). Similarly, the USV data input to this module contains identical data fields. The output from the module specifies the USV adjusted navigational trajectory, path vector and velocity, guiding its movement to prevent collisions. The inner blocks will be explained in detail in the subsequent sections.

4.1 Risk Assessment

The Risk Assessment block is critical in the collision avoidance system, as it is the first line of defense in identifying potential collisions. This block is based on a combination of two methods. The first one is the CPA method, and a variant of the ship domain method is proposed for the second one.

4.1.1 CPA

Through CPA method, the time (t_{cpa}) to the closest point of approach in the vessel's trajectory and the distance (d_{cpa}) between them at that poses are computed using the Eq. 4.1.1 and 4.2.

$$d_{cpa} = \delta_{LOS} \sin \alpha \quad (4.1)$$

$$t_{cpa} = \frac{\delta_{LOS} \cos \alpha}{v_{ref}} \quad (4.2)$$

In the equations 4.1.1 and 4.2, δ_{LOS} is the distance between OS and TS, V_{ref} is a relative velocity between the two vessels, and α is an angle between vector V_{ref} and the vector formed by the vessels position. In Fig. 4.2, the geometric representation of CPA is presented, as well as variables mentioned in equations.

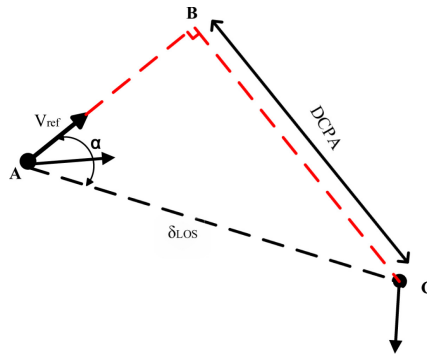


Figure 4.2: Geometric representation of CPA [8].

The resulting values from this calculation are used to evaluate the future physical proximity between the vessels and the time until they reach the closest point between them. The time derived from the CPA calculation allows for the understanding of the relative dynamics between the vessels. This parameter, which may assume positive or negative values, indicates the direction of relative movement: a positive value indicates that the vessels are converging, while a negative value signifies divergence. When T_{cpa} is positive, it is essential to establish a threshold below which the TS present a risk to the OS. Assuming that a collision is imminent and the TS maintains its course, this value explicitly indicates the available time for the OS to react before

a collision occurs. Consequently, the selected time threshold must consider the vessel's maneuverability; the slower the vessel executes a maneuver, the more time is required to achieve a new safe trajectory.

However, risk evaluation should not solely depend on time but also on distance, d_{cpa} . Relying solely on time using this method does not definitively indicate whether a collision will occur. An illustrative example is when the time may fall below the established threshold, but since it represents the time to the closest point of approach between the vessels on their trajectories, the actual distance at this closest point could be substantial, ensuring safe passage for both vessels. Therefore, similar to the time threshold, it is necessary to establish a distance threshold below which action must be taken.

In summary, when applying the CPA method, both computed parameters, t_{cpa} and d_{cpa} , must fall below their respective thresholds. Otherwise, the CPA point could be reached in a short amount of time while the vessels are still significantly distant from one another, or conversely, the distance at the CPA could be minimal, indicating a guaranteed collision, yet the time to reach this point could be extensive, yielding immediate trajectory changes unnecessary.

In Fig. 4.3, a practical representation of each parameter of the CPA method is illustrated.

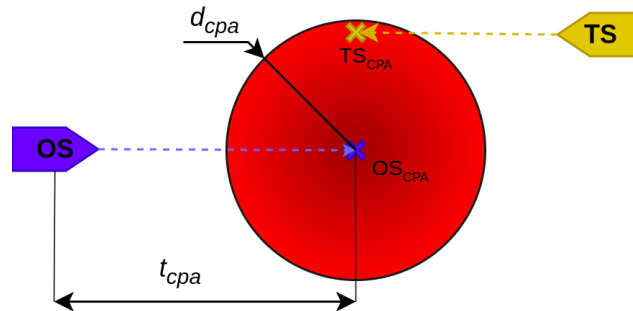


Figure 4.3: Practical representation of CPA parameters.

It can be concluded from the figure that d_{cpa} represents an area within which, if the TS's CPA position falls, it would be considered a risk for the OS. However, given that this area is circular, some regions might not be classified as risky due to their significant distance or posterior position relative to the OS.

A second verification process is proposed based on a ship domain method to address this issue. A detailed explanation of this method is provided in the next section.

4.1.2 Ship Domain Variante

According to the ship domain method, the risk of collision is evaluated based on the areas around the OS and TS. As referenced in Chapter 3, the size and shape

of this area can vary, depending on what is deemed a safe zone for the vessel or obstacle. Continuous monitoring is performed to verify if either of the vessels enters the domain of the other. If this occurs, the risk of collision is acknowledged, and the trajectory is adjusted to ensure the vessels remain outside each other's safe zones.

In the proposed modification of this method, multiple elliptical-shaped zones are introduced. The first, an emergency zone, is centralized at the vessel's current position. The second, the maneuver zone, exceeds the emergency zone in size, and although it is not centered at the vessel's location, its positioning relies on it. The third and last one mirrors the maneuver zone in dimensions and form. However, it is distinctively positioned at the CPA on the vessel's trajectory rather than depending on its current position. Consequently, the circular risk zone, derived from the CPA method and delineated by the distance d_{cpa} , is replaced in this methodology with an elliptical-shaped area. This elliptical zone more accurately reflects the safe navigation area for the vessels, offering a better representation of spatial relationships and navigational safety boundaries.

With the existence of two maneuver zones the nomenclature *local maneuver zone* and *CPA maneuver zone* is used. More comprehensive details concerning all these zones are subsequently provided.

The emergency zone is considered a forbidden zone. If a vessel enters this zone, immediate and emergency actions are imperative to prevent collisions at any cost. The following equations determine the dimensions of this zone's axes:

$$em_x = em_{min} + c_{szem} \times sz_x + c_{vel_{em}} \times v_x \quad (4.3)$$

$$em_y = em_{min} + c_{szem} \times sz_y + c_{vel_{em}} \times v_x \quad (4.4)$$

In these equations, em_x and em_y denote the x-axis and y-axis ellipse dimensions, respectively. The term em_{min} is a fixed base value representing a minimum safe distance, which is combined with the size factor calculated by multiplying the dimension coefficient, c_{szem} , with the received vessel dimensions: sz_x (length overall) and sz_y (beam). An additional velocity-dependent factor is also combined into the zone dimension, which is composed by the coefficient $c_{vel_{em}}$ and the linear velocity aligned with the vessel course, v_x .

The maneuver zone extends beyond the boundaries of the emergency zone. When a vessel crosses into this zone, the risk of collision is acknowledged. However, if the zone is the CPA one, the required actions are not as drastic as those in the local zones. Instead, maneuvers compliant with the COLREG are triggered. The dimensions of

the maneuver zone are calculated using the following equations:

$$mv_x = em_x + mv_{min} + c_{sz_{mv}} \times sz_x + c_{vel_{mv}} \times v_x \quad (4.5)$$

$$mv_y = em_y + mv_{min} + c_{sz_{mv}} \times sz_y \quad (4.6)$$

Here, mv_x and mv_y represent the dimensions of the maneuver zone's x-axis and y-axis, respectively. The initial factors, em_x and em_y , denote the dimensions of the emergency zone, emphasizing that the maneuver zone encompasses the latter. The term mv_{min} is a minimum base value specific to the maneuver zone. The coefficient $c_{sz_{mv}}$ is responsible for the size-dependent factor for the maneuver zone, differing from the emergency zone's size coefficient. A velocity-dependent factor is introduced for the x-axis dimension, which aligns with the vessel's course, where $c_{vel_{mv}}$ denotes the velocity coefficient. This factor varies based on the speed of the obstacle, effectively elongating the zone along the trajectory of the TS. As a result, the faster the TS moves, the more the maneuver zone stretches in its direction of travel.

The emergency zone's center, c_{em} , is coincident with the vessel's pose, ensuring immediate responsiveness to potential collisions. In contrast, the maneuver zone's center, c_{mv} , is not aligned with the vessel's pose. As illustrated in Figure 4.4, the centers of the maneuver zones are offset by size and velocity factors from the zone's dimensions equation relative to the vessel's pose and the CPA pose.

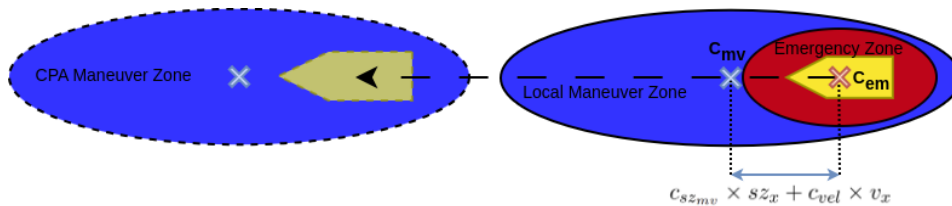


Figure 4.4: Emergency and two maneuver zones.

This offset accounts for the vessel's dynamics and the necessary spatial allowance for executing safe maneuvers, especially avoiding directing the OS straight ahead of TS, where potential danger is more imminent, and instead steering towards the rear of TS, as a safer option.

This block is responsible for verifying whether vessels enter the zones associated with each other, leading to various states shown in Figure 4.5.

From the figure, five stages can be identified. The first one, the emergency state, occurs when either OS enters the emergency zone of the TS or vice versa. This state presents a challenge as a maneuver that prevents a collision in one situation

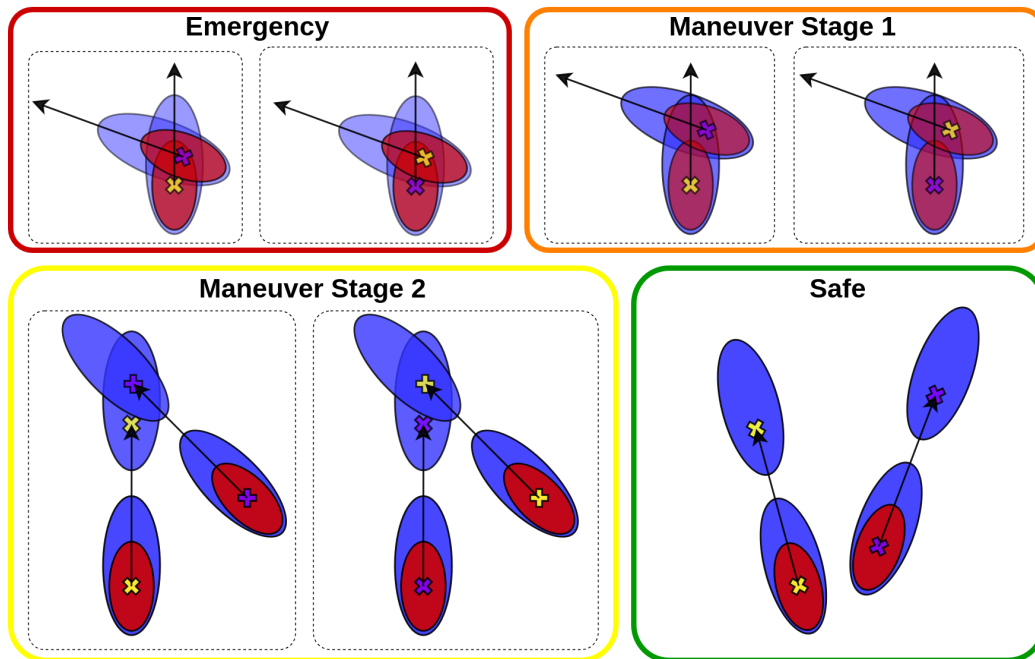


Figure 4.5: Various states of vessels poses and zones intersection.

may cause one in another. Therefore, a careful analysis of the vessels' positions and velocities is essential. Additionally, under Rule 17 of the COLREG, the vessel attempting to avoid an imminent collision must avoid maneuvering to port if the other vessel is on that side. However, if the collision avoidance system is functioning correctly, it should prevent the ship from reaching such a dangerous situation.

The first maneuver stage can be seen as a limit between safety and danger. When vessels adhere to the COLREG, the situation can still be considered safe, often implying that the vessels enter this zone due to limited space. It is crucial, however, to recognize that this stage is merely one step away from transitioning into the emergency stage. In this context, if a TS enters the maneuver zone of the OS, it must be verified that the TS complies with COLREG. If there is any doubt about compliance, initiating a collision avoidance maneuver becomes imperative, as stipulated in Rule 17 of COLREG. This approach is essential to mitigate the risk of a collision before it escalates to the emergency stage.

The second maneuver stage can be seen as the normal operational state. In this stage, the potential for collision is proactively identified through the vessels CPA and their respective maneuver zones. This foreknowledge allows for timely and appropriate actions, ensuring that the situations described in the two preceding stages do not occur.

The final stage is characterized by safety. In this state, the CPA and current positions of the vessels, along with their respective zones, do not intersect, guaranteeing safe passage. This stage signifies that all vessels are effectively navigating to

prevent any risk of collision.

Depending on the outcome of this evaluation, appropriate actions may be initiated. If considered appropriate, the following step in this collision avoidance module involves identifying the suitable COLREG rule described next.

4.2 Rule Identification

After identifying a potential risk, evaluating the current maritime situation is imperative to determine the precise nature of the vessel interaction. This is crucial because the appropriate response to the situation depends on the maritime context in which the vessels are situated.

The rule identification block determines the correct COLREG situation to enable effective collision avoidance. This block evaluates the risk-assessed obstacle data in conjunction with the TS priority proposed based on rule 18 of COLREG. The priority values can vary between 1 and 5, reflecting the priority level of different vessel types ranging from vessels not under command to power-driven vessels, see Table 4.1.

Table 4.1: Attributed priority value based on Rule 18.

Priority Values	Vessel Type
1	Not under command
2	Restricted in her ability to maneuver
3	Engaged in fishing
4	Sailing vessel
5	Power-driven

The USV is considered to be a power-driven vessel, priority value 5, which means that if the TS holds a lower priority value, the USV is programmed to defer and yield the right-of-way. In cases where the TS and the USV are of equal standing in the priority, the system identifies which rules 13, 14, or 15 are applicable following the guidance of [39] and as illustrated in Fig. 4.6.

The figure represents the process of identifying the correct COLREG rule to be applied to the OS, which takes a maximum of three steps. These steps sequentially involve the analysis of relative course and relative bearing from OS perspective, and in the last step the relative bearing from the TS perspective.

In the first step, the relative course is used. This is computed by subtracting the OS course from the TS course, both measured in the global coordinate system. As a result, the course of the TS is expressed in OS local coordinate system. Based on its value, three distinct navigational rules may be identified. However, it is essential to note that the previous block already acknowledged a collision risk and rapid and

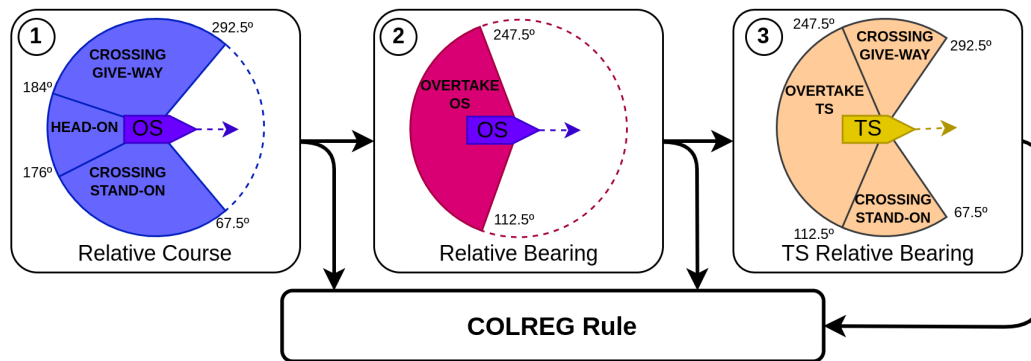


Figure 4.6: COLREG rule identification.

strategic trajectory adjustments need to be performed, which depend on the rule to be applicable between the OS and the TS.

