Collision avoidance of autonomous surface vessels considering proactive COLREG compliance

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How the concept of the ship domain and arena can be applied in a collision avoidance framework of ASVs

Collision avoidance of autonomous surface vessels considering proactive COLREG compliance

by

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to obtain the degree of
Master of Science
in Mechanical Engineering
at the department Maritime and Transport Technology of faculty Mechanical Engineering of Delft University of Technology,
to be defended publicly on Thursday July 18, 2024 at 11:00 AM.

Student number:	4490169	
MSc track:	Multi-Machine Engineering	
Report number:	2024.MME.8956	
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Preface

Dear reader,

About 9 years ago I started a new chapter of my life, beginning my bachelor of Mechanical Engineering at the TU in Delft. Having just turned 17 after I graduated high school, I felt ready to move on to this next step in life, but my first year at uni let me know that I was in for a rude awakening. The change in effort I had to put in to succeed at the TU compared to high school was too much for me the first time around, and I quit my bachelor in February. For the next 6 months, I took time away for myself and worked a job over the summer. I thought a lot about what I wanted in life and felt like this period thought me a lot about myself as a person. By the time September came around again, I was more determined than ever to make this a success and prove to myself I was capable of completing this Bachelor. The second time around, things went a lot smoother. I felt more comfortable throughout the year and felt like I was ready to deliver what was expected from me. Three and a half years later I graduated and I had proven to myself and my family that I was capable of completing my goals if I set my mind to it.

2020 was one of the craziest years of my life, filled with ups and downs. The Covid-19 pandemic took a big toll on society and me as well. None of us ever expected to be forced to study from our room due to a pandemic, but there was nothing we could do. I also started the master track Multi-Machine Engineering in 2020, making it even harder to focus on this without being allowed to go to university. I ended up completing the first year of the track pretty smoothly, for which huge gratitude goes out to my fellow students that I worked with on projects throughout this year. In 2021 I met Vasso, who was so supportive and helpful throughout the research assignment I did with her. After performing a literature assignment with another department, I knew I wanted to do my master's thesis in Vasso's department and with her guidance. She proposed a couple of potential projects, and the challenge on collision avoidance of Autonomous Surface Vessels immediately caught my eye. In October 2022 I started working on this project, being guided by Vasso and Tasos, who have been so helpful throughout this. Even though Tasos was working hard on his own PhD, he always ensured he took his time to help me with any potential struggles and he was always available to guide me when I needed it. This meant more to me than he probably knows, and without his help, I could have never achieved my goals.

A master thesis turned out to be a bigger project for me than I had ever worked on in my life. Many times throughout this work I felt stuck, was unsure how to continue, and at times felt so lost to the point where I was unsure if I was capable of doing this. Tasos and Vasso were so supportive throughout these tough times and they have guided me so well to not only achieve bigger goals with this research but also develop myself as a person, being ready to face challenges I would not have deemed possible in the past. Even though this thesis took longer than I would have hoped, I am proud of how far I have come and of the work I have delivered, and I have certainly come to agree with the statement that struggle makes you stronger. I owe Tasos, Vasso, and Laura, who was of big help to me in Vasso's absence, a huge thank you, without you I certainly would not have been able to complete this work.

Finally, I want to give a special thank you to Karel, Idriss, and Jurrian, the 3 friends for life I made throughout these 8 crazy years. Whether it was advice on a project or report, or just a simple game night to blow off some steam and enjoy ourselves, they have been a major support for me throughout all these years, for which I am forever thankful. I will take some time off now to precisely figure out what the next step will bring for me, but I am convinced it will be engaging and challenging. I am proud of the work I have put into this thesis, but mainly I am proud of the way I have developed myself as a person and I am proud of the people I have in my corner. Without my friends, my family and my supervisors I could not have achieved this, so a major thank you to all of you. I hope you enjoy reading this finalized report of my journey.

D. J. J. Oudshoorn
Delft, June 2024

Executive Summary

Automation has been a primary point of attention, not only in the maritime sector but also in other industries. The use of autonomous vehicles has increased rapidly in recent times, and ASVs have gained increased attention due to the potential increase in efficiency, safety, and the decrease in operational costs. There is a long way ahead till the implementation of ASVs onto waterways, but recent applications of Rolls-Royce, MUNIN, DNV GL, and YARA have shown promising results regarding the implementation of ASVs. The rules of the sea, the COLREGs, were implemented in 1977 and were constructed to display the rules that all vessels need to follow while seagoing. The COLREGs provide detailed and comprehensive rules about the actions that need to be taken by vessels, but the implementation in the framework of ASVs has proven to be a challenging task. Many rules are unquantified and subjective, making it difficult to translate them into control outputs of ASVs.

Many steps have to be taken before ASVs can be implemented onto waterways. The objective of this research is to help bridge these gaps, by precisely and thoroughly defining the COLREGs in collision avoidance of ASVs and sequentially implementing these into a collision avoidance framework. Existing collision avoidance algorithms have evident shortcomings, either in the implementation of the COLREGs into the framework, or due to issues in the computational complexity.

To reach the desired objective, firstly a literature review is performed to elaborate on the state-of-the-art and find the apparent gaps in the existing research. Afterward, the COLREGs are dissected using different variables. Then, the concept of the ship domain and the ship arena is elaborated and the approach to designing the domain and arena for this research is shown. Finally, the implementation of the algorithm is provided and the required results to determine the algorithm's performance are assessed.

Literature review

Collision avoidance has been researched both in the maritime sector and in different sectors where collision avoidance needs to be implemented: Autonomous Aerial, Ground, and Underwater vehicles. Compared to these other sectors, the actual implementation of ASVs is still fairly unknown, and much more progression has been made in different sectors.

In the research of the existing research on ASV collision avoidance, the primary criteria that were analyzed are: Whether the research considers vessel-to-vessel situations or also considers multi-vessel situations, which of the COLREGs were implemented and whether the research was validated by simulations or experiments. Finally, the kind of vessel model used in the research was analyzed, the control method was reviewed and the shared information scheme between the ASV and obstacle vessels was analyzed. The lack of complete COLREG compliance in the state-of-the-art is seen as a massive gap, as well as the strictly reactive nature of existing algorithms. The work performed by Thyri et al. [1] is assumed to be the state-of-the-art in collision avoidance of ASVs using the Velocity Obstacle algorithm, and a comparative study to this research is performed.

Collision avoidance algorithm design

The COLREGs are classified based on the relative bearing β_r and the relative heading ψ_r of the ASV and the obstacle vessel, assigning a specific traffic role and encounter scenario to the ASV for every possible combination of these 2 variables. The concept of the ship domain and the ship arena is explained and the existing approaches are provided. Based on the shortcomings in existing research, an accurate and versatile approach is presented for both the domain and arena, readily implementable in the collision avoidance framework of the ASV.

The baseline algorithm used is the Velocity Obstacle algorithm, which is thoroughly explained by Kuwata et al. [2]. To obtain the edges of the collision cone, lines are drawn from the position of the ASV through

the tangent points with a circle that circumscribes the irregular shape that arises from the Minkowski sum of the ship domain of the ASV and the obstacle vessel. A 3-degree-of-freedom kinematic model is adopted for the ASV and the required information about the ASV and the obstacle vessel is assumed to be available. For every possible encounter situation where the ASV is forced to give way to the obstacle vessel, a preferred passing side is generated through the COLREGs. This preferred passing side is implemented in the control framework by generating a cross-product of the relative position and the relative velocity between the ASV and the obstacle vessel for each candidate velocity. The COLREG incompliant velocity candidates are blocked out, as well as the candidates that lie within any of the collision cones.

Experimental assessment of the collision avoidance algorithm

Finally, the designed collision avoidance algorithm has been assessed through several simulations. Batch simulations are performed to show the compliance with the different COLREGs that consider vessel-to-vessel simulations, and the ASV's target position and starting position shift by 10 meters for each of the simulations. These batch simulations are also performed running the algorithm of Thyri et al. [1], to display the differences and the contribution of this research. This comparative study displays that the newly developed algorithm shows significant improvement in the time that the ASV needs to reach the target position and also in the total amount of heading deviation, showing that the algorithm handles the encounter scenarios in a more proactive way. Complex scenarios are performed to display the adaptability and robustness of the developed algorithm in multi-vessel scenarios.

In summary, the results of the thesis display that the algorithm guarantees full COLREG compliance and adequate collision avoidance for each of the performed simulations. The inter-distance between the ASV and the obstacle vessels is always bigger than the predetermined minimum safe distance and the eye test shows us that the COLREGs are always respected. Possible angles for future research would be a more concise definition of the safe passing distance and a further developed vessel model, accounting for limitations in the movement of the ASV in determining the ship domain and arena.

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1

Introduction

The need for automation and the number of applications involving autonomous machines have been increasing rapidly in today's society. Robots being used in several applications, computers that can learn and process information at a rate that would previously be unthinkable, and self-driving vehicles are just a few examples of the notable growth of automation in today's society. Automated, unmanned systems are becoming an integral part of everyday life, typically employed to perform repetitive tasks that are too tedious for humans quickly and efficiently. Most of these autonomous machines are designed to operate in structured environments where the surroundings do not vary considerably [10]. Automated surface vessels (ASVs) have been a focal point of attention in recent decades, as ASVs have the potential to drastically improve the efficiency, safety, and reduction of calamities on waterways. The shipping industry has been growing continuously, and maritime traffic is becoming denser in many navigable waters including ports, waterways, bays, etc. [11] [12]. The implementation of autonomous vessels has the potential to lead to improved usage of fuel compared to human-operated vessels, could lead to increased efficiency compared to human-operated vessels, and could lead to a significant improvement in safety among waterways, considering that multiple studies have reported that around 75-96% of marine accidents are caused by or are in some way related to human factors [13], [14], [15]. The European Maritime Safety Agency reported that the amount of maritime accidents is continuously increasing, and collisions and groundings are still the main reasons for these calamities, representing 31% of them in 2018 [16]. Therefore, increasing navigational intelligence and implementing automation can be considered the best way to improve maritime safety. Automation in the maritime industry would also lead to less subjective experiences because the decisions of a sailor would no longer play a role in the decision-making process. Since the required information on the states of obstacle vessels is more and more easily obtainable, the risk of collision with obstacle vessels can accurately be computed, which is crucial for the safety of navigation [17]. Therefore, autonomous surface vessels are expected to be the next major step in the shipping industry [18]. However, developing a fully autonomous guidance system that works in any unstructured and unpredictable environment is a challenging task that requires robust and precise control strategies [10]. In this first chapter, the background of the problem is discussed extensively, where the COLREGs and the concept of the ship domain and arena are also explained. The outline of the thesis is then provided.

1.1. Background

This thesis aims to incorporate a precisely defined concept of the ship domain and ship arena into the Velocity Obstacle framework to overcome the apparent shortcomings of this algorithm, which mainly lie in the reactive nature. This section provides the required background knowledge regarding the different subjects of this research and presents some general background information on autonomous vehicles. This section also presents the current applications of ASVs and provides the step-by-step path towards the realization of ASVs onto waterways. Finally, this chapter elaborates on the rulebook of the sea, the COLREGs in short.