When the relative course is within the 176° to 184° range, including these values, the vessels are in a head-on situation. If the course value falls between 67.5° and 176° , including the lower boundary, the vessels are in a crossing situation where OS is classified as a stand-on vessel. Should the relative course range from 184° to 292.5° , including the upper boundary, it indicates a crossing scenario where OS is considered a give-way vessel. If the relative course does not align with the defined ranges, it is crucial to consider additional variables. This is necessary because multiple rules may be applicable within this particular range of relative courses. Consequently, the process advances to step 2, as illustrated in the figure.

In step two, the focus shifts to the relative bearing between the vessels from OS perspective. This value is measured from OS local coordinate system, so if the TS is straight ahead, the relative bearing is 0. Should this value fall within the 112.5° to 247.5° range, the overtaking rule is applied, where the OS is the stand-on vessel. Otherwise, step 3 is invoked.

In this last step, the perspective shifts to observe the relative bearing from the TS viewpoint. It is necessary as, for example, similarly to the previous example, where the TS is straight ahead of OS, it is not clear which rule must be applied as the TS may have a different course for the same bearing. The overtaking rule is considered if this bearing aligns with the range noted in the previous step, but in this case TS is being overtaken by OS. In both steps, the overtaking range is the same as this is the only rule of COLREG with a clearly defined bearing value. The remaining ranges represent the crossing situations. If the bearing falls between 67.5° and 112.5° , the OS must act as the give-way vessel. If the relative bearing is between 247.5° and 292.5° , OS is assigned as the stand-on vessel.

Once the applicable rule is identified, the system determines whether the USV should alter its course to port or starboard. A starboard maneuver is chosen in scenarios where the head-on or crossing rule is applicable. Conversely, if the overtaking

rule is in effect or the vessel is required to give way due to its priority value, the choice of detour direction depends on the relative course value. A relative course over 180° leads to a starboard maneuver, while a lower value dictates a port-side maneuver.

4.3 Path Replanning

The path replanning block receives input from the preceding block, determining whether a detour to port or starboard is necessary or if the USV should maintain its current trajectory depending of the rule in which vessels are. Due to the need for integration of this collision avoidance module within an already existing and complex USV system, the outputs of this block are not directly applied to the USV control system. Instead, it forwards the outputs to the robot's autopilot, which may then consider implementing the desired actions of the COLREG collision avoidance module, if possible, in accordance with the robot's current mission and operational stage.

It is crucial to note that this block does not perform path planning for the USV. Instead, the primary function of this block within the collision avoidance module is to compute a new course and velocity in compliance with COLREG recommendations when the preceding block of rule identification requires a trajectory change. These new trajectory parameters ensure a safe passage between the USV and another vessel.

This block features two operational modes affecting its output: course-only adjustment and course and velocity adjustment.

The initial mode, course-only adjustment, is the default mode because of COLREG rule 8, which advises for course alteration alone when sufficient sea room exists to prevent close encounters between vessels. This mode is especially beneficial when the robot's primary objective is to reach a distant destination without specific intermediate targets, ensuring that trajectory adjustments for safe navigation do not conflict with any path-dependent mission objectives.

The detour angle output for this mode, as depicted in Fig. 4.7, is calculated based on two factors: the original USV path and the TS CPA maneuver zone defined in Section 4.1.2.

As illustrated in the figure, the angle α , representing the output of the path replanning block, is the angle between the original USV path vector and the vector formed by the USV pose and the tangent point to the TS CPA maneuver zone. It should be noted that there are two potential tangent points. However, the one that is further to port or starboard is selected based on the classification from the preceding block.

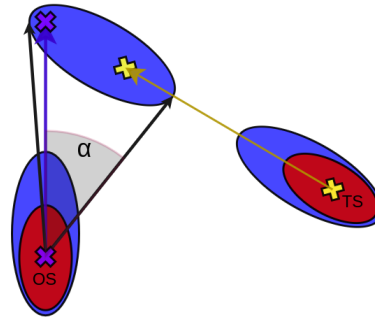


Figure 4.7: Output detour angle of course-only adjustment mode.

As the detour maneuver progresses, the OS path changes, leading to new CPA positions for the vessels involved. Consequently, the centers of the respective zones are updated, and a new detour angle, α , is recalculated.

This process continues until the vessels reach their CPA positions, at which point the path of the OS vessel is established to be from the stern side of the TS and tangent to its local maneuver zone. This configuration ensures that there is no longer any risk of collision.

The second operational mode, course and velocity adjustment, can change both of them to comply with COLREG. This mode is crucial for path-dependent missions like bathymetric surveys, where the USV must adhere to a precise path for accurate data collection.

Adjusting the velocity alone might be sufficient when required to give way to other vessels, particularly in crossing and overtaking scenarios, allowing the target ship clear passage. However, in head-on situations, where a mere velocity change is insufficient for safe passage, a combination of course and velocity adjustments is necessary to minimize deviation from the set path.

Fig. 4.8 illustrates the iterative method employed to determine the outputs of the path replanning block for head-on situations when the second operational mode is preferred.

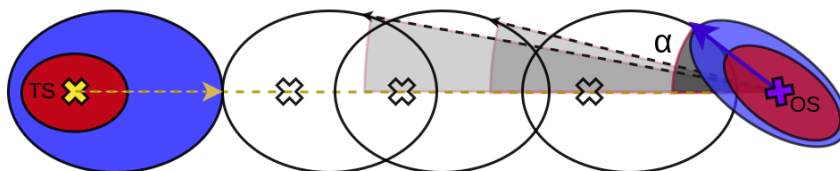


Figure 4.8: Detour outputs for the course and velocity adjustment mode.

In this figure, various TS CPA zones are illustrated without color fill, each representing a different CPA zone that shifts in response to changes in OS velocity. The slower the OS velocity, the closer the TS zone will be to the OS current position.

At the limit, if the paths of both vessels are collinear and the OS velocity reduces to zero, their CPA positions will converge at the OS location, leading to an inevitable collision unless some action is taken.

To prevent such scenarios, a minimum acceptable velocity is determined through an iterative process, ensuring that the OS can safely escape the TS CPA maneuver zone, as depicted in the figure. For each velocity evaluated during this process, a detour path angle tangent to the TS zone is calculated. The velocity is considered acceptable if it yields a path detour angle that remains within the maneuverability limits of the OS.

As the maneuver progresses, the OS will move away from the TS path and its CPA zone, ensuring a collision-free trajectory, allowing for a further reduction in velocity and minimizing deviation from the original path.

For the marine scenarios of crossing and overtaking, as previously mentioned, this mode can be particularly effective where merely reducing velocity is sufficient to prevent a collision.

Fig. 4.9 illustrates the maneuver's velocity determination process.

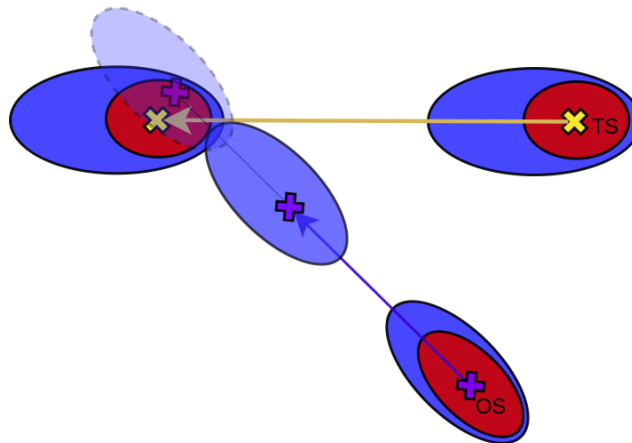


Figure 4.9: Detour maneuver with only velocity adjustment.

This process involves an iterative cycle in which a new velocity is assumed. The CPA positions and their respective zones are computed for each assumed velocity. A velocity is considered acceptable if the resulting OS CPA zone is positioned on the same side as the OS from the TS perspective. In other words, the OS CPA zone at the maximum acceptable velocity should be tangent to the TS path, as depicted in the figure, and the OS path to the CPA pose does not cross TS path.

In cases where the TS already crosses ahead of the OS but has not yet reached the CPA position, which is common in overtaking scenarios when the OS approaches from the stern, the output velocity may be increased since there is no longer a possibility of crossing ahead of the TS.

Chapter 5

Implementation

This chapter describes the steps involved in implementing the collision avoidance module and the corresponding simulation for testing. It provides a description of the robot model used and the construction of the simulation environment. Additionally, the chapter covers the integration of the collision avoidance module within the Robot Operating System (ROS) workflow, providing an in-depth view of both the practical and theoretical aspects of the system's implementation.

5.1 Robot Model

Within the scope of this project, the USV selected for simulation was the robot developed by the CRAS-INESCTEC, specifically designed for the MARIMAR project.

The integration of this robot into the simulator involved several steps. The initial model was provided in SolidWorks assembly format, with all robot components highly detailed. The first step was to eliminate components not essential for simulation, keeping the hull of the vessel, the keel, the domes, the sensor tower, and the thrusters.

Subsequently, certain parts of the model were simplified. This decision aimed to optimize performance in the simulation. In particular, the USV motor underwent significant changes, as its non-submersible part does not impact the vessel's hydrodynamics.

The result of this model simplification process can be observed in Fig. 5.1

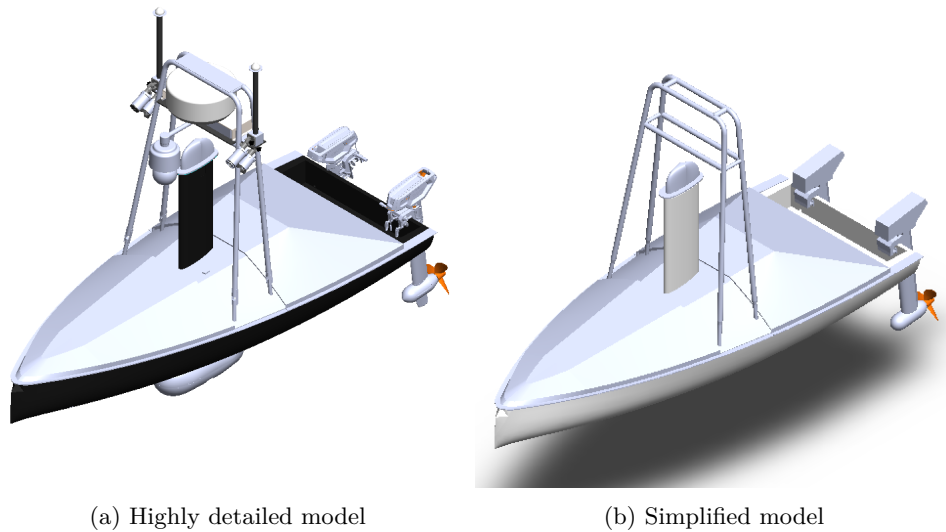


Figure 5.1: Model of the USV used for simulation.

After the modifications, robot components were saved in STL (ASCII) format. Each part was prepared to be imported and used in the simulator.

Using the `sw_urdf_exporter` tool, a SolidWorks add-on, it was possible to define the local origins of each part and create a dependency tree among them, allowing the determination of the geometric transformations between each part. These geometric transformations were used in constructing the XML file, which, combined with the STL models, allows the recreation of the USV in the simulator. The tool `sw_urdf_exporter` can export SolidWorks Parts and Assemblies by creating a package that is similar to Robot Operating System (ROS). This package contains directories for meshes, textures, and the robot's URDF description. By exporting a robot model, it becomes possible to represent it in the ROS visualizer tool RViz.

5.2 Simulation Construction

To construct the simulation scenario in the Stonefish simulator, an XML description file was developed and subsequently loaded to establish the simulation environment using a ROS package, as highlighted in Section B. A main XML file includes the definition of the environment and materials and the robot's definition file.

An ocean scenario was defined as a simulation focused on an autonomous vessel. An environment without waves was selected to focus on the USV ability to navigate and avoid obstacles following COLREG rather than to assess its performance in adverse weather conditions. In this main file, physical and visual material properties only used in the USV were defined as no other objects were used in the simulation.

The robot was described in a separate XML file, which was then included in the main file. This file detailed the robot's structure through links and joints, with all

links referencing a `base_link`, which was chosen to be the vessel’s hull, to which all other parts were connected. All used joints are fixed, and the propeller model, which is the only one that moves, was directly implemented in the actuator definition.

A critical aspect of the simulation involved the material density definition, where it was noted that the simulator does not account for the water displacement of the parts. To solve this, the hull was redesigned in SolidWorks to be a solid body, setting the density for most robot parts at 100 kg/m^3 . To prevent excessive buoyancy and more closely mimic an actual vessel’s dynamics, the density of the keel and additional weights inside the hull’s lower part was set to 3000 kg/m^3 .

In the robot model, two thrusters were implemented, one for each motor, using the actual propeller model. As in the actual robot, both propellers have the same rotation direction. This detail was especially notable in the simulation; when both thrusters operated at the same speed, the vessel exhibited a noticeable deviation to the port side.

In this work, only a virtual odometry sensor was employed to provide information on the vessel’s speed and position.

The simulator creates specific ROS topics for actuators and sensors, enabling the control of thrusters and the acquisition of data from the odometry sensor.

In Fig. 5.2, the result of simulation construction with the USV is presented.

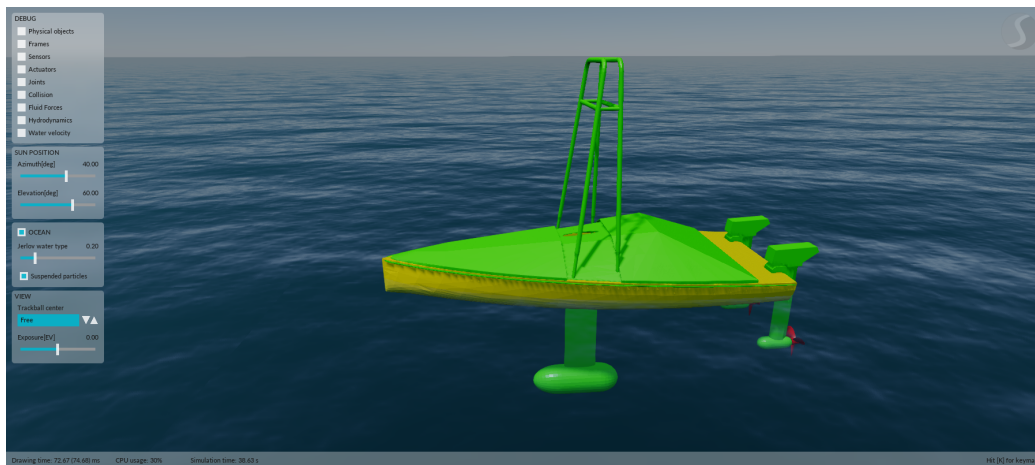


Figure 5.2: Constructed simulation environment with the USV.

Since COLREG specifies actions to avoid potential collision scenarios, an additional vessel was introduced into the simulation alongside the USV. To simplify the process and simulate the presence of multiple robots, the second vessel was created using the model of the first. This approach involves including the same XML robot definition file twice in the simulation setup. However, modifications were made to the robot description file to accommodate two distinct entities in the simulator. These adjustments allow it to accept the vessel’s name and the spawn position and

orientation as inputs, ensuring that each vessel is uniquely identified and correctly positioned within the simulation environment.

5.3 ROS Workflow

As highlighted earlier, the ROS framework is employed to integrate the simulation, the USV control system, and the collision avoidance module. Figure 5.3 illustrates the interconnection between these three components.

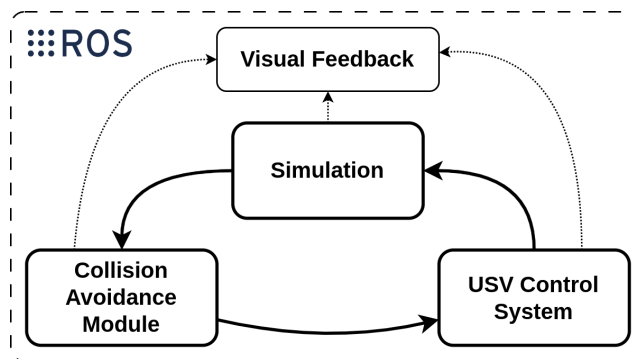


Figure 5.3: Workflow within ROS.

The fourth element, depicted in the figure, represents visual feedback provided by the ROS's tool RViz. This tool serves for visual monitoring of the vessel behavior and overall USV system.

Each block of this figure will be detailed and explained in the following sections.

5.3.1 Simulation

Employing the package from [65], the simulation scene was loaded from an XML file detailing the scenario. This package establishes an interface with the Stonefish libraries. A launch file initiates the simulation node, wherein the path to the scenario description file and additional simulation parameters are specified.

In this work, upon running the scenario that includes two vessels, the resulting diagram, which illustrates the nodes and topics, is presented in Fig. 5.4.

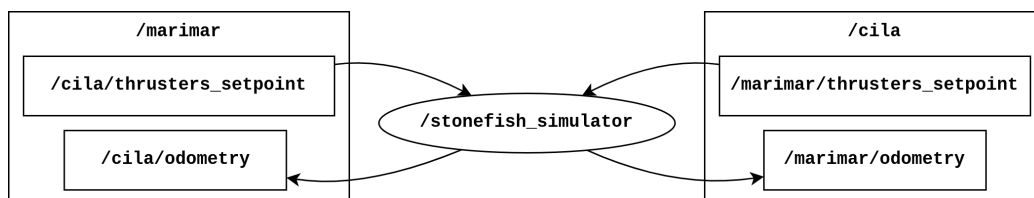


Figure 5.4: Simulation node ROS computation graph.

The simulation node is positioned in the center of the diagram, surrounded by two sets of topics for each vessel, named Marimar and Cila, which are the robots'

names passed to the scenario file. Marimar vessel is the one in which a collision avoidance module was implemented while Cila acted as an auxiliary vessel for obstacle recreation. Each vessel has two topics: one representing the output from the virtual odometry sensor and another as the input through which the thrusters are controlled.

As illustrated in the figure, the vessels in question operate independently and can be controlled separately. To ensure this independence between vessels, a prefix with the vessel's name was utilized in all launch files of the system.

5.3.2 Visual Feedback

To monitor the vessels' behavior and provide visual feedback from vessels operations, the graphical interface of Stonefish was bypassed, and instead, the models of both vessels, Marimar and Cila, were integrated into RViz.

This integration was achieved by using the `sw_urdf_exporter` tool, as detailed in Section 5.1, which allow the generation of a robot description file. This file delineates the relationships between the various components of the robot, and using the `robot_state_publisher` package, these relationships are published as ROS parameters to enable the incorporation of the robot model into RViz [66]. However, given that the same model was used for both vessels, it was necessary to remap the parameters generated by this package within the ROS ecosystem to distinguish between them.

To support the definition of multiple robots from a single file, the system was enriched with XACRO, a macro language designed to extend the capabilities of the URDF file [67]. This enhancement not only allowed for modifying the names of the robot links to solve a conflict between robot parameters but also enabled alterations to the visual attributes of each vessel, ensuring distinct representations in RViz. For Marimar, violet tones were selected, while for Cila, yellow ones were used. In Fig. 5.5, the two vessels can be visualized in the RViz with their respective colors.

The figure reveals that the visualizer's background includes an additional image layer beyond the standard uniform color. To enhance the visual feedback, the RViz plugin `rviz_satellite` was employed, enabling the integration of satellite imagery from map services, as detailed in [68]. The satellite images were sourced using the API provided by Mapbox [69]. The `rviz_satellite` plugin utilizes a specific URL format compliant with the Mapbox API to fetch map tiles [68]. By inputting the desired coordinates, zoom level, and tile count, the plugin retrieves and displays the tiles within RViz, creating a detailed satellite image map that matches the specified dimensions and level of detail.



Figure 5.5: Vessels representation in the RViz.

5.3.3 Collision Avoidance Module

While developing the collision avoidance module, an initial strategy involved creating three separate nodes, each corresponding to a distinct module's block. However, this approach increased the number of nodes, topics, data transfers and configuration parameters. A particularly challenging aspect was managing the input vessel information within the path replanning node, which proved to be the most complex. The difficulty lay in transmitting the various vessel parameters essential for accurate maneuver decision-making through topics.

Consequently, a consolidated approach was adopted by developing a single node to handle the collision avoidance tasks. This change significantly improved data accessibility within the code and simplified the overall interaction with the node. The previously scattered parameters across three different nodes were now centralized, simplifying the process and improving the module's efficiency. A YAML file was created to manage the configurable parameters effectively, containing all the necessary settings. This approach proves particularly advantageous when deploying multiple robots that utilize the node from same package, allowing for customizing parameters to fit specific vessel and scenarios. Additionally, since the environmental constraints may impact module performance, modifying them in real time might be required. The `dynamic_reconfigure` package was employed to address this need, providing a straightforward and user-friendly method for adjusting the node's parameters [70]. This functionality enables the on-the-fly configuration of the node's performance, enabling adaptive responses to dynamic operational conditions.

Fig. 5.6 represents the overall collision avoidance node inputs and outputs topics. From the figure, three input topics can be identified on the left side, and two output topics can be identified on the right.

The `/marimar/pose_setpoint` topic, from USV control system, contains the initial and final points, tracing a vector the vessel must follow. This vector is used

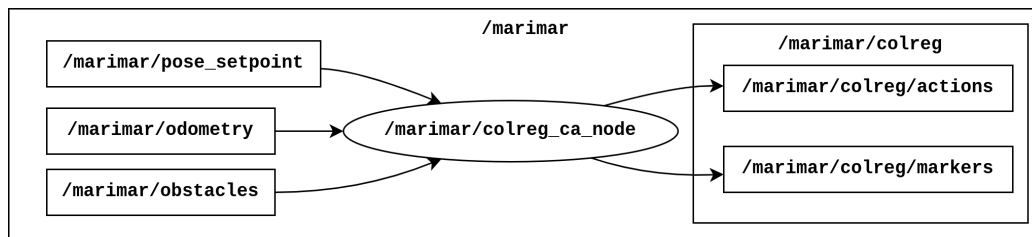


Figure 5.6: Collision avoidance node ROS computation graph.

within the collision avoidance module, particularly for the risk assessment block and path replanning. The risk assessment block verifies if the endpoint is distant from the CPA positions to determine if risk avoidance action is needed. The path replanning block uses the path vector to compute the detour angle for a collision-free trajectory.

Both input topics, `/marimar/odometry` and `/marimar/obstacles`, utilize standard odometry messages from the `nav_msgs` package. These message types encapsulate essential information, including the robot's position, orientation, velocities, and supplementary data. The `/marimar/odometry` topic is directly received from the simulation node. In contrast, the `/marimar/obstacles` topic is published by a node that emulates the vessel's perception system. This intermediary node, bridging the simulation and the collision avoidance node, repurposes the angular velocity fields related to the vessel's roll and pitch rotation to include the dimensions of the obstacle vessel. Furthermore, the obstacle vessel's priority is encoded in the field designated for the z-axis position. These fields were selected based on their perceived irrelevance to the vessel's 2D motion. This prevents the need for an additional input topic.

The primary topic that is published by the collision avoidance module node is the `/marimar/colreg/actions`. The messages transmitted through this topic are generated by the path replanning block. Using the `Float32MultiArray` type from the `std_msgs` package, essential parameters such as action, detour angle, and velocity are transferred to the USV autopilot. The action value determines whether to adjust solely the course, the velocity, or both.

The second output topic, `/marimar/colreg/marker`, is an input to the RViz tool. This topic is crucial in visually assessing the correct functionality of each component within the collision avoidance module.

When new odometry data of the obstacle is received at the collision avoidance node, the system conducts a risk assessment in accordance with the module's architecture. Initially, the parameters for the CPA are recalculated. If these parameters fall below the predefined thresholds, the system updates the zones' centers and dimensions, which are dependent on the obstacle's size and velocity. Subsequently, as previously mentioned, the endpoint of the path vector is used. Should this point be

located prior to the CPA pose and outside the TS CPA maneuver zone, it implies that the OS will not reach the potential collision point, ending its trajectory earlier. If this is not the case, the system advances to the subsequent verification steps.

The final evaluation method of this block consists of verifying whether the OS current or CPA pose is situated within any of the TS zones or vice versa. For further explanation, see Section 4.1.2. Should any combination result in a position falling within the zone, the corresponding state values are assigned to the obstacle, and the process advances to the second block of the collision avoidance module.

For a better understanding of the process of this first block, visual feedback is displayed using the RViz marker topic, see Fig 5.7.

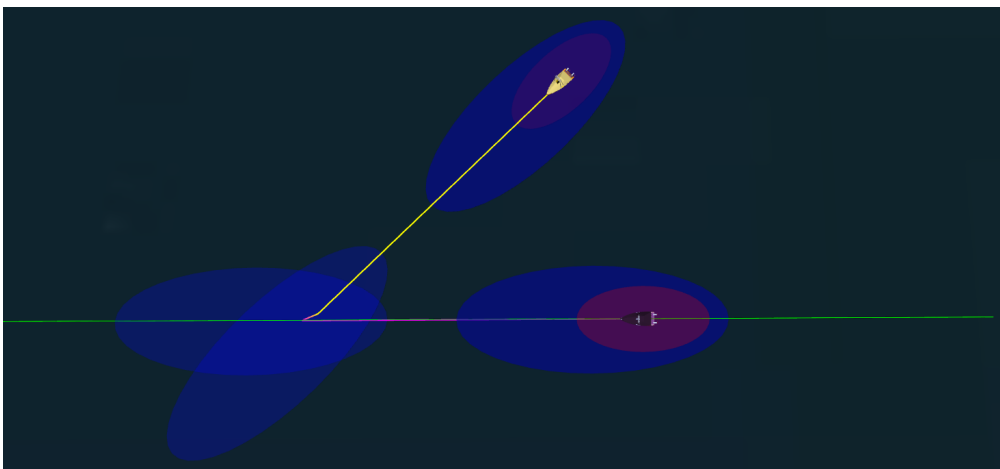


Figure 5.7: Visual feedback from risk assessment block.

In this figure, TS is depicted in yellow, and OS in violet tones. Several elements can be distinguished. Firstly, the path vector is represented as a green line, starting from the right side of the figure, with its endpoint extending beyond the visible area of the figure. To represent the CPA positions, three-segmented lines are employed: the first, in violet, traces from the USV's position to its CPA position; the second, in yellow, connects the TS's position to its CPA; and the third line links their respective CPA positions. This setup allows for the visual determination of whether the endpoint is situated before and outside the CPA maneuver zone of TS and whether any of the vessels' positions intersect with any zone.

In Fig. 5.8, part of the adjustable parameters are displayed within the respective user interface. It illustrates the capability to alter the coefficients for emergency and maneuver zones, which dictate their dimensions. Although both zones utilize the same parameters, minimum size, velocity and size coefficients, they are configured differently to meet specific requirements. The emergency zone is configurable to highlight the vessel's size, while the maneuver zone is adjusted to emphasize the vessel's velocity. Additionally, there is an option to adjust the thresholds for CPA parameters. Lastly, the figure shows the possibility of controlling visual feedback.

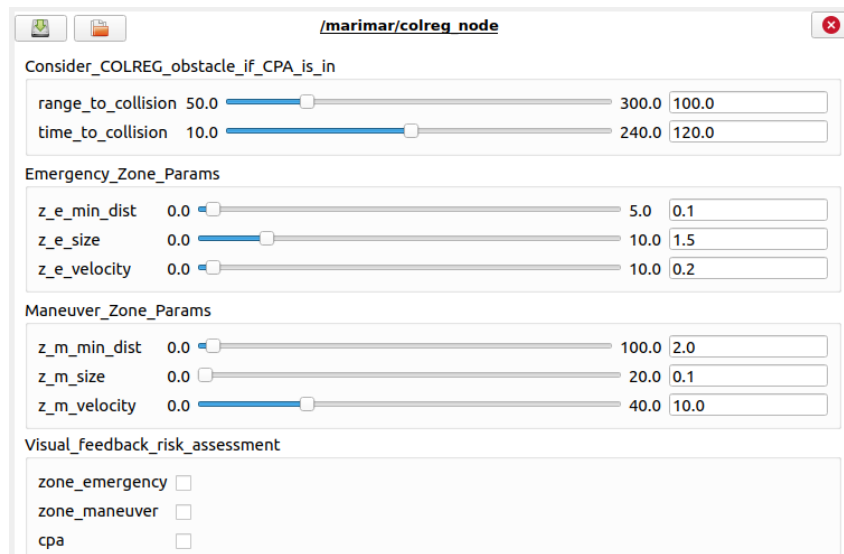


Figure 5.8: Adjustable parameters of risk assessment block.

The rule identification block determines the appropriate navigational response for the USV based on its current maritime context. This block distinguishes the prevailing marine situation and dictates the required maneuver: turning port or starboard or maintaining course and speed if the USV is designated as a stand-on vessel.

The system was developed to recognize five principal navigational scenarios: head-on, crossing from the port or starboard side (with the USV either giving way or standing on), overtaking another vessel, or being overtaken. A Bayesian update-based algorithm has been implemented to enhance decision-making accuracy, especially when the USV is at the juncture of two distinct rules, such as in crossing or overtaking scenarios. This algorithm prevents the USV from oscillating between maneuvers when navigating at the boundary conditions between rules.

The process starts by assigning an initial equal probability to each navigational rule, establishing baseline confidence in the correctness of each rule for any given situation. Upon identifying a specific rule, as detailed in Section 4.2, the algorithm updates the associated probability, thereby increasing confidence in the rule's relevance to the current situation. This update applies a fixed likelihood ratio to the probability of the identified rule, quantifying the degree of trust in the rule identification and increasing the rule's probability. Following applying the likelihood ratio, the system normalizes the probabilities across all rules to ensure their sum remains unity, maintaining a coherent probabilistic framework. A decision-making threshold is defined, and when the probability of any rule exceeds its value, the rule is selected for execution, thereby guiding the USV's navigational response.

In Fig. 5.9, it can be observed that the likelihood ratio, as well as rule selection threshold, were defined as node parameters that can be changed.



Figure 5.9: Adjustable parameters of rule identification block.