1.1.1. Autonomous vehicles

Automation has been a growing research focus in multiple sectors, not just the maritime sector. The number of applications in which unmanned aerial vehicles (UAVs), autonomous ground vehicles (AGVs), and in the last decade or so even autonomous underwater vehicles (AUVs) have been applied and have shown promising results. Autonomous vehicles have provided the ability to perform operations that would be impossible for humans, and in a very impressive manner. Efficiency in certain applications could potentially be increased and with further research in collision avoidance, improved safety could end up being one of the major advantages of this transition towards autonomous vehicles.

Unmanned aerial vehicles (UAVs) have been gaining interest and have shown a promising evolution over the past decade or so [19]. UAVs are being used in the agricultural business to help manage farms, are being deployed for environmental monitoring, and are being used in search and rescue missions. Mohsan et al. [20] report that UAVs are also being deployed for military purposes. They play an integral role in surveillance missions and several countries use drones in their defensive strategic plans. They are also being deployed to detect enemies and for border control, since unmanned aerial vehicles are reliable, versatile, and can be used to monitor any potential movement in illegal areas.

Autonomous cars have gained significant interest as a solution to driver errors, which are the lead cause of traffic crashes and account for over 90% of all reported crashes [21]. AGVs have also been used for off-road operations, such as mining, construction, forest path maneuvering, and defense [22]. AGVs have been developed to be helpful in the agricultural business, for example, to optimize fertilizer usage or perform precise weed control [23], as cost reduction and safety improvements are some of the most desired advantages in this sector. Research towards self-driving cars has made significant and promising progress towards practical application and is regarded as a promising technology with the potential to reshape mobility and solve many traffic issues, such as accessibility, efficiency, convenience, and especially safety [24].

Autonomous underwater vehicles (AUVs) have been the dominating force in the exploration of the deep ocean, performance of various industrial operations, and military missions [25]. AUVs can bring great benefits to research the ocean floor or other operations at depths that might be unsafe or impossible to be performed by humans. AUVs have also been deployed for scientific purposes, such as marine biology studies and geological and archaeological surveys, search and rescue missions, air crash investigations, and the tracking and repairing of underwater cables [26].

Achieving the same level of automation in the maritime sector as in other sectors is not as straightforward as one might hope. The potential advantages of ASVs are evident, which is why the maritime sector has been working hard to continue overcoming challenges in implementing ASVs in mixed traffic. The operational costs shrink considerably when ASVs are deployed compared to human-operated vessels. There would be no crewmembers, and thus no payroll and ASVs are designed more efficiently since shipbuilders can eliminate accommodation structures such as the deckhouse and living quarters, as well as energy-expensive functions such as heating and cooking facilities [27]. The potential increase in the efficiency of ASVs compared to human-operated vessels can be elaborated through an example of barge convoys. Barge convoys controlled by a human operator can only contain a certain amount of barges since these are very complex systems. The human operator loses the ability to control the convoy once too many barges are added. An automated barge convoy can control convoys containing significantly more barges, which conveniently means a singular barge can transport more material. Autonomous vessels would also consume the available fuel more efficiently, since the movement would be much more constant, containing fewer braking and acceleration, leading to less fuel usage.

While we seem to have a long road ahead toward fully autonomous waterways, there have been some recent practical applications where autonomous vessels have been deployed. In 2018, Rolls-Royce opened an autonomous ship research and development center in Turku, Finland [3]. At the end of 2018, they successfully deployed an ASV called the Falco. The vessel detected objects using sensor fusion and artificial intelligence and avoided collisions. It also demonstrated automatic berthing with a recently developed autonomous navigation system. All this was achieved without any human intervention from the crew [3]. An image of the Falco making the world's first autonomous ferry crossing in 2018 can be seen in Figure 1.1.

Figure 1.1: The Falco making world's first autonomous ferry crossing [3]

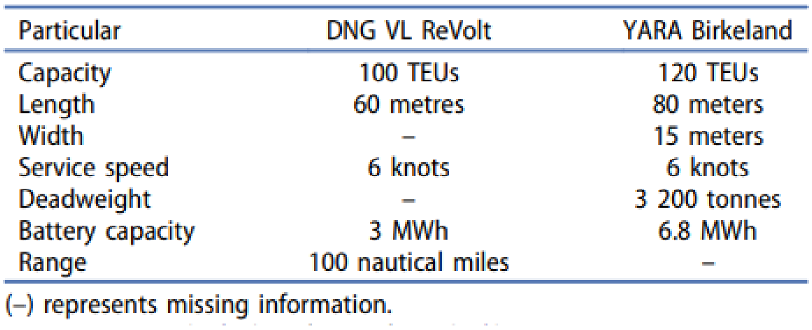
A few other worldwide leading projects in autonomous vessel development are based in Norway. Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) was the first project dedicated to the development of autonomous vessels [6]. A lack of seafarers was one of the main motivations for developing this autonomous ship technology. Over time, this project's interest shifted towards the economic and environmental benefits of ASVs. MUNIN concluded that there are no major obstacles toward the realization of fully autonomous vessels, but a few constraints exist [28]. DNV GL is a company headquartered in Norway, that developed an autonomous vessel prototype dedicated to short-sea shipping. The motivations behind this project were reducing pressure on land-based logistics networks, reducing operating costs, and improving safety in maritime operations [4]. The researchers at DNV GL have developed a vessel that is greener, smarter, and safer than conventionally fuelled and operated vessels, the ReVolt. An image of the DNV GL ReVolt can be seen in Figure 1.2.

Figure 1.2: The ReVolt, a vessel for the future [4]

The autonomous vessel YARA Birkeland is the world's first fully electric autonomous container vessel with zero emissions [5]. It became part of the Norwegian government's 'Maritime Opportunities' in 2015. It was operated semi-autonomously in 2020, and the autonomous vessel made its first test voyage with cargo from Herøya to Brevik in 2021. An image of the YARA Birkeland being deployed can be seen in Figure 1.3.

Figure 1.3: The YARA Birkeland, the world's first fully electric and autonomous container ship with zero emissions. [5]

The MUNIN project focused only on the feasibility of visions of an autonomous ship. As they found it feasible, DNV GL ReVolt and YARA Birkeland took the vision one step further and implemented the learning from the MUNIN project. Some practical information about the DNG VL ReVolt and the YARA Birkeland projects can be found in Figure 1.4.



Particular	DNG VL ReVolt	YARA Birkeland
Capacity	100 TEUs	120 TEUs
Length	60 metres	80 meters
Width	–	15 meters
Service speed	6 knots	6 knots
Deadweight	–	3 200 tonnes
Battery capacity	3 MWh	6.8 MWh
Range	100 nautical miles	–

(–) represents missing information.

Figure 1.4: Practical information about DNG VL ReVolt and Yara Birkeland [6]

Path towards full autonomy of ASVs

Existing research on manned and unmanned vessels has the potential to complement each other well, but this does not result in an immediate transition towards a fully unmanned era in the shipping industry [29]. Huang et al. [29] introduced six levels of control that can indicate which level of autonomy is implemented in collision avoidance. Level 0 refers to a situation where no machine is involved in collision avoidance. This level of autonomy is considered to be passed by now, as almost all ships are required to equip a certain navigational assistant system on board.

At level 1 control, the implemented machine offers support in conflict detection. It shares situational awareness of experts with the officers who are present onboard. They are mainly implemented as supportive systems to help onboard officers take evasive actions before it is too late.

At level 2 control, the assisting function of the machine with conflict resolution gets expanded. Some good examples of this are CTPA (collision threat parameter area) or CDS (collision danger sector) [30] [31]. These models do not work well in close-range encounters, because the vessel dynamics are usually ignored. The vessel is still controlled by human operators on board or in the offshore center at this level of control, and the machine is implemented to offer support.

At level 3 control, the control of the vessels is performed by machines, and the human operators authorize these machines to take the required actions. This requires a deeper interaction between the human operator and the machine, which is rarely discussed in the literature. This is a critical step in improving the autonomy of vessels and is also seen as a strong reason to convince human operators to trust machines.

At level 4 control, the machine takes full control of collision avoidance, and the human operators only supervise the machine whenever necessary. The machine has to be aware of emergencies in which the machine cannot guarantee safety, where human intervention would be required. The studies required for this level of automation are not yet included in most collision prevention studies in maritime research.

At level 5 control, the vessels are fully autonomous, and the human operators are strictly informed about what is happening and they cannot intervene. To achieve a fully autonomous vessel, long-term developments are necessary. The uncertainties of models and parameters become huge challenges, and how to comply with various regulations in complex scenarios is a question yet to be answered in detail. The interaction between human operators and the implemented machine gradually increases from level 1 to 5. In levels 2,3 and 4, the machine contains essential improvements in testing the reliability of autonomous systems, increasing the trust between the machine and the human operator and reducing the workload of the human operator. These steps are believed to be the key to the autonomous era, according to Huang et al. [29]. Propelling autonomous shipping is continuing existing studies on manned and unmanned vessels and filling the gaps that arise when the autonomy levels are increased.

The transition towards autonomous shipping comes with significant challenges and will certainly take some time to accomplish. In 2018, the CEO of Maersk Line, Soren Skou, stated that it is not expected that ultra-large container vessels will be permitted to sail without any human operators on board in his lifetime, because the economic advantages are marginal and there would be no driver of efficiency behind such a move [32]. This situation is completely different for smaller container vessels or other cargo ships. According to Oskar Levander, Senior Vice President of Concepts and Innovation, Digital & Systems of Rolls-Royce, the total transport cost saving for a smaller containership, general cargo vessel, or a bulker, can be reduced by 10-22 % in autonomous operations. This presents an obvious economic driver for the acceleration of automation of these vessels [33]. Levander also stated that the ultra-large container vessels only represent a small percentage of the total fleet in the world and a large part of the total fleet consists of smaller containerships, general cargo vessels, and bulkers. And even if the ultra-large container vessels would not be fully automated, implementing automation in certain areas could still significantly improve efficiency and safety.

1.1.2. COLREGs

The ongoing research concerning safety in autonomous maritime operations primarily focuses on autonomous vessels' obligation to follow existing regulations. The general guidelines that aim to be implemented in the motion control of autonomous vessels are the rules constructed by the Convention on the International Regulations for Preventing Collisions at Sea, the COLREGs. The COLREGs were adopted in October 1972 and were fully implemented by July 1977 [34]. The COLREGs consist of different sections, where section A presents some general rules regarding the application of the COLREGs and the responsibility of the human operators. Section B covers rules regarding vessels in sight of one another and the rules that apply in any form of visibility. Section C elaborates on some rules that consider the lights and shapes of vessels, which is crucial considering the lights can be the main form of communication between vessels in sight of one another. Section D elaborates on rules regarding sound and light signals, which can again be crucial in the communication between vessels and the prevention of the risk of collision. Section E of the COLREGs discusses some exemptions on the rules and section F considers the verification of compliance with the provisions of the convention.

The COLREGs provide very detailed and comprehensive rules for traffic at sea, but implementing these rules into the motion control of autonomous vessels has proven to be a complex and challenging task. The main reason for this is that the COLREGs were initially designed for vessels that are in some way controlled by one or more human operator(s), not accounting for the maritime sector pushing towards the implementation of autonomous or partly autonomous vessels at some point. The COLREGs were composed while barely quantifying any of the rules, assuming one or more expert(s) would be present on the ship, and they would be applying their expert knowledge to best comply with the rules in any encounter scenario. The lack of quantification in the COLREGs causes the implementation of the COLREGs in the motion control of autonomous vessels to be a challenging task. Will the COLREGs need to be amended so they can potentially be implemented in the motion control of autonomous vessels? Should the COLREGs be completely quantified? These questions are difficult to answer but represent a crucial bridge toward the motion control of fully autonomous vessels complying with the COLREGs to guarantee safety in any possible encounter scenario.