The path replanning block generates new path vectors for the USV to follow when a collision situation is identified. As described in Section 4.3, this block features two operational modes. The default mode produces detour maneuvers that involve only a change of course, and the second mode allows for velocity adjustments, which alone can be sufficient to prevent a collision. Mode changes can be made using node parameters, as depicted in Fig. 5.10.

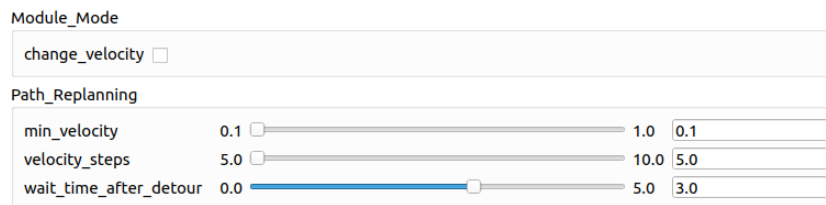


Figure 5.10: Adjustable parameters of path replanning block.

In the same figure, additional parameters of the path replanning block can be observed. These include the allowed minimum velocity that can be assigned to the vessel to prevent it from stopping completely, which helps mitigate potential drift due to currents or wind.

The `velocity_steps` parameter plays a critical role in the second operational mode of the path replanning block. This mode employs an iterative process to identify the optimal velocity that aligns with the rules and conditions outlined in Section 4.3. The parameter specifies the number of iterations before concluding the velocity selection. A binary search method was employed to determine the appropriate velocity. With the parameter set to a minimum setting, the resulting resolution of the velocity adjustment is approximately 0.03.

After executing a detour maneuver and successfully avoiding a collision, the USV will reach the CPA position from which the vessels begin to diverge. However, the OS may be off its initial trajectory, and an additional maneuver may be required to return to the original path. To prevent the USV from executing this maneuver immediately after passing the current CPA position, which could potentially lead to dangerous situations, an additional wait time configurable parameter is employed, see Fig. 5.10. This allows the vessel to diverge further based on the time to CPA positions. For instance, if this parameter is set to 3, the vessel will continue to follow its current path vector until the time to the CPA point is less than the negative value of this parameter.

Despite the robust functionality of the developed algorithm, critical situations where an evasive maneuver is necessary to avoid collisions are always possible. An example of such a scenario occurs when the TS does not follow COLREG rules and violates the OS's right of way, leading to a potential collision. To address such scenarios, the collision avoidance module includes an evasive maneuver triggered when the risk assessment block recognizes an emergency state, as shown in Fig. 4.5.

It is important to note that the maneuver executed to avoid a collision cannot be standardized for all situations; a maneuver to starboard that avoids a collision in one context might cause one in another. As illustrated in Fig. 5.11, the diagram indicates the preferable side for taking the maneuver, to port or starboard, based on the bearing and relative course from the TS perspective. Initially, the bearing is

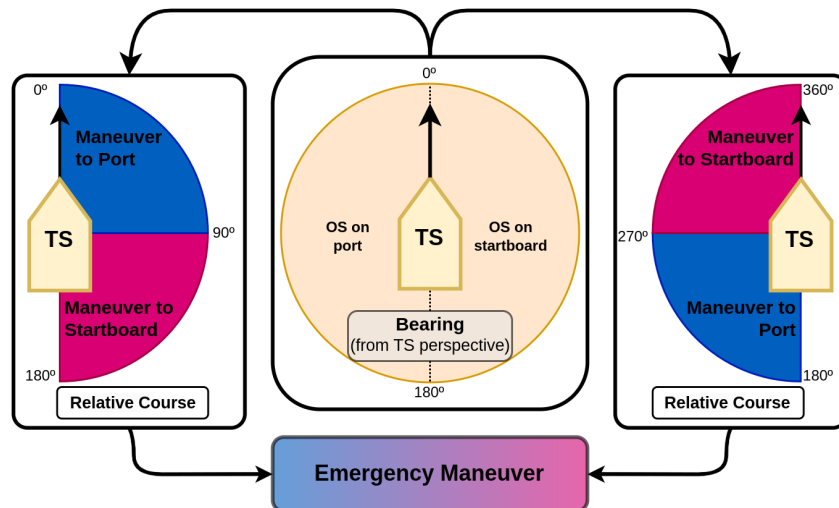


Figure 5.11: Emergency maneuver identification.

considered: a different maneuver is required if the OS is on the port side than on the starboard side. Subsequently, the relative course is assessed, with the division made across the vessel beam to determine the most appropriate and fast maneuver for the OS vessel to clear the path of the TS vessel. Additionally, the course for the path vector is set parallel to the TS vessel, ensuring that as their courses become parallel, the risk of intersection and subsequent collision is mitigated.

5.3.4 USV Control System

In this work, an already developed and sophisticated USV control system was used. The system features a complex architecture, and improper integration of a newly developed collision avoidance module could negatively impact its functionality. Therefore, it was critical to ensure that the integration did not disrupt the system's primary objectives and tasks. Accordingly, the collision avoidance module output was designed to interconnect with the USV autopilot, avoiding direct interactions with the lower-level control blocks.

Modifications were necessary to allow the autopilot to effectively implement commands from the collision avoidance module. Thus, when the USV follows a predefined path determined by the autopilot via a path vector, and a new command is published by the collision avoidance block, the autopilot adjusts the path vector based on the received data. Additionally, if required, the autopilot also sets a new velocity.

These adjustments to the path vector and velocity are crucial for maintaining a safe trajectory for the USV, ensuring compliance with COLREG standards.

However, when no new data is received from the collision avoidance module, as no long intervention to USV trajectory is needed, the system's ability to revert to its predetermined mission trajectory is paramount.

Three distinct path resumption modes were developed and implemented to accommodate various mission requirements and enhance the USV's operational flexibility, see Fig. 5.12.

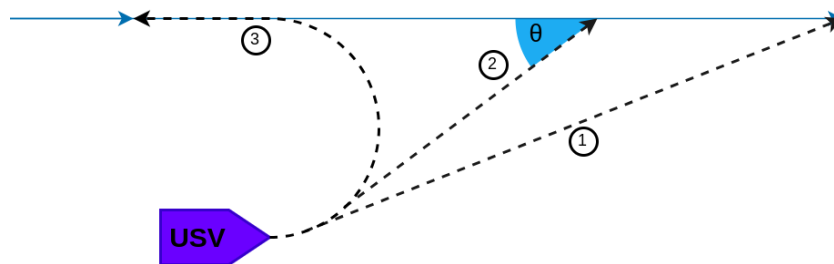


Figure 5.12: Autopilot return to path resumption modes.

The first mode allows the USV to head directly toward the mission's endpoint, establishing a new course from the USV's current position. This mode is particularly advantageous when time efficiency is crucial to the mission's success.

The second mode introduces a strategic path resumption, allowing the USV to realign with its original path at a specific angle, θ from Fig. 5.12, predetermined by the configurable parameter. This method balances a direct approach and adherence to the original path, enabling a smooth transition back to the mission trajectory while considering the USV's current position and heading.

The third mode is designed for instances where the USV has surpassed the mission's endpoint during the collision avoidance maneuver. In these cases, the autopilot directs the USV to circle back and reach the endpoint, ensuring that the mission objectives are fully met despite any deviations from the initial path. This mode emphasizes the system's adaptability and dedication to mission completion, even when unexpected detours occur.

To facilitate the interaction between the return modes and enable the autopilot to receive path vector modification commands from the collision avoidance module,

a set of parameters that can be adjusted via the dynamic reconfigure interface was developed, as shown in Fig. 5.13.

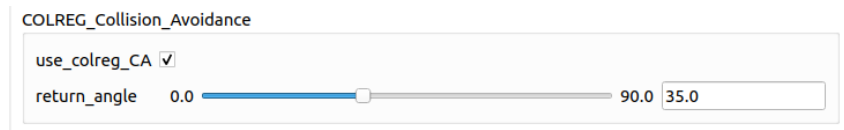


Figure 5.13: Configuration parameters of return maneuver.

The figure illustrates two key functionalities: the first parameter enables the reception of path changes from the collision avoidance module, and the second allows changing between the first and second return modes to USV's original path. The first mode is activated when the parameter value is set to 0; otherwise, the second mode is used with the respective return angle value. Conversely, the third return mode is automatically engaged when the USV surpasses the endpoint.

An additional node was developed to command the vessel within the simulation environment. The control system of the USV generates motor reference data in a custom message topic, which is incompatible with the simulation's input requirements. Consequently, an auxiliary node was created to enable data remapping, allowing the simulator to receive the appropriate messages and, therefore, closing the control loop.

Chapter 6

Results

To evaluate the performance of the proposed collision avoidance module, specifically in adherence to COLREG rules 13 to 15, scenarios mirroring marine situations described in these rules were recreated. The Stonefish simulation libraries within the ROS framework were used for these recreations. To replicate the appropriate marine interaction, two vessels were used in the simulation, both based on the same USV model. These vessels, equipped with autonomous control systems, were programmed to follow predefined paths that would intersect and consequently collide, simulating the scenarios dictated by the COLREG rules. However, the collision avoidance module that follows COLREG is employed in only one of them.

The primary focus of this tests is to observe the correct USV behavior guided by the developed module, ensuring not only the avoidance of collisions but also maintaining a safe distance between the vessels, adhering to COLREG-prescribed actions, and avoiding any potential danger.

This chapter is structured to perform an individual evaluation of each marine situation. For each rule, the corresponding recreated scenario is described, followed by a discussion on the USV responses and adherence to the specific COLREG rule.

However, before embarking on these rule-specific evaluations, a comparison between the proposed risk assessment methodology and an alternative approach will be presented.

6.1 Risk Evaluation

According to Chapter 3, the most prevalent methods for risk evaluation to determine the necessity for collision avoidance path replanning are the Closest Point of Approach (CPA) and the ship domain method. However, as presented below, these methods exhibit certain weaknesses in specific case scenarios. Consequently, this work introduces an approach that combines the strengths of the CPA and the ship domain method, excluding their limitations.

Figure 6.1 depicts scenarios that underscore the limitations inherent in the CPA risk assessment method.

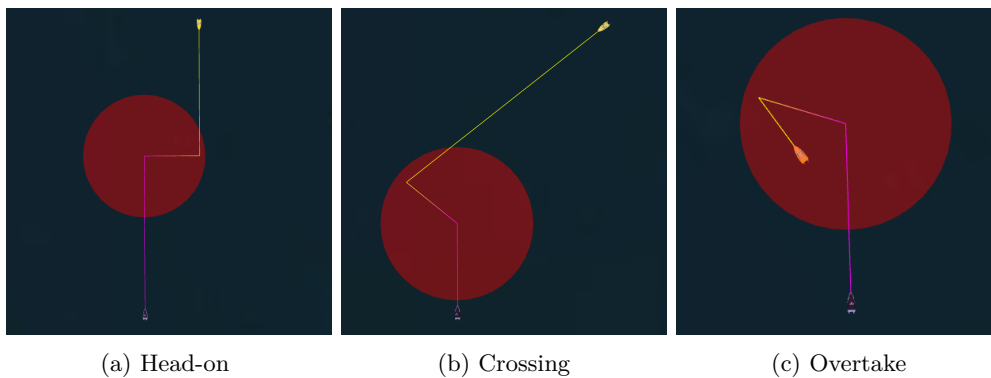


Figure 6.1: Risk assessment only based on CPA method.

The red circular area denotes a defined distance threshold below which a situation may be classified as dangerous. While this method is generally effective, the circular threshold represents a critical vulnerability. As illustrated, there are circumstances where the CPA method might signal a potential risk, suggesting the need for trajectory change, even in cases where such interventions may not be necessary.

In Figure 6.2, the delineated red line represents the potential boundary of the ship domain area, crucial for risk assessment under COLREG rule.

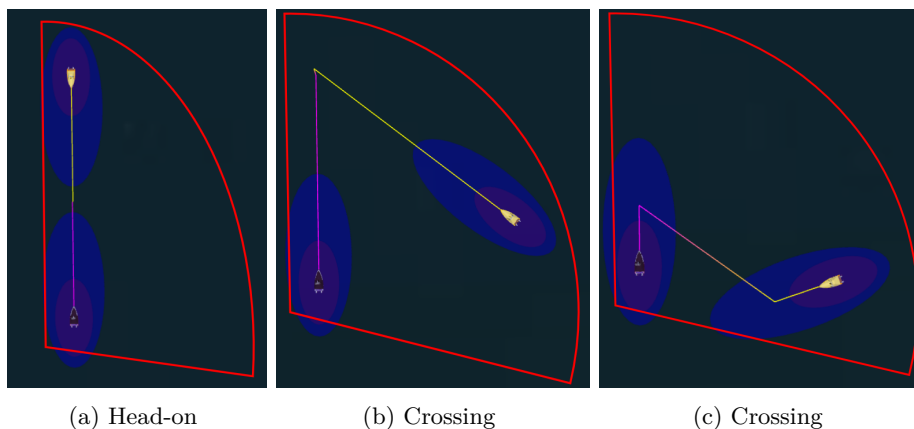


Figure 6.2: Risk assessment only base on ship domaine method.

However, this demarcated area is larger than the proposed one, which is also present in the figure. According to this method, risk is only recognized when the TS intrudes upon this area. Moreover, there are scenarios where the ingress of the TS into this zone does not necessarily correlate with an imminent risk to the OS.

In Figure 6.3, scenarios illustrating the weaknesses of the previous methods are presented, showcasing the application of the proposed risk assessment method.

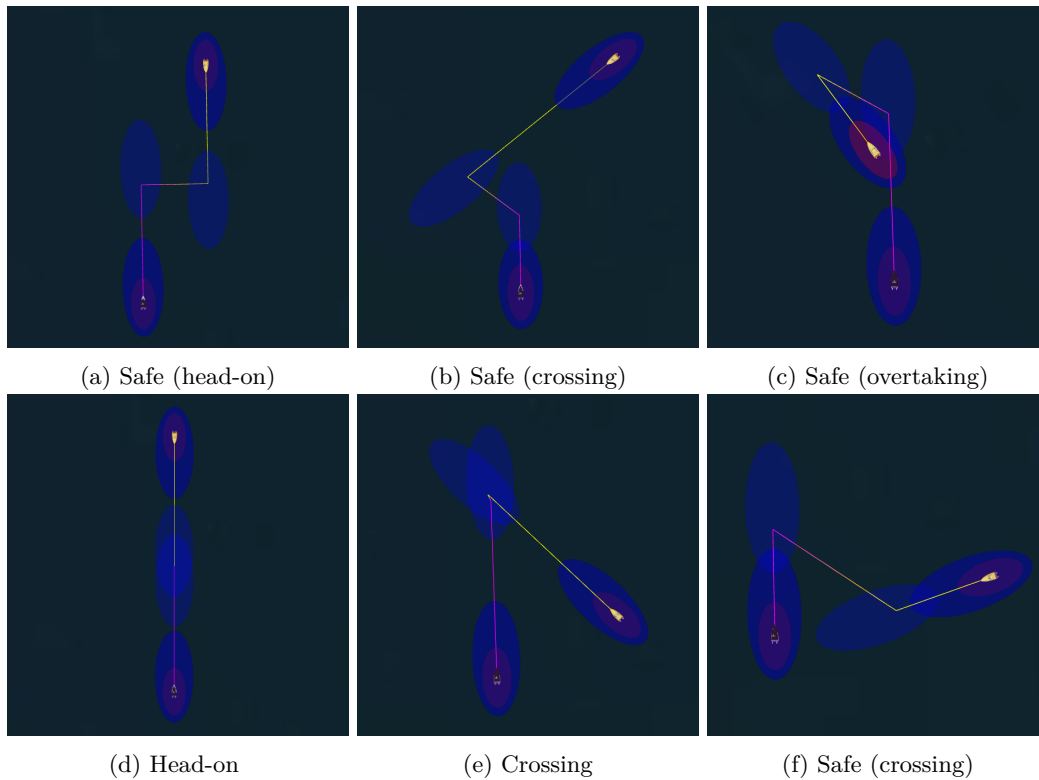


Figure 6.3: Proposed risk assessment method.

This method incorporates the CPA while modifying its traditional application. It moves away from the conventional circular area defined by the fixed distance threshold, replacing it with a zone more accurately representing the vessel's dimensions and speed. This adjustment is inspired by the ship domain method, where a similar area around the vessel is used to ensure the vessel's local security. This approach not only improves the risk assessment process but also aligns it more closely with the characteristics and operational context of the vessel.

As a result, and as illustrated in Figure 6.3, this method effectively differentiates between scenarios that other methods might inaccurately identify as posing a risk. Where previous methods may indicate false positives, this approach clearly distinguishes risk situations, thereby improving the accuracy and reliability of the risk assessment process.

6.2 Course Only Manoeuvre

This section presents detour maneuvers involving only changes in course. These maneuvers correspond to the default mode of the path replanning block in accordance with COLREG Rule 8, as detailed in Section 4.3. The subsequent subsection corresponds to the marine scenarios described in COLREG Rules 13 to 15, respectively.

It is important to note that this section only presents changes in trajectory for which the collision avoidance module is responsible. The maneuver to return to the original path, managed by the autopilot module, will be discussed in a separate section.

6.2.1 Head-on

For recreation of the head-on rule, the two vessels within the simulation are positioned directly opposite one another, with their path vectors being collinear and having symmetrical directions. Consequently, this alignment predisposes the vessels to a frontal collision, which must be avoided. In Fig. 6.4a, this initial scenario from the simulation is depicted.

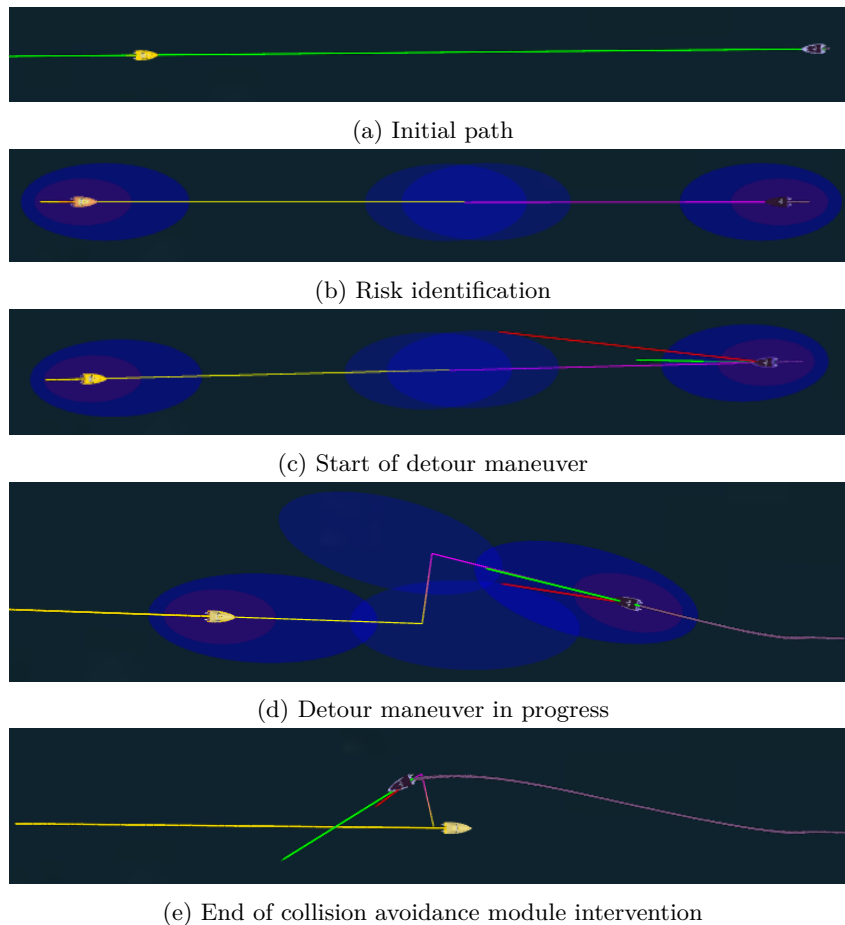


Figure 6.4: USV path alteration in head-on situation.

In conformity with the COLREG, in such circumstances, the vessels must pass each other while ensuring that each keeps the other on its port side. Therefore, both vessels must maneuver to starboard to avert a collision. However, in the simulation, only the Marimar vessel is equipped with the COLREG compliance collision avoidance module, which results in the vessel Cila going straight ahead and not following the regulation.

Once the vessels begin movement and adhere to the predefined path, the OS detects a risk of collision. This moment, marking the detection of collision risk, is depicted in Fig. 6.4b. From this figure, it is evident that the CPA poses of the vessels are approximately at the same location and equidistant from each vessel. This occurs when the vessels maintain identical velocities and follow collinear trajectories. The figure also reveals that the CPA positions fall within other vessel CPA maneuver zones. According to Section 4.1.2, this scenario is classified by the risk assessment block as maneuver stage 2 (see Fig. 4.5). This classification triggers the subsequent collision avoidance block, the rule identification.

The effectiveness of the rule identification phase is confirmed by observing the start of the maneuver depicted in subsequent Fig. 6.4c, showing the appropriate response to the identified collision risk, maneuver to starboard.

In this figure and the following one, Fig. 6.4d, the red arrow represents the tangent line from the USV pose to the TS CPA maneuver zone, and as described in Section 4.3, the detour angle is computed based on this line.

However, as can be observed in Figure 6.4d, it is noticeable that the green path vector that guides the USV does not align with the red arrow. An additional fixed value angle has been incorporated into the initial path replanning detour angle for directing the USV away from the obstacle's CPA zone border while keeping it in the surrounding area. This supplementary factor guarantees that the USV heads clear of the zone, ensuring maximum safety and avoiding any potential hazards.

The overall changes in the path for which the collision avoidance module is responsible are presented in Fig. 6.4e. It can be observed that the actions of the module continued even after the USV passes the position where the time parameter from CPA becomes negative. The intervention ends when the time to CPA passes the threshold of negative three, ensuring that the vessels have safely passed each other and are moving apart.

6.2.2 Crossing

In accordance with COLREG, the crossing rule is applied when two approaching vessels present a risk of collision. The vessel that has the other on its starboard side shall keep out of the way. This scenario has been recreated in simulation and can be observed in Fig. 6.5 from which it is clear that it would be the Marimar, the one giving way to Cila.

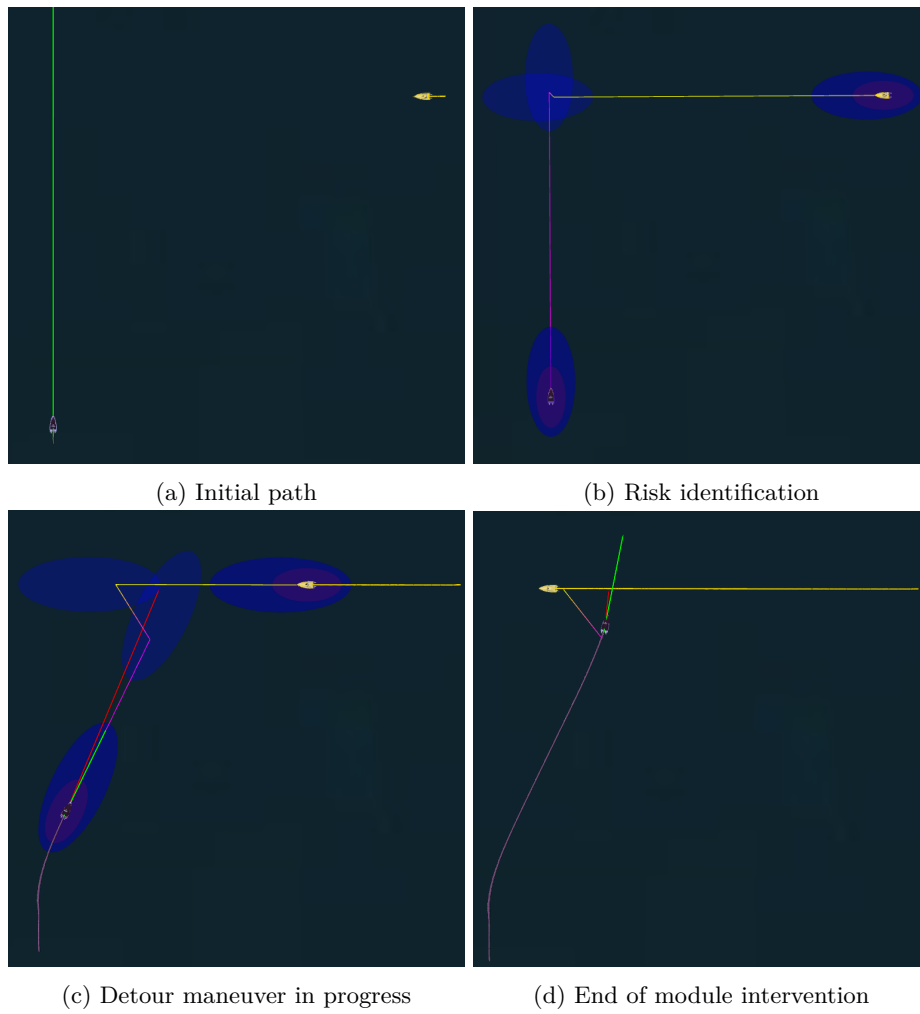


Figure 6.5: USV path alteration in crossing situation.

To ensure the possibility of a collision in simulation, the vessels' paths were configured to intersect perpendicularly. The initial conditions of this scenario are depicted in Fig. 6.5a.

In Fig. 6.5b, the zones of the vessels and their CPA poses are illustrated. Based on this, it is evident that a collision is imminent without intervention.

Following the tree block architecture, the risk is assessed, the relevant rule is identified, and the current path is altered to prevent the collision. The detour process is presented in Fig. 6.5c. As previously mentioned, the red arrow represents the tangent line to the TS's maneuver zone; however, the OS is directed slightly to the starboard to prevent the Marimar from entering Cila's maneuver zone.

In Fig. 6.5d, the moment when the action by the proposed module ends, ensuring no longer possibility of collision and letting the autopilot take control for return to the original line.

6.2.3 Overtaking

The overtaking scenario was recreated in simulation, as depicted in Fig. 6.6.

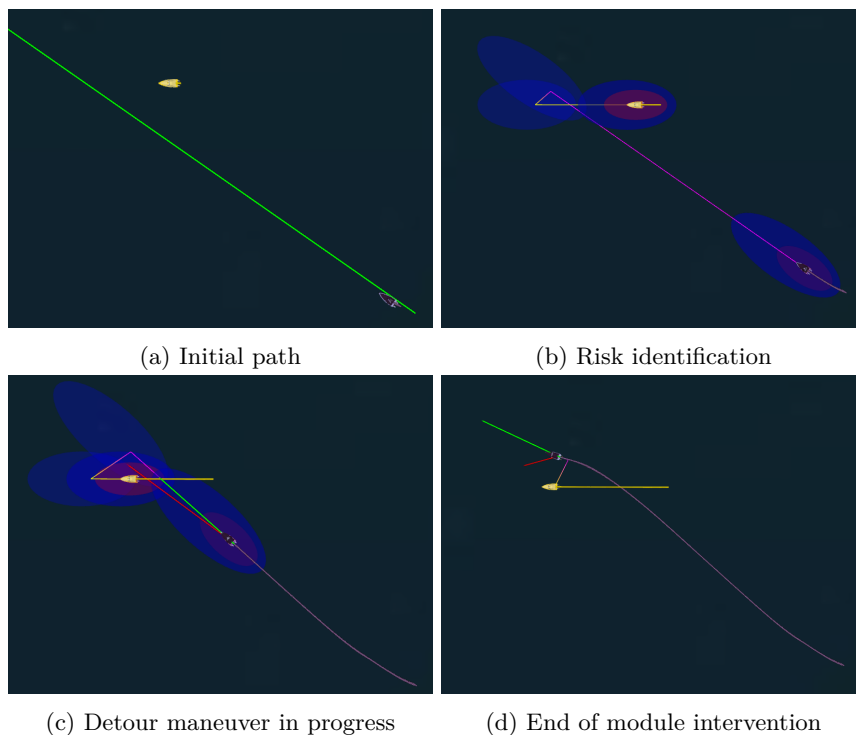


Figure 6.6: USV path alteration in overtaking situation.

The paths of the vessels were defined such that the Marimar would approach the Cila from its stern, aligning with the COLREG rules that specify an approach “from a direction more than 22.5° abaft her beam”. This initial condition can be observed in Fig. 6.6a.

Risk assessment process can be observable in Fig. 6.6b, where the USV's CPA point falls within the obstacle CPA maneuver zone. The detour maneuver is depicted in Fig. 6.6c, with the red arrow being tangent to the same zone used in the risk assessment.

Finally, Fig. 6.6d presents the moment after the collision avoidance module's actions have ended.

6.2.4 Discussion

The default mode of the collision avoidance module is the one that follows the COLREG recommendations in executing the collision avoidance maneuver without changing the vessel's velocity. As was presented in Figs. 6.4, 6.5 and 6.6, the OS is guided to the stern of the TS CPA position using the tangent line to the respective maneuver zone with an additional safety fixed angle. Although the local pose or zone of the TS is not used, the maneuver ensures a collision-free and safe distance passage as real-time monitoring and updating of the CPA positions and respective zones are employed. This constant updating allows the establishment of a trajectory that allows the OS to safely navigate and cross the TS path from the stern side at moment of the closest approach.

6.3 Course and Velocity Manoeuvres

As delineated in Section 4.3, the path replanning block incorporates two potential detour maneuvers based on its defined objectives. The first maneuver involves an adjustment exclusively to the vessel's course, as discussed in the preceding section. The second maneuver, however, allows for modifications to both the course and the vessel's velocity. The results of this dual-adjustment strategy are presented in the current section, further divided into subsections corresponding to marine situations described by rules 13 to 15.

6.3.1 Head-on

Figure 6.7 illustrates the resulting maneuver in the head-on scenario of the second operational mode of the path replanning block. This maneuver aims to minimize deviation from the predetermined path. The initial simulation position and the risk assessment phases are consistent with those illustrated in Figures 6.4a and 6.4b and are not repeated here.