Hannaford et al. [35] presented a licensed deck officer survey regarding the potential amendment of the COLREGs and how these can potentially be implemented in the future of ASVs. The COLREGs are examined as barriers in the implementation of autonomous vessels and the current collision avoidance systems are not always fully compliant with the COLREGs [36], especially in complex encounter scenarios [37]. The future of the COLREGs is unknown and a limited amount of research exists that analyzes the implementation of the COLREGs to autonomous vessels in great detail [38]. Hannaford et al. attempted to fill this gap in the research by holding a survey among licensed deck officers, to provide valuable insights regarding the future of COLREGs and the implementation of the rules on the motion control of autonomous vessels. This is extremely relevant since the COLREGs were initially constructed to be implemented according to the knowledge of these experts and autonomous vessels will have to be operated by competent human operators in the early stages [39]. Some experts have identified the misunderstanding, interpretation, or incorrect use of the COLREGs as a main contributing factor to navigational casualties [40] [41]. Wang et al. [42] reported that poor theoretical knowledge of the COLREGs under human operators leads to an increase of 233.8 % chance of fatal accidents. The level of amendment in implementing the motion control of autonomous vessels has led to a wide discussion. Some researchers believe the COLREGs should be changed significantly [43], some researchers think the COLREGs should be slightly amended [38] and some researchers believe that the autonomous vessels should simply comply with the existing COLREGs since the first wave of autonomous vessels will be applied in mixed traffic regardless [44]. The biggest issue of applying COLREGs to the motion control of autonomous vessels comes from the fact that most COLREGs are very situation-dependent. Many subjective terms like ‘early’ and ‘as soon as it becomes apparent’ are used in the rules, making it difficult to apply them in an autonomous motion controller. Another apparent issue is that most COLREGs provide required actions in situations where 2 vessels are present, so-called vessel-to-vessel situations. Extending this to multiple vessel encounter scenarios is not as straightforward as one might think [37]. The reason for the survey of Hannaford et al. is that the licensed deck officers have first-hand experience with practicing the COLREGs and would likely be the first remote control operators of autonomous surface vessels [45]. Hannaford et al. concluded their survey with the fact that the in-depth research regarding potential solutions to overcome the barriers to implementing the COLREGs into the motion control of autonomous surface vessels is very limited.

Hannaford et al. [35] also concluded that most licensed deck officers that participated in the survey prefer the original COLREGs to the proposed amended versions for most of the rules. This could potentially reflect the common acceptance that the maritime industry is slow to change [46]. Since automation has been kept at bay by industry concerns, this might show that some participants were not willing to accept automation, and it shows that some human officers are hesitant about autonomous shipping [47] [48]. However, the results could also just display that the participants were not agreeing with the amendments made by Hannaford et al., and not that they were completely against adjusting the rules in general. Most participants seemed to be against quantifying the COLREGs, which still leaves the challenge of implementing the rules in motion control of autonomous surface vessels unsolved, and some amendments to the rules may be necessary before this is possible. Undoubtedly, mariners must be prepared for the future with the implementation of autonomous vessels and the impact this will have on compliance with the COLREGs.

1.1.3. The ship domain and arena

The ship safety domain, or ship domain in short, is a term that has been widely used in research on collision avoidance of autonomous surface vessels [8], and generally represents a safe distance around a vessel that is meant to be kept clear of target vessels at any time. Papers that provide overviews and applications of ship domains are numerous, but the number of cases where the concept of the ship domain is implemented in practice is minimal [8]. Any violation of the ship domain is interpreted as a threat to safety [49] and should be avoided at all costs. Ship domains can generally be divided into three categories: domains developed by theoretical analyses, domains based on expert knowledge, and domains determined empirically, although these are not mutually exclusive, as Dinh and Im [50] displayed. Empirical ship domains have mainly been applied in determining the potential capacity of local waterways and not so much for vessel-to-vessel encounter situations, because these models are simpler and require more exact knowledge of parameters. Knowledge-based and analysis-based models have mostly been applied to more complex problems, and their scope is much wider.

The so-called ship arena presents an area around the ASV that provides an ‘action area’ [51], which is by default much larger than the ship domain. The dimensions of the ship arena are not predetermined and a separate ship arena is generated for every obstacle vessel the ASV encounters. Whenever the obstacle vessel violates the correspondent ship arena, a warning signal is sent to alert the control system that a collision avoidance alteration has to be performed. Only if the future positions of the respective target ship lead to infringement of the ship domain, the course and/or speed are altered [51]. If the ship domain is not entered, the collision is assumed to be successfully avoided, and there has not been any risk of collision for that particular vessel-to-vessel encounter. The ship domain and the ship arena can have many different shapes and dimensions, and the dimensions could or could not account for the velocity dependency of the ASV and the obstacle vessel. A more detailed overview of the existing applications where the concept of the ship domain and arena are applied and the elaboration on the dimensions and shape of the domain and arena throughout this research is provided in the according chapters. A basic schematic overview of the domain and the arena can be seen in Figure 1.5.

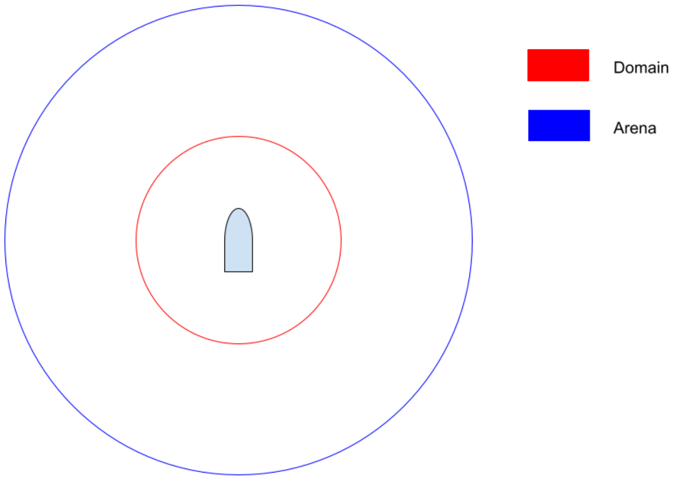


Figure 1.5: A basic example of a circular ship domain and arena surrounding the ASV

1.2. Thesis outline

Chapter 2 contains an extensive explanation of the state-of-the-art regarding collision avoidance and motion control of autonomous vessels and explains why collision avoidance is such an important step towards implementing autonomous vessels onto existing waterways. Chapter 3 specifies the COLREGs and presents an approach to transform the relevant COLREGs into constraints for the motion control of the ASV. Chapter 4 provides an extensive overview of the role of the ship domain in collision avoidance and presents a well-defined approach to determine the shape and dimensions of the ship domain. Chapter 5 presents the role of the ship arena in collision avoidance and displays how the shape and dimensions of the ship arena are determined and defined. Chapter 6 presents the different methods that are proposed to obtain the finalized control algorithm. Chapter 7 presents the results of the performed simulations to prove the robustness and effectiveness of the designed control algorithm. Finally, chapter 8 provides conclusions from the research based on the results. Recommendations for future research are also provided based on the drawn conclusions.

2

Collision Avoidance

To realize an innovative collision avoidance algorithm, firstly existing research in this field needs to be consulted. Since it was agreed that autonomous vessels must be at least as safe as manned vessels, the approaches to autonomous collision avoidance have widely been discussed in the literature [52]. The current state-of-the-art in collision avoidance for ASVs is discussed in this chapter and the different applied control methods are evaluated alongside their advantages and shortcomings. The gaps that arise from this existing research are pointed out, providing the areas to target in this research.

2.1. Collision avoidance of ASVs

Many different control methods have been used in existing research on collision avoidance of autonomous surface vessels. This section provides an overview of the different applications of various control methods in the collision avoidance of ASVs and discusses the apparent shortcomings of the methods that have been applied. The different control methods are discussed somewhat chronologically while grouping collision avoidance algorithms with a similar nature. The obtained shortcomings are used to bridge the gaps in the state-of-the-art to the scope of this research.

Some of the earliest approaches to collision avoidance of ASVs are based on heuristic algorithms [53], [54] [55], such as genetic algorithms (GA) or rule-based systems. GA is a commonly applied control tool in collision avoidance of ASVs, [56], [57] and it searches for the optimal solution by simulating the natural evolution process, resulting in the shortest route that guarantees collision avoidance. Genetic algorithms are inspired by the natural evolution process where only the fittest organisms have a chance for survival. The algorithm starts looking for a solution by generating a random population of possible solutions and selections are made to eliminate the least suitable solutions. The algorithm keeps running the selections while adding to the successive possible solutions that are closer and closer to the correct result. The main advantage of the GA method is the possibility of fast and global stochastic searching for optimal solutions. In addition, the algorithm is easy to implement and can be used to solve complex problems. Due to the random nature of searching for solutions, the algorithm reduces the risk of the local minima problem. The potential disadvantages of applying the genetic algorithm are that it can be a slow and expensive method that is difficult to optimize due to its nature. Ning et al. [56] proposed path planning with global search capability realized by multi-objective decision theory combined with a genetic algorithm. Wu et al. [58] proposed a multi-vessel collision avoidance strategy for ASVs based on GA in a congested port environment. The fitness function and the basic parameters of the GA are designed to construct the collision avoidance system.

Fuzzy logic-based algorithms have been applied for the collision avoidance of ASVs since the early 2000s [59] and have been commonly applied over the last few decades [60], [61] because of their intelligent learning capabilities as they represent human-like thinking. Fuzzy logic methods are based on the evaluation of input data depending on fuzzy rules that can be determined by using the experience and knowledge of experts. The fuzzy controller processes data about the surrounding environment and makes decisions based on this. At first, the incoming data is fuzzified, e.g. assigned to the right membership function. Then, a data evaluation is performed based on if-then statements and the defuzzification process determines the specific system output values. The method can be used for both static and dynamic obstacles but is heavily dependent on experts' knowledge in unknown environments. It is an easily implementable algorithm, but additional algorithms might be required in certain cases. Fuzzy logic-based approaches are not viable in complex, multi-vessel encounter situations, where unexpected movements of the target vessels could occur [62]. Perera et al. [60] proposed a fuzzy logic-based decision-making system for collision avoidance of ASVs under critical conditions. Hu et al. [61] proposed an approach where the learning method is based on Fuzzy Case Base Reasoning containing basic expert knowledge, and the solutions to finding a new heading command were retrieved from this knowledge base.

Search-based methods, such as the A* algorithm and the Rapidly Exploring Random Tree (RRT) algorithm have also been employed in collision avoidance of ASVs since the late 2000s [63]. The A* algorithm [64], [65] divides the known area into individual cells and calculates the total costs of reaching the target for every one of them. It focuses on finding the shortest path to a destination while avoiding obstacles, assuming both the environment and the location of the obstacles are known in advance. A large amount of computation is required for large areas or areas including many obstacles. He et al. [64] proposed a dynamic anti-collision A* algorithm for multi-ship encounters to enable collision avoidance with known moving obstacles considering time factors. Liang et al. [65] proposed an improvement to the traditional A* algorithm by including the safe distance to the shoreline rather than setting the danger zones manually. The RRT algorithm [66], [67], [68] is a sampling-based method. Any node in the spatial domain is randomly determined from the initial point, and depending on the direction of movement and the maximum length of the section, the intermediate node is determined. If any obstacle is detected between waypoints, further route calculation in that direction is completely ignored. This method is easy to process and always ensures finding a collision-free path in any unknown environment. It is noted however that this method might not always be efficient when the path to the target leads through a narrow opening or gap. It also requires information about large areas of the environment, which is not always possible in practical implementations. Additionally, the obtained path is suboptimal, which requires the use of extra optimization algorithms. Zaccone [67] proposed an RRT-based optimal path-planning algorithm to plan the path in real-time and to guarantee adequate collision avoidance. Enevoldsen et al. [68] proposed a COLREGs-informed RRT approach, where the RRT algorithm was integrated with novel sampling strategies to minimize the deviation of the length of the path. The A* algorithm and the RRT algorithm are still not readily applicable to include all COLREGs and they might lead to the controller failing to obey certain rules in multi-vessel scenarios.

The particle swarm optimization (PSO) method is another method that has been applied to path planning and collision avoidance of autonomous vessels since the early 2010s [69]. PSO is a population-based stochastic optimization algorithm motivated by the intelligent collective behavior of some animals such as flocks of birds or schools of fish [70]. This method optimizes a problem by iteratively trying to improve a candidate solution about a given measure of quality [71] [72] [73]. The two main groups of PSO alternatives consist of variations using a local neighborhood (local best), and those using a global neighborhood (global best) [74]. With PSO, a population of candidate solutions moves through the search space seeking optimal solutions to given problems. Each particle's movement is influenced by its own best-known position and the global best-known position found by any particle in the swarm. By iteratively updating their positions based on these influences, particles collectively converge toward the optimal solution. In the context of ASVs, each particle in the PSO algorithm can represent a potential trajectory or path for the ASV to follow. The position of a particle corresponds to a specific set of parameters defining the trajectory, such as waypoints, speeds, and headings. An objective function is used to evaluate the quality of the obtained solutions. PSO can provide approximate solutions to complex problems. However, a common trend with particle swarm optimization is that premature convergence might occur. Hu et al. [73] proposed a multi-objective optimization approach, where the particle swarm optimization algorithm is used to generate new paths, particularly when the obstacle vessel is in breach of the COLREGs. Zheng et al. [72] proposed a decision-making method for ship collision avoidance based on improved cultural particle swarm optimization. The PSO algorithm is improved by introducing the index of population premature convergence degree to adaptively adjust the inertia weight of the cultural particle swarm to avoid the algorithm falling into a premature convergence state.

The Artificial Potential Field (APF) algorithm is a popular approach in the path planning of autonomous vessels, reigning from the mid-2010s [36], [75]. The APF method assumes the presence of a repulsive field around the obstacle and an attractive area around the target. The resultant force is used to determine the direction the AUV would head to. Prior knowledge of the environment and the location of the obstacles is not required and both static and dynamic obstacles can be avoided. However, accurate obstacle detection is crucial for this algorithm to be successful. This method is easy to implement and computationally cheap, which makes it possible to control ASVs and avoid collisions close to real-time. The possibility of local minima and trap situations is seen as a big disadvantage of this method, however. APF is a very safe method that is rather simple to apply but is a reactive algorithm that is difficult to apply alongside traffic regulations, potentially leading to rule violations of ASVs. Lyu et al. [36] used modified APF to establish real-time path planning of ASVs complying with COLREGs. The APF contained a new modified repulsion potential field function and the corresponding virtual forces to address collision avoidance with dynamic and static obstacles, including emergency situations. Wang et al. [75] proposed a ship domain model for multi-vessel collision avoidance decision-making with COLREGs based on APF. The APF was mainly used for the path planning of the ASV but accounts for the speed and heading angle of obstacle vessels to judge them more accurately.

The velocity obstacle (VO) algorithm was first applied in 1993 by Fiorini and Shiller [76] and has since then been a popular approach for collision avoidance systems in dynamic environments [1]. The velocity obstacle method and its extensions are popular methods for collision avoidance in autonomous vessels [77], [78], [79], because they are computationally efficient and simple to apply. However, the VO algorithm is sensitive to uncertainty and has a reactive nature, making it challenging to apply alongside the COLREGs. The velocity obstacle algorithm generates a cone-shaped obstacle in the velocity space, which contains all the velocities that will lead to collision with the target vessel within a certain time. As long as the controller picks a velocity vector outside this obstacle cone, there will be no future collision with the according target ship [2]. The velocity obstacle algorithm assumes constant relative velocity, which is a critical assumption in implementing this algorithm. The computational load of the VO algorithm can become quite substantial, but since a single collision check accounts for collision avoidance at all future time points, VO is fast to compute [2]. The VO algorithm also extends well to high-speed operations with short reaction time, which is desired in collision avoidance. Another big advantage of using the VO algorithm for collision avoidance in the maritime sector is that it is relatively easy to incorporate the COLREGs into the VO framework because both the VO algorithm and the COLREGs are defined in the vessel's fixed body frame. The initial VO algorithm is reactive and may produce unfeasible decisions for slow applications like marine vessels, but incorporating the vessel dynamics into the algorithm can help overcome these shortcomings [78]. Kuwata et al. [2] proposed an approach for safe navigation complying with COLREGs using the VO algorithm, where the COLREGs were encoded into the framework naturally. Shaobo et al. [77] proposed a collision avoidance decision-making system for ASVs based on modified VO. A finite state machine was incorporated to handle the dynamic behavior of obstacle vessels and consider the actions taken by the obstacle vessels. Thryi and Breivik [1] proposed a partly COLREGs-compliant collision avoidance for ASVs using encounter-specific velocity obstacles, where they assigned an encounter-specific domain to the obstacle vessel and formed an additional VO for the generated domain. Generally, the VO algorithm provides a convenient framework for COLREG-compliant decision-making compared to other well-known collision avoidance methods, which is why it is applied in this research.

The reciprocal velocity obstacle (RVO) method [78] is an extension of the VO algorithm and introduces the idea of sharing the responsibility to avoid collision between the vessels. Instead of taking full responsibility, as specified by the VO algorithm, both vessels take 50% of the responsibility to ensure collision is avoided. RVO can ensure both collision-free and oscillation-free navigation [80] and takes the reactive nature of the obstacle vessels into account. This makes it an appropriate method for handling the problem of reactive collision avoidance. It can, however, only guarantee safe collision avoidance under certain circumstances. Kufoalor et al. [78] proposed a dynamic RVO method to deal with the uncertainty of the future behavior of obstacle vessels and to encourage dynamic obstacles to cooperate according to the COLREGs. The Optimal Reciprocal Collision Avoidance (ORCA) algorithm was generated to overcome these limitations. ORCA provides an appropriate condition for multiple agents, making it suitable for ASV collision avoidance. The Optimal Reciprocal Collision Avoidance method is mainly used for motion and path planning [80], but there is no existing literature where environmental conditions are taken into account in motion planning. ORCA is particularly well-suited for decentralized collision avoidance, where each agent independently computes its own velocity adjustment to avoid collisions while respecting the constraints of other agents. Zhao et al. [80] proposed a real-time collision avoidance learning system for ASVs, where they implemented the ORCA algorithm to make a plausible decision concerning collision avoidance while complying with the COLREGs, while simultaneously taking the reactive nature of the obstacle vessel into account.

Another group of popular methods in the motion control of autonomous vessels complying with COLREGs are methods using some form of model predictive control (MPC). MPC is a powerful control method that combines feedback control with dynamic optimization to find an optimal control action over the prediction horizon. MPC uses dynamic models for predicting future states and considers uncertainties, constraints, and objectives with a cost function to choose the optimal control action. Constraints of different natures can be combined in one scheme when MPC is used, which is a huge advantage over other control methods. The limitations in the application of MPC arise from deadlocks, due to the local nature of the computed path, and potential high computational demands, depending on the complexity of the problem at hand. Wang et al. [17] used distributed MPC of the path following to obtain the control layer of the autonomous vessel. Kufoalor et al. [81] used maritime radar tracking and considered the uncertainties that come with this application. They applied this alongside a collision avoidance method that was based on MPC. Kufoalor et al. [82] presented an approach using automatic identification system (AIS) data of other vessels and applied model predictive control for safe navigation and collision avoidance. Akdag et al. [83] aimed to improve the existing scenario-based model predictive control algorithms by including route exchange-based trajectory predictions and called it the informed scenario-based-MPC. This involved target vessels communicating their trajectory plans to vessels in the vicinity. Akdag et al. based their research on existing research proposed by Johansen et al. [37], where MPC was applied with a small number of control behaviors, to avoid numerical optimization and the associated computation of gradients that are inherent in conventional MPC. Ferranti et al. [84] used distributed nonlinear MPC but with communications to other vessels. Thanks to tailored interactions, the solution is the same as if the approach was centralized. Hagen et al. [85] proposed a method that facilitates simulation-based MPC. The main objective of the MPC is to compute modifications to the desired course and speed that lead to a COLREGS-compliant ASV trajectory. Tengesdal et al. [86] proposed the application of probabilistic Scenario-Based Model Predictive Control using an exemplary intent model, when statistics about traffic rules compliance and the next waypoint for an obstacle are assumed to be known. The researches of Akdag et al. [83], Hagen et al. [85], Tengesdal et al. [86] and Kufoalor et al. [81] provide extended research on the research proposed by Johansen et al. [37]. They all considered a finite space of control inputs, to limit the number of potential routes. Unlike typical MPC formulations, these methods do not identify the best action at every time step during trajectory generation. Tsolakis et al. [87] presented an approach based on Model Predictive Contouring Control, where the COLREGs are implemented. Safe navigation is guaranteed in mixed-traffic conditions, and they provided an ingenious approach to implement the COLREGs into the control framework.

Deep reinforcement learning (DRL) is another popular method in collision avoidance studies [88], [89] because it performs well in handling unexpected changes during the simulations. However, to control multiple states of a vessel using deep reinforcement learning, very complex neural networks might be required. DRL is a machine learning approach that combines reinforcement learning with deep neural networks so that agents can learn optimal behaviors through trial and error. The ASV operates in the maritime environment and maps the states into actions that minimize risk of collision while maximizing the progress towards a desired goal. Zhao et al. [88] proposed a COLREG-compliant multi-vessel collision avoidance algorithm based on DRL, where the proposed method directly maps the states of encountered vessels to steering commands of the ASV in terms of rudder angle using the Deep Neural Network. Chun et al. [89] proposed a DRL-based collision avoidance algorithm for ASVs, where the DRL was used to generate a safe path and determine the avoidance time with the most dangerous obstacle vessel in terms of collision risk.

An overview of the classification of some of the reviewed literature can be seen in Table 2.1, where the literature is divided based on the (dis)regarding of multi-vessel situations, what COLREGs have been considered and whether the research has been validated by simulations or experiments. Another overview is provided in Table 2.2, where the vessel model that has been used is presented, the applied control method is shown, whether information is exchanged between the vessels throughout the operation is judged and whether the algorithm is reactive or proactive is displayed.