According to the algorithm described for this operational mode in Section 4.3, the OS velocity is changed to the minimum value necessary to navigate around the TS CPA maneuver zone. However, as evidenced in Figure 6.7a, the maneuver's start

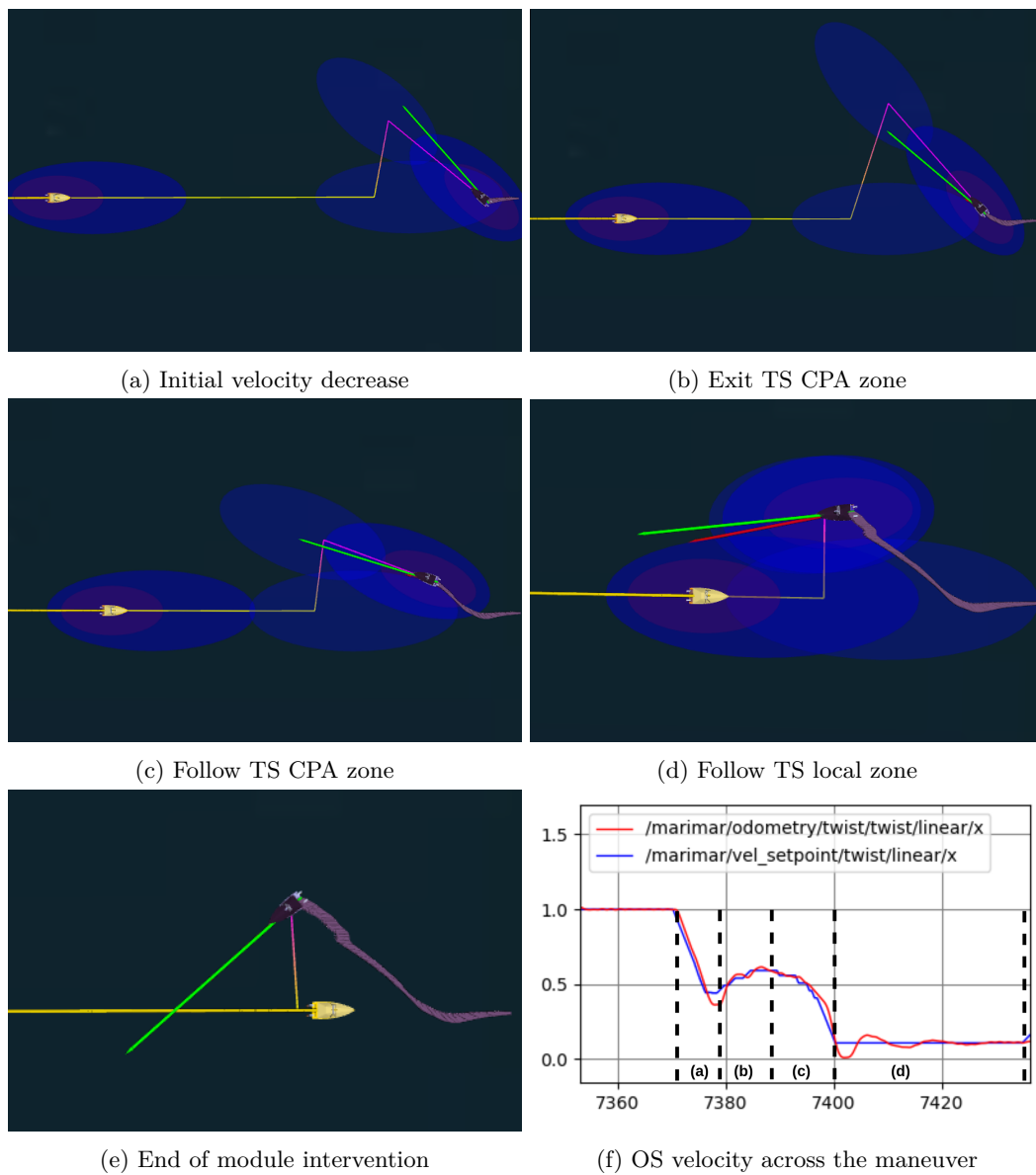


Figure 6.7: USV trajectory alteration in head-on situation.

is marked by velocity and direction changes, which result in the Marimar entering Cila's maneuver zone.

Despite this, the algorithm, which is designed for real-time application, promptly detects this situation, and the velocity is increased to prevent the TS from remaining within the undesirable zone. Figure 6.7b illustrates the moment when the OS exits the obstacle zone due to increased velocity.

Figure 6.7c delineates the return to regular operation within this mode, where the algorithm adjusts the vessel's path vector to align tangentially to the obstacle maneuver zone.

At the same time, as the collision risk diminishes with the Marimar moving out of the direct path of the Cila CPA maneuver zone, the velocity is reduced to its minimal setting to prevent the vessel from moving along a path that was not predefined by the mission. This reduction in velocity is observable in Figure 6.7d, in which, despite the path vector's orientation, the vessel's inertia causes a lateral deviation.

When the angle of the tangent line from OS to TS CPA zone becomes larger than the angle to its local maneuver zone, the path vector is realigned to be tangent to the local zone, incorporating an additional angle previously mentioned. This adjustment is implemented to prevent the OS from prematurely reverting to its original route, thereby mitigating the risk of entering the TS local maneuver zone as it approaches its CPA position.

Figure 6.7e marks the conclusion of the collision avoidance module's intervention as the time to the CPA become negative. Finally, Figure 6.7f displays the Marimar's velocity throughout the entire maneuver, correlating each phase with the respective figures. The red line represents the actual Marimar velocity, while the blue line represents the goal velocity.

6.3.2 Crossing

In Fig. 6.8, the maneuver in the crossing scenario within the second operational mode of the path replanning block is presented.

In this marine context, the variation in velocity proves particularly advantageous, as the adjustments in speed alone is sufficient to avert a collision without the need for course alteration. Similar to the preceding subsection, the initial conditions and risk assessment for this scenario are not depicted in the figure but align with those shown in Fig. 6.5a and Fig. 6.5b. Upon identification of the collision risk, the vessel's velocity is adjusted according to the procedure described in 4.3. Fig. 6.8a shows the initial velocity reduction with an overshoot. Subsequently, in Fig. 6.8b, the vessel stabilizes at the desired velocity, maintaining its CPA zone clear of the TS path to avoid any possibility of crossing ahead of it. After the Cila crosses the Marimar's path, Marimar no longer risks passing ahead of Cila on its current

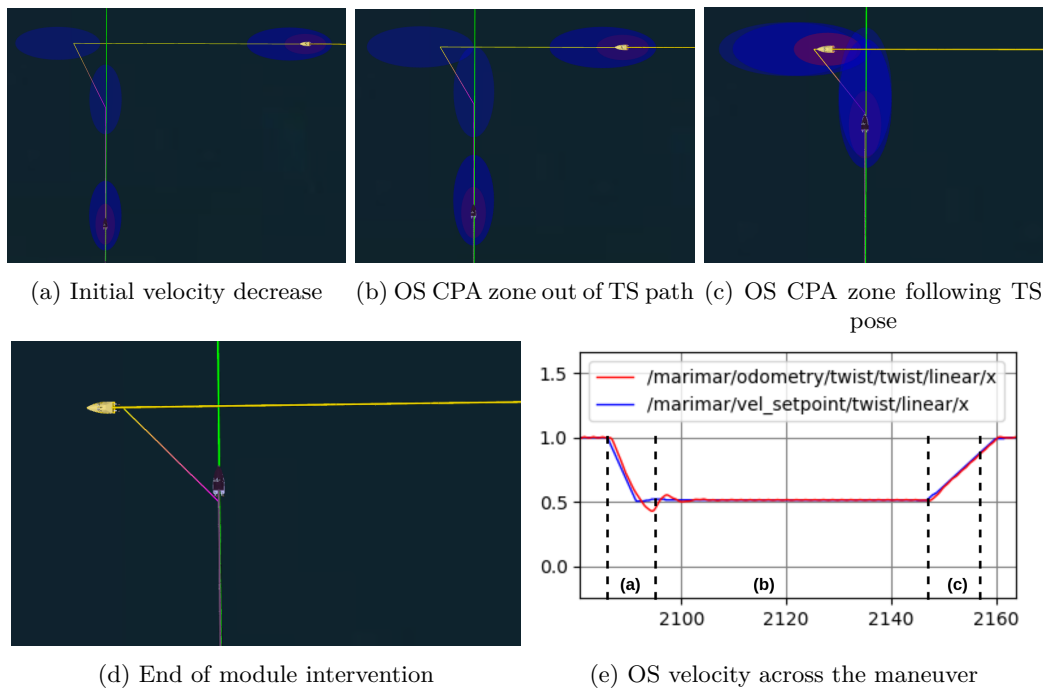


Figure 6.8: USV trajectory alteration in crossing situation.

trajectory. Consequently, the OS velocity is increased but ensuring that the TS current pose does not enter the OS CPA zone, as depicted in Fig. 6.8c. Finally, Fig. 6.8d displays when the collision avoidance block ends its intervention. Fig. 6.8e presents the overall vessel and setpoint velocities, represented with red and blue lines, respectively.

6.3.3 Overtaking

The maneuver in an overtaking situation, where a change in velocity is preferred over altering course, is depicted in Fig. 6.9.

This maneuver follows the same methodology as in the crossing scenario discussed in the previous subsection. Initially, there is a reduction in velocity as shown in Fig. 6.9a, followed by a stabilization of it to ensure that the OS CPA zone remains behind the TS path, as illustrated in Fig. 6.9b. When the Cila passes ahead of the Marimar path, the velocity is increased to maintain Cila's current position outside of the Marimar CPA zone, as shown in Fig. 6.9c. In Fig. 6.9d, it is observed that the risk of collision no longer exists, and the velocity is returned to its initial level. However, the maneuver concludes only when the CPA time becomes negative, as shown in Fig. 6.9e. These velocity changes throughout the maneuver are presented in Fig. 6.9f.

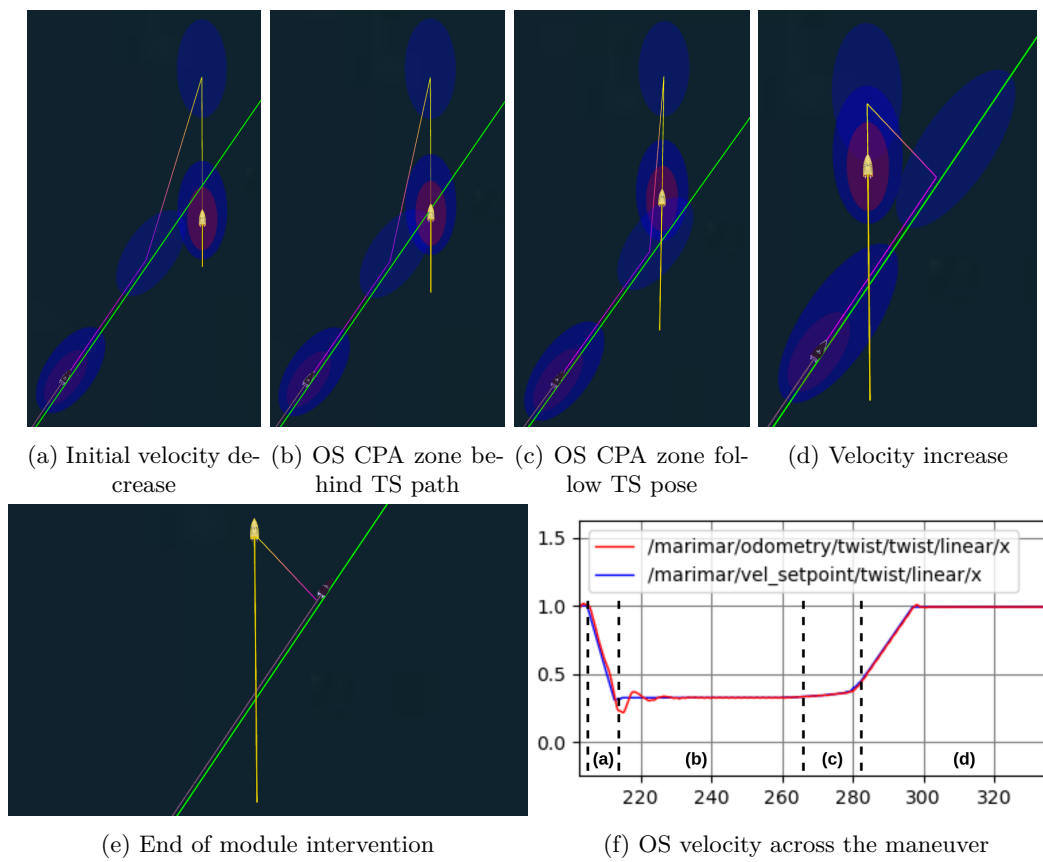


Figure 6.9: USV trajectory alteration in overtake situation.

6.3.4 Discussion

Despite not strictly following the COLREG recommendation of avoiding collisions solely by course alteration, the second operational mode of the path replanning block uses the vessels' maneuver zones to compute the suitable output velocities. These zones are designed to reflect the vessels' dynamic characteristics, resulting in significantly reduced velocity, signaling the OS's intention to avoid collision.

In crossing and overtaking maneuvers, reducing velocity alone ensures the safe passage of the TS. The output velocities are calculated to delay the OS CPA zone, ensuring it remains behind the TS path and preventing the USV from crossing into the path of the obstacle vessel until reaching the closest point of approach. This results in a velocity decrease, which, although more substantial than necessary, ensures clear passage for the TS, as depicted in Fig. 6.9d. This precautionary reduction in velocity is preferred over maintaining a closer, potentially riskier proximity that could lead the TS to perceive a collision threat.

In head-on situations, reducing velocity might appear counter-intuitive, as non-proactive action leads to a collision. However, the developed maneuver combines velocity reduction with course alteration, ensuring collision avoidance even if the TS does not comply with COLREG. Additionally, as demonstrated in the scenario presented in Fig. 6.9, if a risk of collision persists, the module is designed to increase velocity rather than maintain it at the initially computed lower value. Thus, this operational mode may be considered safe and more efficient compared to the default mode.

6.4 Maneuver with Less Priority

This section is dedicated to maneuvers where the OS holds less priority and is required to give way to the TS. The crossing situation was recreated in a simulation in which TS vessel, approaching from the OS port side, would typically be the give-way vessel under power-driven conditions. However, for this simulation, the TS was designated as a sailing vessel with the right-of-way over power-driven vessels.

The initial conditions of this scenario are displayed in Fig. 6.10a.

The risk assessment process, including the CPA positions and zones, is illustrated in Fig. 6.10b. Upon recognizing the risk and given that the obstacle vessel has priority over the USV according to Rule 18 of the COLREG, the USV approaches this scenario as a crossing situation where it must give way. However, instead of the typical starboard deviation, a port-side detour is executed to prevent crossing ahead of the obstacle vessel. The execution of this detour maneuver can be observed in Fig. 6.10c. Fig. 6.10d captures the moment when the collision avoidance module ends its intervention in the USV path.