Table 2.1: Overview of the aspects of different literature

	Vessel-to-vessel	Multiple vessels	COLREGs	Validated by
Tsolakis et al. [87]	✓	X	1-18	Simulations
Thyri and Breivik [1]	X	✓	13-15, 17	Simulations
Zaccone et al. [66]	✓	X	13-17	Simulations
Wang et al. [17]	X	✓	4-18	Simulations
Kufoalor et al. [82]	X	✓	2,5-8,13-19	Experiments
Akda et al. [83]	X	✓	13-18	Simulations
Naeem et al. [10]	✓	X	8,14	Simulations
Hu et al. [73]	✓	X	13-17	Simulations
Perera et al. [60]	✓	X	4-19	Simulations
Hagen et al [85]	✓	X	4-19	Simulations
Constapel et al. [57]	✓	X	13-18	Simulations
Tengesdal et al. [86]	✓	X	13-18	Simulations
Johansen et al. [37]	X	✓	6,8,13-19	Simulations
Lyu and Yin [36]	X	✓	13-17	Simulations
Chun et al. [89]	X	✓	13-17	Simulations
Ning et al. [56]	X	✓	4-18	Simulations
Campbell and Naeem [55]	✓	X	13-17	Simulations
Shaobo et al. [77]	X	✓	13-17	Simulations
Enevoldsen et al. [68]	✓	X	13-17	Simulations
Kang et al. [71]	✓	X	8,13-17	Simulations

Table 2.2: Overview of the aspects of different literature

	Model	Control method	Info exchanged y/n	R/P
Tsolakis et al. [87]	Kinematic	MPCC	No	Proactive
Thyri and Breivik [1]	Kinematic	VO	No	Reactive
Zaccone et al. [66]	Kinematic	RRT	No	Proactive
Wang et al. [17]	Linear Maneuverability	Distributed MPC	Yes	Proactive
Kufoalor et al. [82]	Kinematic and Kinetic	MPC	Yes	Both
Akda et al. [83]	Kinematic	SB-MPC	Yes	Proactive
Naeem et al. [10]	Kinetic and Kinematic	PID Control	No	Reactive
Hu et al. [73]	-	PSO	No	Proactive
Perera et al. [60]	Kinematic	Fuzzy logic	No	Both
Hagen et al [85]	Kinematic	SB-MPC	Yes	Proactive
Constapel et al. [57]	Kinematic and Kinetic	HA	Yes	Both
Tengesdal et al. [86]	Kinematic	PSB-MPC	Yes	Proactive
Johansen et al. [37]	Kinematic and Kinetic	MPC	Yes	Proactive
Lyu and Yin [36]	Kinematic	APF	Yes	Both
Chun et al. [89]	Kinetic and Kinematic	DRL	Yes	Proactive
Ning et al. [56]	-	Genetic algorithm	Yes	Proactive
Campbell and Naeem [55]	Constant linear	HA	Yes	Proactive
Shaobo et al. [77]	Constant linear	VO	Yes	Reactive
Enevoldsen et al. [68]	Ship domain	RRT	Yes	Proactive
Kang et al. [71]	Dynamic ship domain	PSO	Yes	Proactive

PSO = particle swarm optimization, RRT = rapid random tree, APF = Artificial potential fields, HA = Heuristic algorithm, VOM = Velocity obstacle method, DAA-star = Dynamic anti-collision A method

2.2. Risk assessment of ASVs

The collision risk measurement is essential for successful collision avoidance [90]. Without proper risk measurement, the ASV cannot recognize dangerous situations where a potential collision avoidance maneuver needs to be performed. It is important that the maneuver is performed proactively, to guarantee the ASV has collision-free routes available. However, performing the collision avoidance maneuver too early might lead to complicated situations and unnecessary additional encounters with other obstacle vessels.

One of the most commonly applied risk assessment metrics is the Closest Point of Approach (CPA), where the two widely accepted indicators are the Distance at CPA (DCPA), which shows the minimal distance at the moment of CPA, and the Time to CPA (TCPA), which displays the time until the ships reach the closest point of approach. The closest point of approach ensures that the algorithm steps in and computes a different route whenever the predetermined collision risk thresholds for the CPA components are passed. CPA is considered to be the most simple and effective way to predict an obstacle vessel's position and to estimate the relative risk of collision between 2 vessels [17]. The simplest application of the CPA concept only compares the DCPA value to a certain threshold for the minimum allowed DCPA [91], assuming both vessels maintain their current velocity. If the DCPA is lower than this safe passing threshold, risk of collision is deemed to exist. It was then concluded that only using DCPA is not a sufficient indicator to determine the risk of collision, as a low DCPA at some point in the far future does not necessarily imply an immediate risk of collision[91]. This is why Hu et al. [92] proposed that risk criteria should be in some way composed of both DCPA and TCPA. A big part of existing research combines DCPA and TCPA into one collision metric, the collision risk index [29]. Once the risk index exceeds a certain predefined threshold, risk of collision is deemed to exist and a potential collision avoidance maneuver needs to be performed. Determining these thresholds is usually based on experts' knowledge, however. More risk indicators can be included in the calculation of the collision risk index, such as the relative distance, relative bearing, ratio of speeds, ship domain, etc. Although there is no doubt about the usefulness of the CPA in a daily navigational routine, the CPA does not provide direct information about the parameters of an evasive maneuver [93]. The velocity vector is also assumed to be constant in CPA-based approaches, so this method still requires a time-consuming operation to find a feasible solution to a close-quarters situation [94].

Another widely applied risk assessment measurement technique is the ship domain. Compared with the

CPA-based method, where a circular safe zone around the ASV is considered, the ship domain sets different safe distances in all directions around the ASV [91], thus providing a more refined approach to risk measurement. This means that the ship domain, which embodies the safety zone around the ASV, can have an irregular shape and be of different sizes in different directions. However, as the safety range of vessels traditionally heavily depends on experts' knowledge, expanding this concept to apply it to ASVs has proven to be quite challenging. When correctly applied, the ship domain concept can help overcome the apparent shortcomings of CPA-based approaches [95]. One of the major weaknesses of the CPA approach is the inability to differentiate between the different passing sides. As Szlapczynski and Szlapczynska [8] rightfully pointed out, CPA-based methods may not be sufficient for estimating ship collision risk in some situations, and has some deficiencies such as the use of fixed safety distance and the incomplete consideration of relevant ship motion parameters. As the COLREGs state that a vessel is forced to give way to an obstacle vessel approaching from fore or starboard side, a fixed safety distance would lead to insufficient consideration for these differences, where a ship domain with an atypical shape could account for these differences. CPA-based algorithms have also proven difficult to apply to multi-vessel situations, which often occur in high-density waters [90]. Further elaboration on the concept of the ship domain/arena is provided in the following chapters.

2.3. Research gaps in collision avoidance of ASVs

As has been pointed out in the previous sections and has been indicated using the various tables presented thus far in this chapter (Tables 2.1 and 2.2), a big part of the existing research only covers specific vessel-to-vessel situations and it is not as easy to extend this to multi-vessel operations as some may think. Part of the existing research only considers a specific part of the COLREGs, which is undesirable as it may lead to incomplete frameworks and failure in certain situations. Big parts of the applied research algorithms are highly reactive, making it challenging to meet the demands of the COLREGs to act 'early' and 'in ample time'. The main control methods where this is an issue are the Velocity Obstacle algorithm and its extensions [1], [77], [2], [78] and the Artificial Potential Fields algorithm [36]. Other control methods that have been applied, such as MPC and its variations, have shown that separate constraints of different natures can be combined [87], [85], [83]. MPC is, however, very computationally expensive.

The COLREG compliance has also proven to be a challenging aspect of collision avoidance of ASVs. Svec et al. [96] claim COLREG compliance, yet they display results where the ASV crosses ahead of the obstacle vessel, which is not in line with the COLREGs. Kuwata et al. [2] claim that their approach is COLREG compliant, yet presented results where the ASV turns into a vessel approaching from its port side, leading to a dangerous scenario. Complete and consistent COLREG compliance is crucial for the eventual implementation of ASVs onto mixed waterways.

The risk assessment measurements in existing research where the Velocity Obstacle algorithm is applied mostly consist of CPA-based methods [78], [1], [2], [77], [97]. As was mentioned earlier in this research, the CPA algorithm cannot account for the COLREGs in determining the risk of collision. It also struggles with multi-vessel scenarios and can lead to counter-intuitive decision-making. Implementing the concept of the ship domain and arena into the Velocity Obstacle framework is an undiscovered area of research, and the proactive nature of the ship domain/arena can potentially help overcome the primary weaknesses of the VO algorithm, which lie in the reactive nature.

2.3.1. Research objective

The objective of this research is to extend the Velocity Obstacle algorithm by combining it with a precisely determined approach to the ship domain and the ship arena. The simplicity of the VO algorithm comes at the cost of being more reactive, making it a challenging task to incorporate the COLREGs into the framework. This research aims to overcome these limitations by using the concept of ship domain and especially ship arena to make the algorithm more proactive, making it better suited for implementation alongside the COLREGs. After thoroughly analyzing the state-of-the-art collision avoidance where the VO algorithm has been applied, the work done by Thyri and Breivik [1] is considered the current state-of-the-art in this sector. It has become clear that there is a severe lack of readily implementable work where efficient collision avoidance is applied alongside the COLREGs. The work done by Thyri and Breivik is advanced but shows shortcomings due to its reactive nature and incomplete COLREG compliance. Implementing the concept of the ship domain and arena helps bridge these gaps and provides a more readily COLREG-compliant collision assessment method for ASVs, covering the major shortcomings of CPA-based algorithms that have been applied in existing research. The dimensions and shape of the ship domain and arena are determined precisely to obtain a widely applicable model for collision avoidance of ASVs. The COLREGs are analyzed one by one to realize which of the COLREGs are relevant for the motion planning of the ASV. Afterward, the relevant COLREGs are translated to constraints of the ASV, and the implementation of the different aspects of the control algorithm is presented. The proposed algorithm is validated by running several simulations displaying the effectiveness and consistency of the algorithm.

2.3.2. Research questions

The research objective explained in the previous section can be used to obtain several research questions. The main research question that can be deducted is:

How can the integration of the ship domain and arena improve the reactive nature of the Velocity Obstacle algorithm and guarantee COLREG-compliant collision avoidance?

To answer this main research question, several research questions need to be answered. These research questions are answered in the remainder of this research, either by literature research or simulations. The following research questions are computed to help answer the main research question:

1. How can the COLREGs be effectively classified and prioritized within the decision-making of ASVs to ensure robust and compliant collision avoidance?
   (a) What are the challenges in implementing the COLREGs into the ASV framework?
   (b) How are the encounter variables translated to motion constraints of the ASV?
2. What is the role of the ship domain and what are the primary factors influencing the definition of the ship domain?
   (a) What approaches are used in existing research regarding the ship domain?
   (b) What are the key factors influencing the size and shape of the ship domain?
3. What is the role of the ship arena and how does it impact ASV collision avoidance?
   (a) What approaches are used in existing research regarding the ship arena?
   (b) How are the shape and dimensions of the ship arena calculated?
4. How does the integration of the ship domain and arena influence the performance of the VO collision avoidance algorithm?