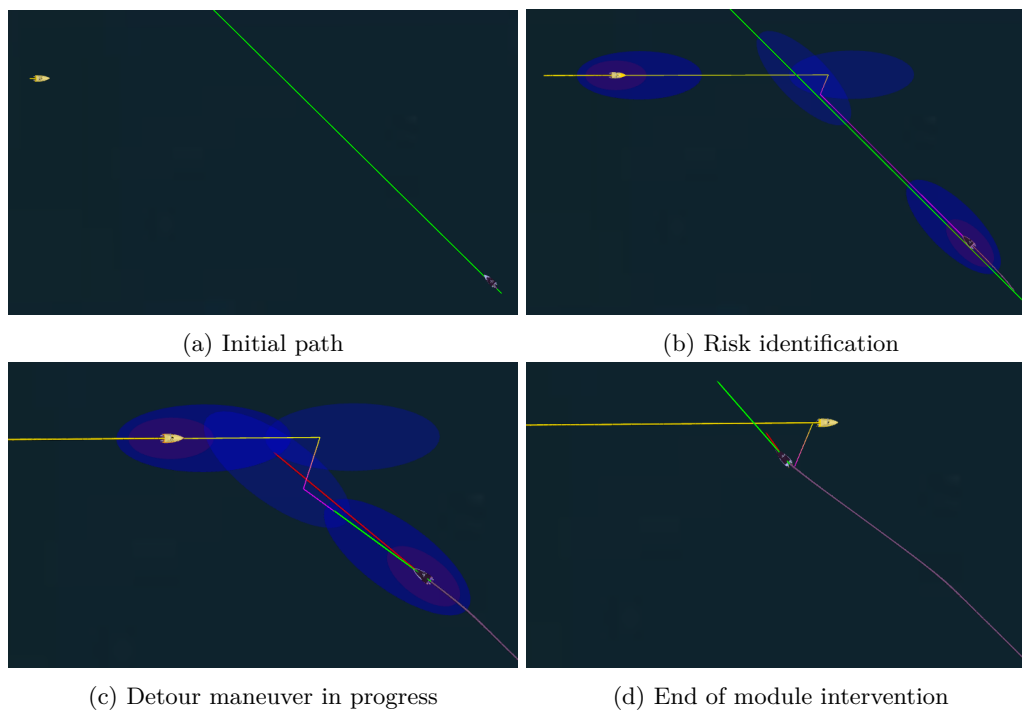


Figure 6.10: USV path alteration in less priority crossing situation.

Although the presented detour maneuver involves changing course, this is the default mode of the path replanning block.

As illustrated in Section 6.3, it is feasible to avoid the obstacle vessels by solely altering velocity while adhering to a predefined path. This strategy is employed in the second operational mode of the path replanning block, with the resulting maneuver displayed in Fig. 6.11.

In this recreated scenario, the situation is treated as a crossing, where initially the USV reduces its velocity to ensure the OS CPA zone remains behind the TS path, as shown in Fig. 6.11a. After the TS crosses the OS path, the velocity is increased, ensuring that the TS's current position stays outside the OS CPA zone, illustrated in Fig. 6.11b. Fig. 6.11c marks the conclusion of the module's intervention. Fig. 6.11d demonstrates the changes in velocity throughout the maneuver.

6.5 Return Maneuver

After the proposed collision avoidance module deviates the vessel from its original path to prevent a collision, the autopilot is tasked with executing the maneuver that allows for a return to the original predefined path, if so configured. Section 5.3.4 describes the various possible return maneuvers. These include establishing a new path to the destination point, returning to the original path with a predefined angle, or reverting to a destination point if it was bypassed during the detour maneuver.

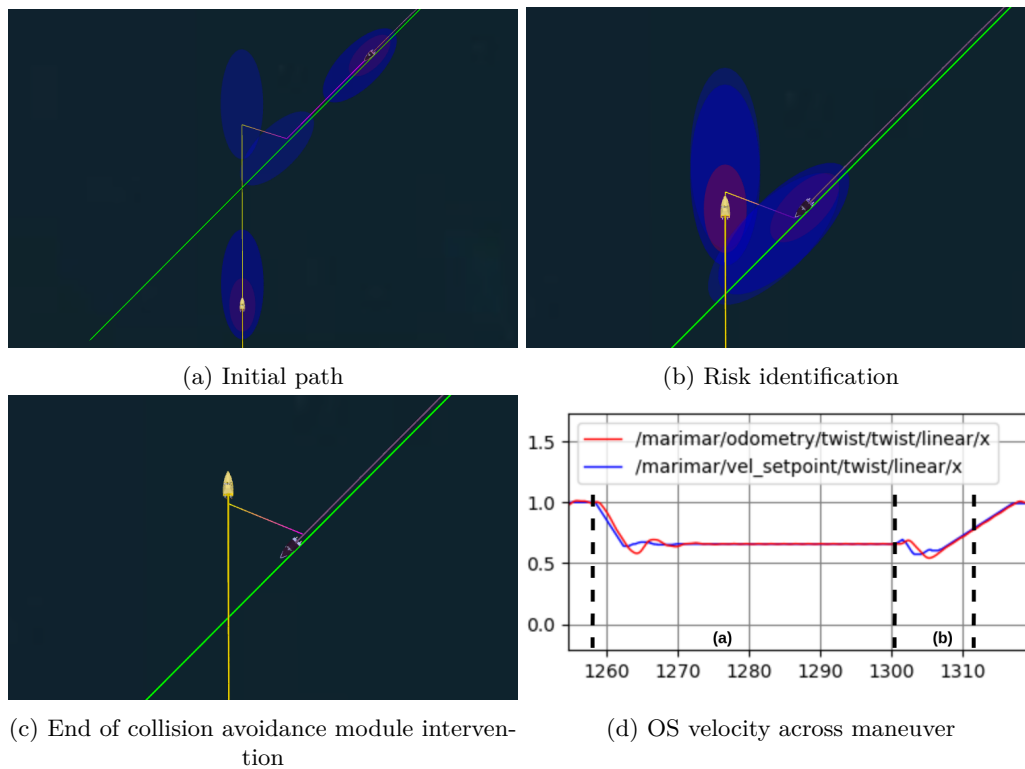


Figure 6.11: USV trajectory alteration in less priority crossing situation.

The first type of return maneuver is displayed in Fig. 6.12.



Figure 6.12: New path to destination point.

In the presented scenario, the OS vessel encountered a crossing situation with the TS approaching from the starboard side. Following COLREG recommendations, a detour maneuver involving only a course change was performed to avoid a collision. After the end of intervention of the proposed module in the OS path, the autopilot configured a new path, represented by a green arrow in the figure, originating from the robot's position at that instance to the destination point. Initially, the robot was not perfectly aligned with this path vector, leading to some deviation. However, as time progressed, the USV adjusted its course and aligned itself with the path vector, eventually closely following it to the destination point.

Although this maneuver appears simple from a path planning perspective, it can produce abrupt responses from control systems, particularly if the new path vector

is not aligned with the current orientation of the USV. This misalignment may lead to drastic changes in both velocity and course.

A more suitable maneuver, configurable in the autopilot, involves returning to the original path at a predefined angle. This type of maneuver is pictured in Fig. 6.13, where the return angle was set to 45° .

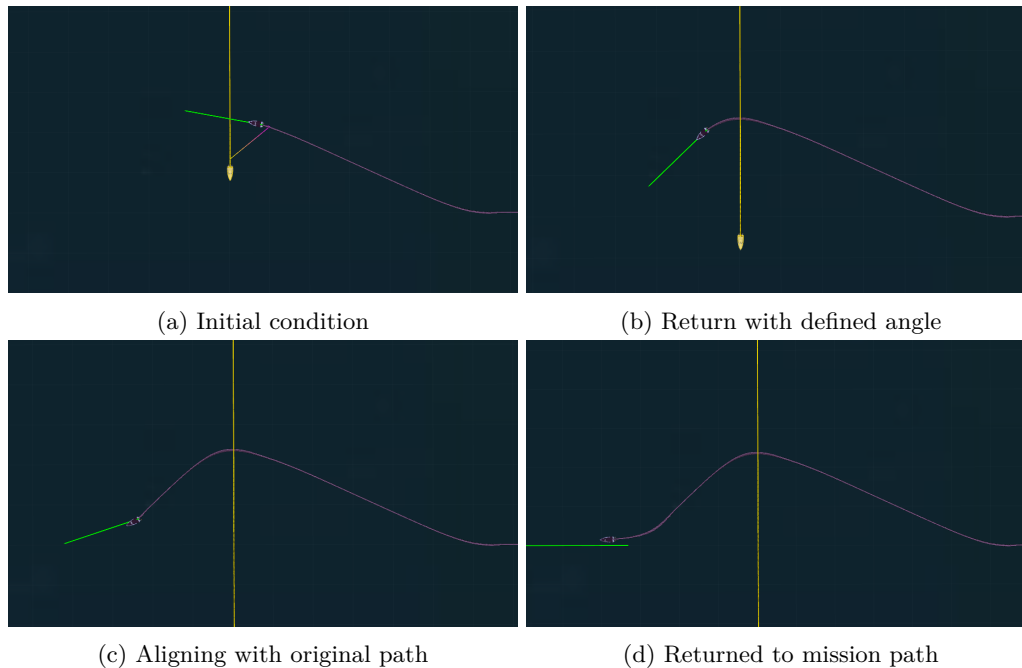


Figure 6.13: Return to the original path with an angle.

The moment at which the collision avoidance module concludes its action is depicted in Fig. 6.13a. Following this, as shown in Fig. 6.13b, the autopilot assumes control and adjusts the path vector to establish a predetermined angle with the original USV path. The vessel continues along this adjusted path until it reaches the point where alignment with the original path begins, as illustrated in Fig. 6.13c. Once the USV is aligned and sufficiently close to its initially programmed path, this path is restored, thus completing the return maneuver.

The limit condition where the return angle is defined near 90° is presented in Fig. 6.14. Consequently, the autopilot executes the defined return angle, as shown in Fig. 6.14a. However, due to the high value of this angle, an overshoot can be observed during the alignment maneuver, as seen in Fig. 6.14b.

Furthermore, if the distance deviation of the USV from its original course is slight, the autopilot may initiate the alignment maneuver before reaching the predefined return angle. This happens because aligning with the original path is prioritized over adhering strictly to the set return angle.

A case where a third type of maneuver is requested from the autopilot is depicted in Fig. 6.15.

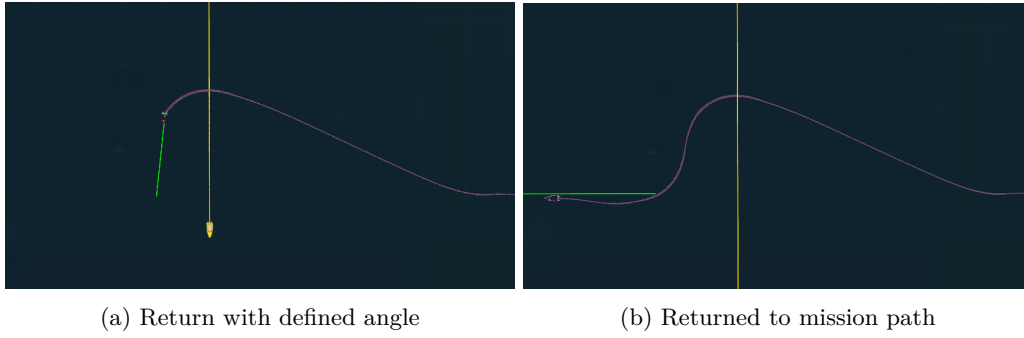


Figure 6.14: Return to the original path with a high-value angle.

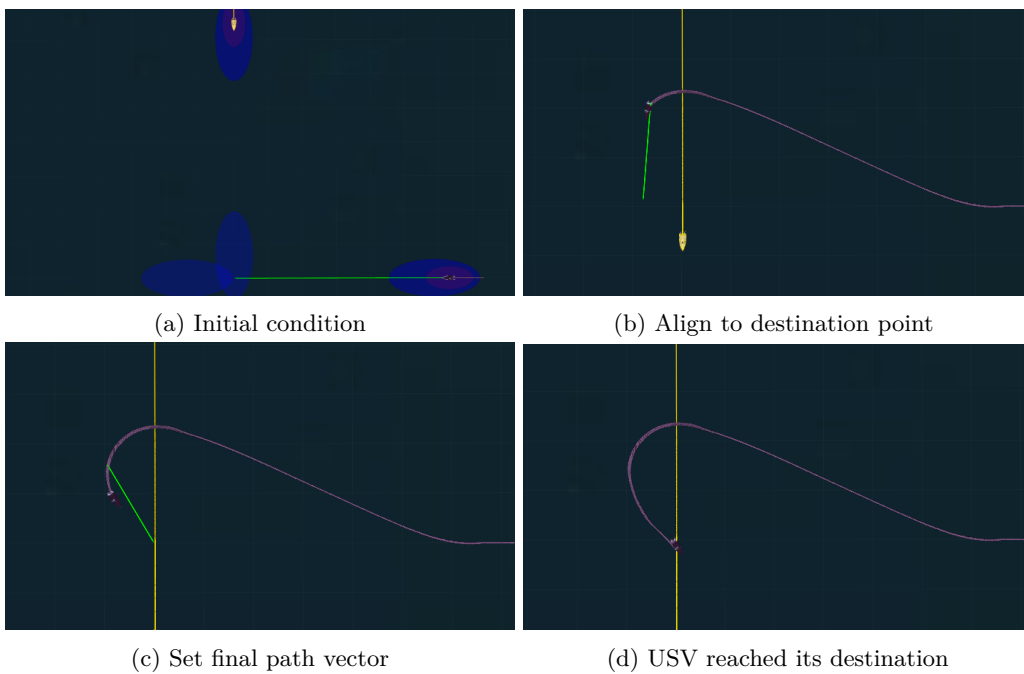


Figure 6.15: Return maneuver to destination point.

The initial condition is shown in Fig. 6.15a, where it can be observed that the destination point of the OS lies on the TS path. In this scenario, the OS is responsible for giving the way to TS. The most appropriate maneuver under these circumstances would preferably be the one of the second operational mode of the path replanning block, which involves decreasing velocity to allow the TS clear passage. However, the default operational mode of the path replanning block was employed to demonstrate the return maneuver and for cases where a change in velocity alone does not resolve the possibility of collision.

After the collision avoidance module concludes its actions, the autopilot assumes control. Initially, it aligns the OS towards the direction of the destination point, an action observable in Fig. 6.15b. Once the OS heading is aligned within the defined limits, the path vector is established based on the OS's position at that moment and the final point, as seen in Fig. 6.15c. From this moment forward, the return maneuver can be considered complete, as no further actions are undertaken, and responsibility for following the established path is transferred to lower-level controls. Fig. 6.15d shows the vessel entering the acceptance radius of the destination point, concluding the mission and illustrating the overall vessel path.

6.6 Evasive Maneuvers

The collision avoidance module developed in this work has shown effective results in identifying the risk of collision and implementing the necessary actions in accordance with COLREG regulations, as presented in Section 6.1. However, despite these capabilities, it is essential to include an additional security system to address immediate hazard situations. A possible scenario arises when the OS has priority over the TS, but the latter fails to comply with the COLREG and continues on its course despite the risk of collision.

In Fig. 6.16, a maneuver implemented to evade the collision caused by the previous situation is depicted.

Fig. 6.16a presents the moment before the initiation of the maneuver, where neither vessel is within the other's local maneuver zones; therefore, under normal circumstances, no action would be required as it is the responsibility of the TS to alter its course to avoid collision. However, Fig. 6.16b shows the moment when the TS vessel enters the OS local maneuver zone, producing a change in obstacle classification by the risk assessment block from safe to Maneuver stage 1, see Section 4.1.2 for more detail.

The immediate maneuver, consisting of reducing the velocity to its minimum, is implemented. Supposing the maneuver zones are correctly dimensioned using the respective coefficients, in that case, this maneuver should be sufficient to avoid a collision and allow the TS to pass ahead of the OS. When the risk of collision no

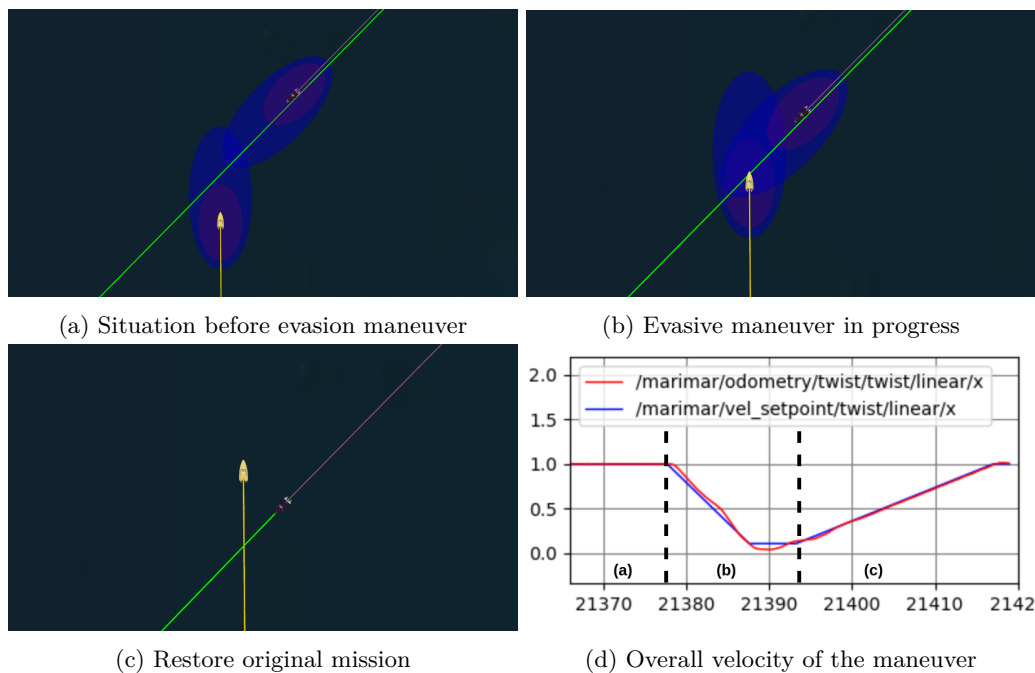


Figure 6.16: Evasive maneuver caused by Maneuver Stage 1.

longer exists, as determined by consulting the time to CPA poses, the maneuver is completed, and the USV resumes its mission and recovers its initial velocity, as shown in Fig. 6.16c. Fig. 6.16d illustrates the overall velocity changes during this maneuver.

In scenarios where a simple reduction in velocity is insufficient, and one of the vessels enters another's emergency zone, additional measures must be taken. This scenario is depicted in Fig. 6.17.

Although the OS has priority over the TS according to COLREG rules, the TS does not comply, leading to a hazardous situation. Fig. 6.17a displays the moment when the Cila enters Marimar's local maneuver zone. Consequently, the velocity of the USV decreases as depicted in Fig. 6.17b. However, the rate of velocity reduction is insufficient, causing the situation to be classified by the risk assessment block as an Emergency state. As a result, a more aggressive maneuver is outputted from the collision avoidance module for the USV control system to implement, detailed in Section 5.3.3. The path direction is adjusted to be parallel to the obstacle to avoid collision, and the velocity is forced to reach its minimum value. The OS follows this path at the minimum velocity until the CPA time parameter becomes negative, indicating that the risk of collision has disappeared. The original path is then restored, as can be observed in Fig. 6.17d. Fig. 6.17e shows the velocity profile of this maneuver, clearly indicating the moment when the more aggressive maneuver was applied, resulting in significant oscillations compared to the target velocity.

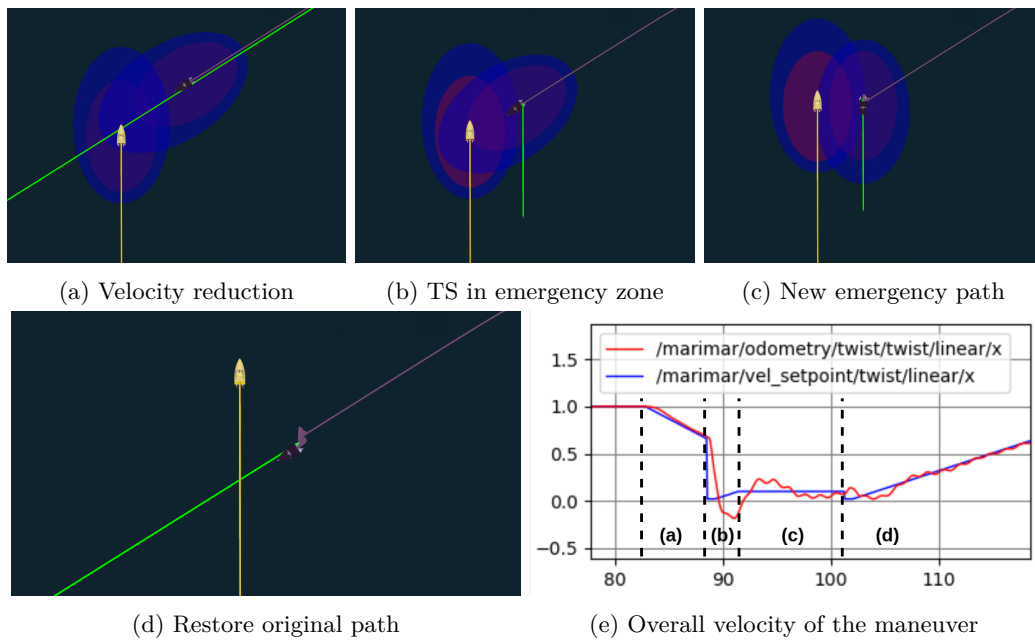


Figure 6.17: Evasive maneuver caused by Emergency state.

Chapter 7

Conclusion

Unmanned Surface Vehicles (USV) are increasingly seen as an effective way to handle dangerous or repetitive tasks for human operators, reducing their exposure to risk. However, these autonomous vessels must comply with the International Regulations for Preventing Collisions at Sea (COLREG), especially when navigating areas with human-operated vessels. This thesis presented a collision avoidance module that adapts COLREG, originally designed for human operators, for use in autonomous navigation systems.

The development of this module involved several areas, including collision detection, rule identification, and path replanning. Through a detailed review of existing studies, the most adequate methods were identified and enhanced, and in some cases, new approaches were proposed.

The developed module is based on a three-block architecture, including risk assessment, which uses methods like the Closest Point of Approach (CPA) combined with the ship domain to identify potential collision based on proposed zones; rule identification, which employs a three-step process to determine the appropriate COLREG rule to the marine scenario; and path replanning, which offers two strategies, one following COLREG recommendations and another prioritizing safety while minimizing deviation from mission's path.

Simulations were conducted using the Stonefish libraries integrated with the ROS framework to validate the collision avoidance module. The tests involved two vessels equipped with advanced control systems designed to execute path-planned missions.

The collision avoidance module was integrated into only one of these vessels, allowing for a controlled study of its performance under various navigational scenarios.

The module demonstrated its ability to effectively respond in situations where it was required to give way, following the COLREG. This included executing appropriate maneuvers during head-on, crossing, overtaking situations, and emergencies when the obstacle vessel failed to comply with the rules. Additionally, the module was tested for its ability to realign the USV back to its original mission path after deviations caused by necessary detour maneuvers. This capability is crucial for maintaining the effectiveness of the mission while ensuring navigational safety under the COLREG.

In summary, the developed module has successfully adhered to COLREG Part B, Rules 13 to 18, for which it was designed. Its integration into the existing control system enables the module to redirect the USV to a collision-free path under the respective rules. This capability ensures compliance with maritime regulations and enhances the safety and reliability of autonomous maritime operations. Importantly, it ensures safe coexistence between manned and autonomous vessels, enabling harmonious integration within diverse maritime environments.

7.1 Future Work

While the simulation results are promising, there are some opportunities for further improvement in the collision avoidance module. Currently, the module is designed to handle only one obstacle vessel at a time. Further improvements to the module could enable handling multiple obstacles, thereby enabling the generation of detour maneuvers that comply with the COLREG in more complex navigational scenarios. Alongside these improvements, there is room to augment the module's environmental awareness in the path replanning block. For example, incorporating information about physical constraints, such as those present in harbors, could significantly enhance the USV ability to navigate in more complex and variable environments. These enhancements would improve safety and increase the operational efficiency of the USV by enabling more precise and context-aware navigation decisions. Another essential step involves real-world testing to uncover issues that simulations might not reveal. This critical stage will help refine the module's performance, ensuring it is ready for practical deployment.

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Appendix A

ROS Framework

ROS is a set of libraries, functions, and tools that, as the name suggests, aims to be an operating system applied to a robotic system. It effectively presents features such as hardware abstraction, low-level device control, implementation of standard functionalities, message passing between various processes, and package management [71]. This framework is open source, and its main objective is to promote the reuse and sharing of research and robotic development codes. Thus, the files are organized into packages to encourage sharing and facilitate implementation in a new system [72]. Besides this primary goal, ROS has other advantages that justify its use [73]. It is multilingual, supporting programming languages like C++ and Python. Its modular structure favors scalability and allows for dividing tasks into various blocks, simplifying each task and thus building a more reliable and stable system and facilitating intervention to correct its operation if necessary. It tries to be as “lightweight” as possible to not interfere with the main algorithm and can be integrated with other systems. The communication between modules is done according to the peer-to-peer typology; thus, the modules must establish a connection based on the TCP/IP communication protocol for data exchange. Last but not least, it has a set of tools that allow building, testing, running, and exploring the various components of the system.

ROS utilizes a simplified message description language to define the data values essential for ensuring consistent and predictable communication structures [74].

A notable example is `navigation_msgs`, which explicitly provides message structures for navigation-related tasks, like sending goals to robots or receiving odometry information. This description language facilitates the automatic generation of source code for various target languages, enhancing the development process. ROS achieves modularity and interoperability by employing standardized messages like `navigation_msgs`, enabling different system components to communicate seamlessly and efficiently, thereby enhancing the system’s overall functionality and collaboration potential.

ROS architecture is built around the concept of nodes, which are processes that perform computation. Nodes communicate with each other by passing messages. A central tool known as the Master provides name registration and lookup to the rest of the system. This allows nodes to find each other and exchange messages seamlessly. Communication primarily happens through topics—named buses over which nodes exchange messages. Nodes can publish or subscribe to these topics, see Fig. A.1.

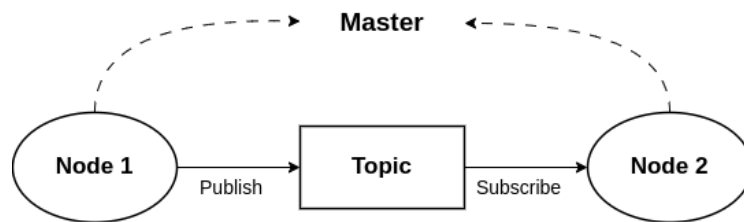


Figure A.1: ROS Architecture.

Within the modular and scalable framework of ROS, RViz stands out as an integrated visualization tool to enhance the system’s interactivity and data interpretation capabilities. As ROS supports a diverse range of functionalities from hardware abstraction to low-level device control, RViz provides a vital interface for visualizing the outcomes of these processes in real time. It allows users to visualize robots, sensor data, and environmental states, offering an intuitive and interactive way to monitor and debug complex systems. The tool’s adaptability complements ROS multilingual and modular nature, supporting various visualization formats like 3D models, paths, and point clouds. RViz provides a clear, customizable visual feedback loop for developers and researchers alike.

Appendix B

Stonefish Simulator

Simulation is a fundamental tool in developing and testing marine robotic systems. Given the specificities and requirements of a USV project, the Stonefish simulator is a suitable option.

Stonefish, a C++ library, combines an advanced physics engine with an optimized rendering pipeline. This combination provides realistic simulations of marine robots, supported by the core functionality of the Bullet Physics library [75].

One of the most significant benefits of Stonefish is its advanced hydrodynamics calculation based on the actual geometry of bodies. This allows for a more precise approximation of hydrodynamic forces and accommodates impossible effects using symbolic models. The rendering pipeline, designed from its inception, offers a realistic visualization of the atmosphere, ocean, and, most importantly, the underwater environment. Special attention has been paid to the latter, incorporating effects such as wavelength-dependent light absorption and dispersion.

Another crucial aspect is its integration with ROS. Stonefish can be used autonomously or in combination with the ROS package, which implements a standard simulator node, loading the simulation world from an XML description file, see Fig. B.1. This simulator node effectively manages interaction with ROS through messages and services. The XML parsing function can also be applied to customize the simulation as described next.

The XML file must comply with Stonefish documentation standards, and configuration begins with environment setup, an oceanic environment for marine robots.

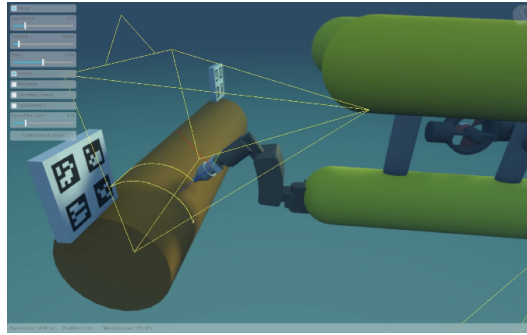


Figure B.1: GIRONA500 robot in Stonefish simulator [75].

Key parameters include density, impacting object buoyancy; viscosity characteristics, influencing the motion and resistance of objects under water; and turbidity, affecting visibility beneath the water's surface. Moreover, the configuration can extend to oceanic conditions like wave heights, ocean currents, and temperature variances.

To ensure a realistic physical simulation, materials used in simulation are defined. Properties such as density, restitution coefficients, and friction coefficients determine the behavior of interactions between simulated objects. For example, density affects an object's buoyancy in water, while friction coefficients influence how objects slide over each other.

Besides the physical characteristics of materials, the visual ones are also important as they influence the appearance of objects and how sensors perceive them. Parameters that can be defined include color and texture, reflection and refraction, brightness and roughness, transparency, and light absorption and dispersion.

After an environment and its materials are defined, the robot can be constructed through elements called links and joins.

Links refer to the individual parts of the robot, such as the robot's body. Each link has an associated material and a geometric shape that result in characteristics such as mass, center of mass, and moment of inertia, influencing its dynamic behavior in the simulation. Joints represent the connections between links. They define how the links interact and move relative to each other. There are three types of joints: fixed, which keep two links in a firm relationship; rotary and prismatic joints, which allow respective movements between connected links. Starting from a `base_link`, the entire robot is constructed by combining joints and links, allowing the recreation of robot models with detail and precision that faithfully reflects the design and behavior of the actual robot in the simulated environment.

The simulator allows the integration of numerous sensors, which can be categorized into three main groups: joint sensors, link sensors, and vision sensors. Joint sensors are dedicated to monitoring the inertial states of the joints, including rotary encoders, torque sensors, and 6-axis force-torque sensors. Link sensors are designed

to measure values associated with the robot's movement or environmental conditions, containing devices such as gyroscopes, accelerometers, inertial measurement units, GPS systems, compasses, and Doppler velocity logs. Finally, in the group of vision sensors, in addition to color and depth cameras, various types of sonars are included to assist in underwater perception and mapping.

Regarding actuators, the Stonefish simulator distinguishes between those intended for links and joints. Joint actuators, such as servomotors, apply torque or force between two links, allowing precise articulated movements. On the other hand, link actuators are designed to apply force or torque directly to the link, influencing its movement or position. In this category are propellers, suitable for operation in the atmosphere and maritime context, thrusters, and the variable buoyancy system (VBS). Additionally, the simulator includes light, allowing the simulation and testing of vision algorithms and the recreation of images with a realistic look under various lighting conditions.

In summary, Stonefish offers a unique combination of realistic physics, high-quality rendering, ROS compatibility, and customized simulation.