This chapter has provided an overview of the existing research on collision avoidance in different sectors. The collision avoidance methods for ASVs have been thoroughly researched to find out what methods are commonly applied for different applications. The obtained research questions are answered in the following chapters. The next chapter gives an in-depth explanation of the COLREGs. The COLREGs are classified and the chapter elaborates on how the different traffic roles are assigned to the ASV in different encounter situations.

3

Convention on the International Regulations for Preventing Collisions at Sea

To guarantee safe journeys for seagoing vessels, rules need to be set out that instruct vessels in avoiding collision with other vessels. The Convention on the International Regulations for Preventing Collisions at Sea, the COLREGs in short, provide the so-called ‘rulebook of the sea’. The COLREGs were adopted in October 1972 and fully implemented by July 1977 [34]. The COLREGs set out the navigation rules that every seagoing vessel has to follow. It goes without saying that ASVs are also obligated to comply with these rules to avoid collision with other vessels. The COLREGs are classified into sections A to F, which cover different aspects of the rules. Section A elaborates on some general rules that explain the application of the COLREGs, some general definitions, and the responsibility of vessels concerning other vessels. Section B presents steering and sailing rules, which also cover rules regarding vessels in sight of one another and in limited visibility. Section C elaborates on the rules regarding the lights and shapes of different types of vessels. Section D presents some rules on sound signals and Section E displays some exemptions to the rules. Lastly, section F presents the verification of compliance with the provisions of the convention. Section A, which contains some general definitions, and Section B, which considers rules regarding vessel-to-vessel interactions, are the main focus for ASVs and this research. This part of the rules elaborates on how vessels are meant to act when encountering another vessel. The different encounter situations are analyzed and sufficient actions are discovered for any potential encounter situation.

Implementing the COLREGs into the control framework of an ASV has proven to be a challenging task. As was mentioned earlier in this research, the COLREGs contain a lot of subjective terms such as ‘early’, ‘action that will be best to avoid collision’, and ‘as soon as it becomes apparent’. The COLREGs were originally designed to be complied with by manned vessels, where experts’ knowledge is required to correctly assess a situation during an encounter. The uncertainty of how to implement these rules in the control framework of autonomous surface vessels has proven to be a huge bump in the road toward the implementation of ASVs. This chapter provides a comprehensive classification of the COLREGs that are relevant for the collision avoidance of ASVs. The COLREGs are classified to understand which rules are relevant for the motion control of the ASV. The relevant COLREGs are further classified to understand their impact on the motion control of the ASV. For every rule relevant to the desired actions of the ASV, a clear elaboration is provided that presents the respective (sub)rule and explains which states it impacts. This chapter also lays the foundation for the finite state machine that is implemented for the motion control of the ASV. The research question that is answered in this chapter is: ‘*How can the COLREGs be effectively classified and prioritized within the decision-making of ASVs to ensure robust and compliant collision avoidance?*’

(a) What are the challenges in implementing the COLREGs into the ASV framework?

(b) How are the encounter variables translated to motion constraints of the ASV?

3.1. COLREGs Classification

COLREG 1-18 are analyzed individually to classify them and to recognize what (sub)rules are relevant or irrelevant for the motion planning and the performed actions of ASVs. These rules are covered individually to judge which rules impact the ASV's motion planning and to elaborate on which states are impacted. The vessels are assumed to have a planar motion, so the following states are considered: $z = (x, y, \theta, u, v, r)$, where x and y display the position of the ASV, θ provides the heading of the ASV, u defines the surge velocity of the ASV and r defines the yaw velocity of the ASV. v defines the sway velocity, but the simplifying assumption that the sway velocity is zero is made, such as by Eriksen et al.[98]. Every relevant COLREG is cited directly from the IMO [34], after which the impacted states are discussed and the effect on the motion planning is explained.

COLREG 1-18 were first distinguished based on their relevance towards the motion planning of the ASV. It was concluded that COLREG 1-3, which discusses very general information about the application, the responsibility, and the general definitions of the COLREGs are not relevant for the motion planning of the ASV. COLREG 4 states that all rules in part B are applicable in any state of visibility, which is again not relevant to the motion control of the ASV. COLREG 11 states that the rules within this section apply to vessels in sight of one another, which is not directly relevant to motion control. COLREG 12 considers a rule about 2 sailing vessels meeting each other, but we are considering power-driven vessels for this research, meaning that this rule is considered irrelevant.

The rest of COLREGs 1-18 are considered relevant for the motion control of ASVs and all play some part in the collision avoidance framework. These rules are further classified based on their relevance in the perception of the ASV or the actions that the ASV performs to avoid collision. COLREG 5 states that every vessel shall maintain a proper lookout, which is considered to be part of the perception of the ASV. COLREG 9 considers actions that a vessel has to take in narrow channels and COLREG 10 considers traffic separation schemes. These rules are also considered to be part of the perception module of the ASV. Finally, rule 18 discusses responsibility between different types of vessels. This is also assumed to be part of the perception module and is not directly implementable in the control framework of the ASV.

The remaining COLREGs are assumed to be relevant for the motion control of the ASV and are further classified into rules that belong to the encounter situation analysis, situation-dependent rules, and situation-independent rules. These groups are, however, not mutually exclusive. A schematic overview of this discussed overall classification of COLREG 1-18 can be found in table 3.1.

Table 3.1: Classification of the COLREGs

Not relevant to ASV motion control	Relevant to ASV motion control			
	Perception of the ASV	Performed actions of the ASV		
		Encounter Situation Analysis	Situation Dependent	Situation Independent
1-4 11-12	5 9-10 18	7 13-18	8b-c,e 13-17	6 8a,d,f

3.2. COLREGs relevant for the actions of the ASV

The rules that directly consider vessel-to-vessel encounter situations can be translated to transition functions of the Finite State Machine (FSM). The COLREGs considered for this are COLREG 13-15 and 17, concerning head-on, crossing, and overtaking encounter situations. These rules are firstly quoted from the rulebook to understand their impact on the states of the ASV in different encounter situations. The relative bearing β_r describes the position of the obstacle vessel (OV) compared to the heading of the ASV. The relative heading ψ_r represents the difference in the heading angle of the two vessels. A more thorough explanation of these variables is provided after the relevant COLREGs and their impact on the motion control of the ASV have been covered.

Rule 13: Overtaking

"(a) Notwithstanding anything contained in the Rules of Part B, Sections I and II any vessel overtaking any other shall keep out of the way of the vessel being overtaken.

(b) A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5 degrees abaft her beam, that is, in such a position concerning the vessel she is overtaking, that at night she would be able to see only the stern light of that vessel but neither of her sidelights.

(c) When a vessel is in any doubt as to whether she is overtaking another, she shall assume that this is the case and act accordingly.

(d) Any subsequent alteration of the bearing between the two vessels shall not make the overtaking vessel a crossing vessel within the meaning of these Rules or relieve her of the duty of keeping clear of the overtaken vessel until she is finally past and clear."

Rule 13 elaborates on overtaking situations. Part (a) explains each vessel's role in an overtaking scenario. Parts (b) and (c) point out when a certain encounter situation should be deemed to be an overtaking situation. Part (d) elaborates on the aftermath of an overtaking action, where the overtaking vessel is not relieved of its duty to give way until the vessel is finally past and clear.

To implement this rule in the motion control of the ASV, the angle at which the ASV is approaching the OV plays a crucial role. Part (b) states that the ASV is overtaking whenever the ASV is approaching the OV from a direction that is more than 22.5 degrees abaft the beam of the OV. This means that the relative bearing between the vessels would need to be somewhere between 112.5 and 247.5 degrees; $112.5 < \beta_r < 247.5$. The COLREGs do not distinguish overtaking maneuvers to port or starboard side, but this is assumed to be extremely relevant in this research. The port and starboard overtaking maneuvers are distinguished for different combinations of β_r and ψ_r. This is done to ensure that the vessels would not find themselves in a sequential crossing encounter once the overtaking situation has been resolved, as this could potentially lead to confusion and danger. A schematic overview of this difference in passing side based on β_r and ψ_r is presented in Figure 3.1.

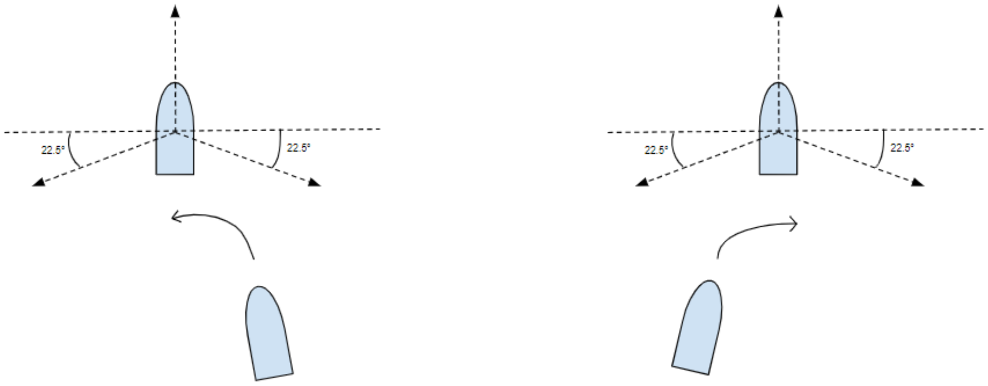


Figure 3.1: The difference between starboard and port overtaking

Rule 14: Head-on Situation

"(a) When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.

(b) Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.

(c) When a vessel is in any doubt as to whether such a situation exists she shall assume that it does exist and act accordingly."

To establish whether a certain encounter situation is a head-on situation, the relative bearing and the relative heading between the ASV and the OV need to be established. If the relative bearing, β_r, and the relative heading, $\psi_{ASV} - \psi_i$ are both approximately 180 degrees, we speak of a head-on situation. If there is no significant change in the relative bearing as the vessels are closing in on each other, it can be confirmed this is a head-on scenario. In any head-on scenario, the ASV always alters to starboard side to avoid colliding with the OV.

Rule 15: Crossing situation
"When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel."

To establish whether an encounter situation is a crossing situation, it has to be excluded that it is a head-on or overtaking encounter since any other encounter is automatically a crossing situation. Whether the ASV becomes the give-way or stand-on vessel in the crossing situation, depends on the side the OV is approaching from. If the OV is approaching from the ASV's starboard side, the ASV has to alter to avoid collision. If the OV is approaching from the ASV's port side, the OV becomes the give-way vessel and the ASV is the stand-on vessel. To avoid crossing ahead of the OV whenever the ASV is the give-way vessel, an alteration to starboard side will always be the preferred maneuver.

Rule 17: The action by the stand-on vessel
"(a)(i) Where one of two vessels is to keep out of the way the other shall keep her course and speed.
(ii) The latter vessel may however take action to avoid collision by her manoeuvre 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.
(b) When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision.
(c) A power-driven vessel which takes action in a crossing situation in accordance with sub-paragraph (a)(ii) of this Rule to avoid collision with another power-driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side.
(d) This Rule does not relieve the give-way vessel of her obligation to keep out of the way."

This rule discusses potential action that needs to be taken by the stand-on vessel, covering emergency situations. Since the ASV can only be assigned the stand-on role when being overtaken and in a port crossing encounter, these are the only scenarios that have to be covered. In a crossing scenario where the give-way vessel is not taking substantial action to avoid collision, the ASV would have to make a bold alteration to starboard, an alteration to port is prohibited. In an overtaking scenario, the alteration the ASV makes as the stand-on vessel again depends on the direction that the OV is approaching from. Based on the distinction between starboard- and port overtaking, as was elaborated with COLREG 13, the ASV decides to which side it makes a bold alteration to avoid collision if the OV fails to take sufficient action.

A schematic overview of the different kinds of encounter situations considered within COLREGs 13-17 can be seen in Figure 3.2, as presented by Thyri and Breivik [1]. These rules combine to create a control architecture for the ASV that outputs the required action for each encounter situation. The arrows in the graphic provide the obligated alterations of the vessels according to the COLREGs.

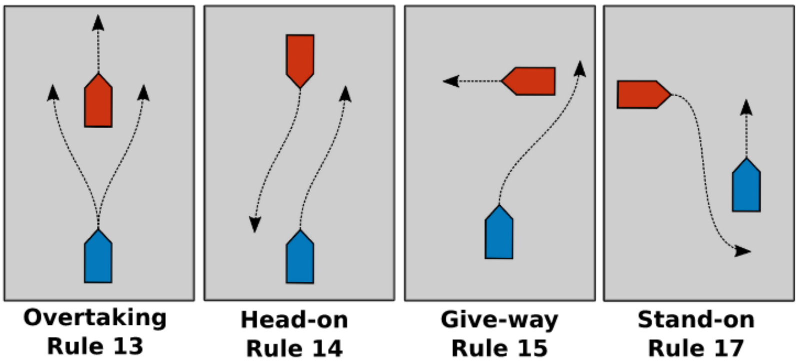


Figure 3.2: The different kind of encounter situations [1]

3.3. Determining factors for classification

As was briefly mentioned earlier in this report, the relative bearing β_r^i of OV_i with respect to the ASV and the relative heading ψ_r^i between the ASV and OV_i are the determining factors for the classification of the encounters. Once OV_i has entered the correspondent ship arena A^i, any potential combination of β_r^i and ψ_r^i leads to a conclusive analysis of the situation. The relative bearing β_r^i is calculated by deducting the heading of the ASV from the true bearing of OV_i. The true bearing θ_i of OV_i is calculated as follows, where x and y embody the x- and y-position of the ASV and OV_i:

$$\theta^i = tan^{-1}\left(\frac{x^i - x}{y^i - y}\right) \tag{3.1}$$

The relative bearing β_r^i of OV_i from the ASV is given by deducting the heading of the ASV from this true bearing θ_i. If the resulting relative bearing is below zero, 2π is added:

$$\beta_r^i = \theta_i - \psi_{ASV} \tag{3.2}$$

$$if\ \beta_r^i < 0, \beta_r^i = \beta_r^i + 2\pi \tag{3.3}$$

The relative heading ψ_r is calculated by deducting the heading of OV_i from the heading of the ASV. If the relative heading ψ_r is below zero, 2π is added:

$$\psi_r^i = \psi_{ASV} - \psi_i \tag{3.4}$$

$$if\ \psi_r^i < 0, \psi_r^i = \psi_r^i + 2\pi \tag{3.5}$$

A graphical overview of how the relative bearing β_r and relative heading ψ_r are established can be seen in Figure 3.3

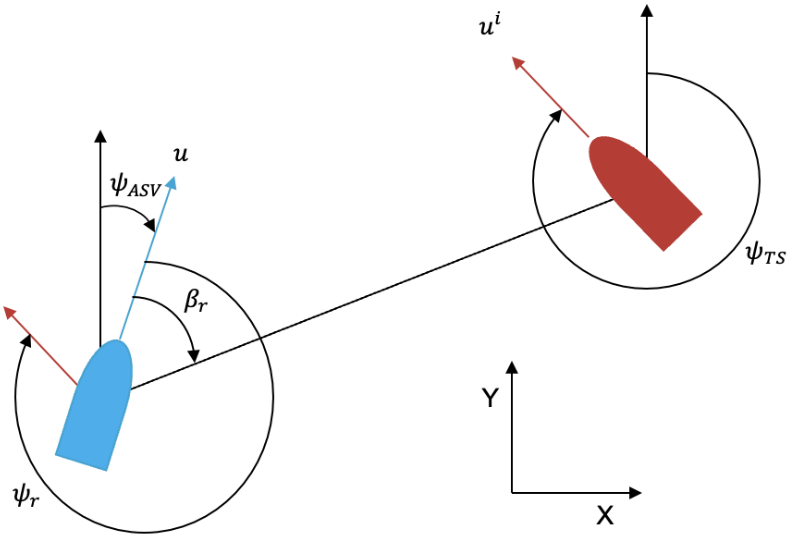


Figure 3.3: A schematic overview of how the relative bearing β_r and the relative heading ψ_r are obtained from the ASV's heading ψ_{ASV}

For the encounter situation analysis based on the relative bearing and relative course, an approach similar to the one used by Cho et al. [7] is used. They provide the encounter classification based on values of the relative bearing and course ranging from 0 to 360. A schematic overview of this approach can be seen in Figure 3.4.

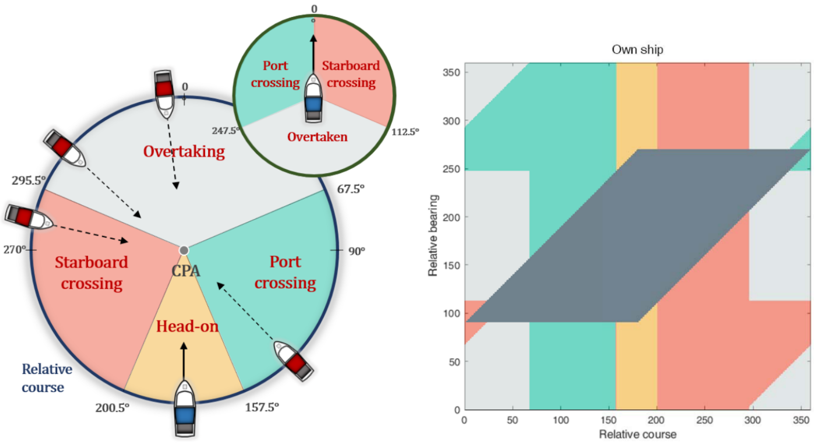


Figure 3.4: The encounter classification based on relative heading and relative bearing performed by Cho et al. [7]

The encounter classification variables used in this research are an extension of the work of Cho et al. As can be seen in Figure 3.4, Cho et al. presented a dark grey area in the center, that represents combinations of β_r and ψ_r that are considered to be safe, leaving the ASV in stand-on state. For this research, however, the encounter situation is only classified once OV_i has violated the correspondent ship arena $\mathbf{A^i}$. Violating the arena means risk of collision is deemed to exist, and the encounter situation needs to be classified based on β_r and ψ_r. Cho et al. [7] also simplified the classification by neglecting the differences in starboard- and port overtaking scenarios, even though these differences can potentially be crucial for the required action of the ASV. For this research, the grey area that Cho et al. consider 'safe' is extended to be assigned to one of the encounter situations. The boundaries of the different encounter types in this analysis are the fundamentals for the transition states of the finite state machine, which is elaborated later on.

The graphical representation of the encounter type classification based on the relative bearing and relative heading between the ASV and the OV can be seen in Figure 3.5. The GW role represents give-way roles, which contain all traffic situations where the ASV is forced to give-way according to the COLREGs. The EM role represents emergency situations, where the OV is initially meant to give way but fails to take substantial action, failing to dissolve the potentially dangerous situation. The GW and the EM traffic roles are further classified based on the separate encounter situations. The colors in Figure 3.5 display the different types of encounter situations between the ASV and the OV, where the legend contains further information on the abbreviations.

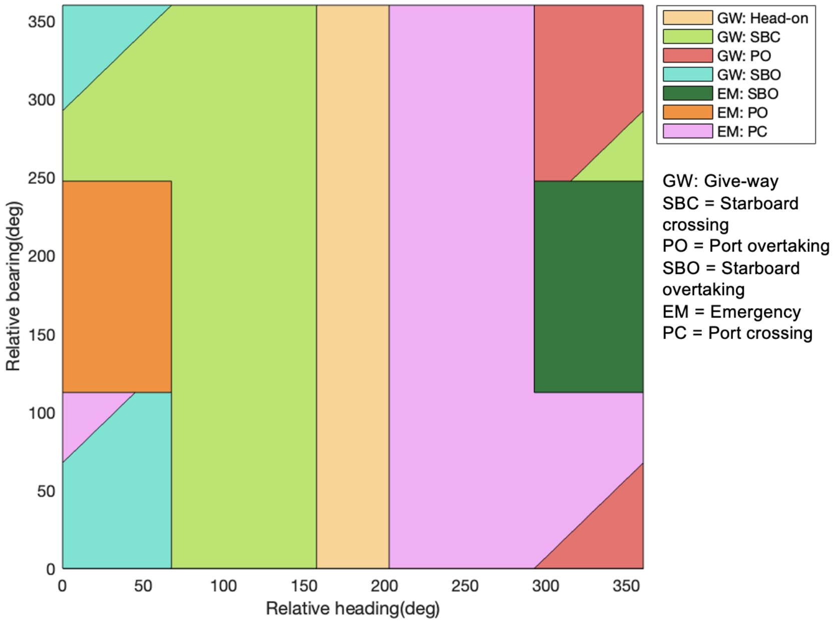


Figure 3.5: The encounter classification based on relative heading and relative bearing

The difference in give-way and emergency situations is accounted for by precise definition of the dimensions of the arena. The pseudocode describing the encounter situation classification can be found in algorithm 1. This pseudocode presents a more concise overview of the finite state machine that assigns the correct encounter situation to the ASV for every OV. The expression in line 1 displays that whenever OV_i has not entered the correspondent ship arena, the state is equal to 1 (stand-on). The base transition from stand-on to one of the encounter situations always starts with $r^i < A^i(\beta_r)$, showing the correspondent arena $\mathbf{A^i}$ has been violated. The different values for the relative bearing β_r and the relative heading ψ_r coincide with the values displayed in Figure 3.5. For the transition back to standing on, thus meaning the encounter situation has been fully resolved and no further risk of collision exists, the exit criteria need to be fulfilled. These exit criteria require the Distance to the Closest Point of Approach (DCPA) to be larger than a predetermined exit value and the Time to the Closest Point of Approach (TCPA) to be less than a predetermined exit value. These criteria are displayed in equation 3.6.

$$exit^i = \begin{cases} D_{CPA} > D_{CPA}^{i,exit} \\ T_{CPA} < T_{CPA}^{i,exit} \end{cases} \quad \forall i \in [HO, SBC, PO, SBO, EPC, EPO, ESBO] \tag{3.6}$$

Algorithm 1 Encounter situation classification

```
Input: Relative bearing $\beta_r$ and relative course $\psi_r$
Output: Encounter situation S
Procedure:
Initial S = 1
Define States: {SO, HO, SBC, PO, SBO, EMPC, EMSBO, EMPO}
Initialize S ← SO
Define Transitions:
    $(SO, HO)$: if $r^i < A^i(\beta_r) \wedge 157.5 < \psi_r \leqslant 202.5$ then SO ← HO
    $(SO, SBC)$: if $r^i < A^i(\beta_r) \wedge ((67.5 < \psi_r \leqslant 157.5) \vee (\psi_r < 67.5 \wedge (247.5 < \beta_r < (\psi_r + 292.5))) \vee ((315 < \psi_r < 360) \wedge (247.5 < \beta_r < (\psi_r - 67.5))))$ then SO ← SBC
    $(SO, PO)$: if $r^i < A^i(\beta_r) \wedge (((292.5 < \psi_r < 360) \wedge \beta_r < (\psi_r - 292.5)) \vee ((292.5 < \psi_r < 315) \wedge 247.5 < \beta_r) \vee (315 < \psi_r < 360 \wedge (\psi_r - 67.5) < \beta_r))$ then SO ← PO
    $(SO, SBO)$: if $r^i < A^i(\beta_r) \wedge (((0 < \psi_r < 67.5) \wedge \beta_r > (\psi_r + 292.5)) \vee ((45 < \psi_r < 67.5) \wedge \beta_r < 112.5) \vee (\psi_r < 45 \wedge \beta_r < (\psi_r + 67.5)))$ then SO ← SBO
    $(SO, EMPC)$: if $r^i < A^i(\beta_r) \wedge ((202.5 < \psi_r \leqslant 292.5) \vee (\psi_r > 292.5 \wedge (112.5 > \beta_r > (\psi_r - 292.5))) \vee ((\psi_r < 45) \wedge ((\psi_r + 67.5) < \beta_r < 112.5)))$ then SO ← EMPC
    $(SO, EMSBO)$: if $r^i < A^i(\beta_r) \wedge (\psi_r > 292.5 \wedge (112.5 < \beta_r < 247.5))$ then SO ← EMSBO
    $(SO, EMPO)$: if $r^i < A^i(\beta_r) \wedge (\psi_r < 67.5 \wedge (112.5 < \beta_r < 247.5))$ then SO ← EMPO
```

3.4. Conclusion

This chapter has provided a thorough answer to the first research question: *How can the COLREGs be effectively classified and prioritized within the decision-making of ASVs to ensure robust and compliant collision avoidance?* This chapter has provided a thorough analysis of the Convention on the International Regulations for Preventing Collisions at Sea, the COLREGs in short. The COLREGs were analyzed individually to obtain the COLREGs that are relevant towards the ASV motion control in this research. The variables β_r and ψ_r used to classify the relevant COLREGs were elaborated and the values of these variables that are used to assign a certain encounter situation have been proposed. The work of Cho et al. [97] has been extended to cover all possible combinations of β_r and ψ_r. The FSM concept was proposed and the transition functions were provided. The next chapter switches the focus to the ship domain and shows how this concept is implemented throughout this research.

4

Ship Domain

4.1. Concept of the ship domain

The ship domain provides a certain safe space around the ASV that can under no circumstances be entered by an OV. Defining the size and shape of this so-called ship domain has proven to be a difficult task, considering it is dependent on so many factors. In the past 40 years, many researchers have presented various ship domains using different shapes and sizes and have taken different factors into account in determining the ship domain [99].

Very early methods of determining the ship domain dimensions were mostly based on statistically processed radar data, such as in the research of Fuji and Tanaka [100], Goodwin [101] and Coldwell [102]. Nowadays, AIS has replaced radar data, and more advanced methods are used to determine the dimensions of the ship domain. Different interpretations of the concept of the ship domain have caused the definitions of this principle to be significantly different. As was stated by Szlapczynski and Szlapczynska [8], 4 types of safety criteria have been used in the application of the ship domain:

1. The ASV's domain should not be violated by an OV
2. The OV's domain should not be violated by the ASV
3. Neither of the ship domains should be violated (a conjunction of the first two conditions)
4. Ship domains should not overlap - their areas should remain mutually exclusive (the effective spacing is a sum of spacing resulting from each domain)

It can be argued that the differences between these criteria are as relevant as the size and shape of the ship domain, as it heavily impacts the actual spacing between the vessels. A graphical representation of the differences between these types of applications of the ship domain is shown in Figure 4.1. Szlapczynski and Szlapczynska concluded that the third option is the only criterion that is both safe and compliant with the classic definition of the ship domain. This is also how the ship domain principle is applied throughout this research. This section now shifts its focus to a few different approaches to determine the domain dimensions in existing research.

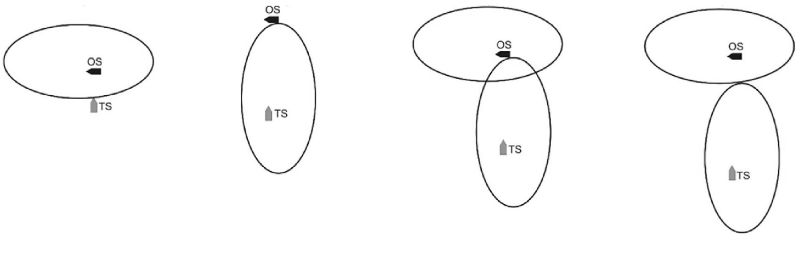


Figure 4.1: A graphical overview of the different kind of ways to implement the ship domain principle, as explained by Szlapczynski and Szlapczynska [8]

Several domain shapes have been considered in the existing research, such as circular domains, elliptical domains, and polygonal domains. Some researchers have considered complex domain shapes, and it could be questioned whether this is an efficient approach. As is observed by Stankiewicz et al. [95], many of these complex domain properties can be approximated by an elliptical domain. This would be desired, because the governing equations of a decentralized ellipse can be solved analytically while still creating a domain that emphasizes COLREGs maneuvering compliance. The size and shape of the ship domain can change depending on several factors including the physical characteristics of the vessels, the COLREGs encounter scenario, the maneuverability of the vessel, the human element, the ocean conditions, and fairway characteristics [103]. In part of the research, the ASV is positioned in the center of the domain, but in other parts of existing research, the ship domain is shifted slightly to account for the COLREGs. Some of the presented domains are adjustable and depend on real-time variables, such as the velocity of the ASV, yet some domains consist of 4 predetermined sides, solely based on the length of the ASV. Creating a consistent and widely applicable method of determining the sizes of the ship domain has turned out to be challenging and has thus far not been presented. This research aims to contribute towards bridging this gap and obtaining a more universal way of determining the ship domain size and classifications. A few existing approaches applying the ship domain concept are now presented.

4.2. Existing approaches

The first work using the ship domain is the work from Fuji and Tanaka [100], dating from 1971, where an elliptically shaped ship domain was applied based on mass recorded data in Japanese waters. The dimensions of the effective domain were defined as the distance from the central ship at which the density of other ships reaches a local maximum. In 1975, Goodwin [101] came up with a circular ship domain that was also derived based on large numbers of data. The domain consisted of 3 areas of different sectors with different sizes, optimized based on data from the sunk area of the North Sea. In the early 1980s, Davis et al. [51] came up with a modified circular ship domain that is similar to the model of Goodwin, but where the ship was shifted within the domain to maintain the weighting of the differing areas for various sectors. The model consists of 2 circles, the second of which was named the ship arena. More information on the ship arena is provided in the following chapter. In 1983, Coldwell et al. [102] assembled another elliptically shaped ship domain, where the dimensions depended on the type of encounter scenario. For head-on scenarios, the bottom side of the domain is no longer visible, as the COLREGs were adequately accounted for. The dimensions of the ellipse were only dependent on the vessel length, not accounting for the ship dynamics.

Kijima et al. [104] presented one of the first approaches that considered blocking areas in the ship domain applications. The blocking area is used to evaluate collision risk among vessels. They presented a so-called ‘blocking area’ and ‘watching area’ around the vessel, where the watching area defines the area around the ship where if an OV enters, the own ship is watching out for potential collision with this ship. The shape of the domain defined by Kijima et al. is described by a combination of two ellipses, and the formulas for these ellipses also contain the advance and the tactical diameter. They rightfully point out that knowing these parameters for other ships is usually quite challenging, again making this approach difficult to apply to other cases.

Bakdi et al. [105] presented a polygonal-shaped ship domain, consisting of 4 separate blocking areas that combine to create an off-centered, adjustable ship domain. They applied spatial risk functions to identify collision and grounding risk based on the motion and maneuverability of vessels. They determined the vessel’s maneuverability based on the tactical diameter and the advance of the considered ship. The blocking areas were dependent on the speed over ground of the vessel and these maneuverability parameters. This approach differs from the conventional approaches for safety domains because it considers the speed and the domain is not solely based on the vessel length. However, whether or not this approach would be generally applicable to every vessel could be questioned, as the presented functions to define the size of the blocking areas contain complex logarithmic functions.

Szlapczynski et al. [106] presented a ship domain-based approach to determine the latest time at which a particular collision avoidance maneuver can still be successfully performed. They used a model of the ship’s dynamics to assess the time and distance necessary for a maneuver resulting in avoiding the domain violations when the own ship has to give way. They use a ship domain where the dimensions are solely dependent on the vessel length, based on recent empirical data. Basing these dimensions solely on the vessel length and not considering any additional dynamics might lead to inappropriate applications at lower speeds [105], and does not present a very sophisticated approach to designing the ship domain.

Rawson et al. [103] presented a more practical application of the ship domain, designed specifically for the port of London. Rawson et al. rightfully pointed out that only very few applications of the ship domain facilitate the assessment of system-specific navigation risk. As this research was performed to be suited for the river Thames, one of the busiest waterways in the world, the general applicability of this approach was not as relevant for the authors as in other research. They proposed a predefined ship domain with a fixed 7-meter buffer around the vessel, with a dynamic ‘nose’ that extends forward depending on the reaction distance. The average beam of a Thames passenger vessel was used as the minimum distance, and the reaction distance was assumed to be superior to the stopping distance because it better reflects the navigation of vessels on the river. The reaction distance represented by the dynamic nose was calculated by multiplying the distance that the vessel would travel in 10 seconds based on the current speed over ground. While this is a valid and advanced approach for this particular application, the general applicability of this domain approach would be nonexistent.

Wang et al. [107] presented a novel ship domain model called the quaternion ship domain, which presents a diamond-shaped ship domain consisting of blocking areas. This model is more flexible and dependable than other ship domains regarding decision-making. The 4 directions of the ship domain are decided by taking factors such as the maneuvering capability, the vessel speed, and the vessel course into account. They propose fuzzy domain boundaries to make the approach more generally applicable and related to practical applications, but one could wonder whether making the ship domain this complex would be beneficial for practical approaches. As is rightfully pointed out in [8], this complex model does not come without limitations. If there is not enough searoom to use it, this approach might not be practical for several applications. Also, a large number of parameters can make the domain calculation inconvenient, as it would require these parameters to be updated constantly throughout a vessel encounter situation. They also mention that the OV’s length and speed are taken into account in the domain calculation, but these parameters are absent in the formulas they provide for the calculation of the domain dimensions.

Hansen et al. [108] attempted to estimate the minimum size of the ship domain at which a navigator still feels comfortable. They estimate the free space surrounding a ship that should be kept free of other vessels and obstacles, which is useful for estimating the maximum flow through a channel or a bridge span. The size of their ship domain is based on a large amount of empirical AIS data from relevant areas in Denmark and Germany. The shape of their ship domain is based on the standard ship maneuvers in an area with good space for maneuvering. The safety criteria were irrelevant in determining the ship domain, as strictly empirical AIS data was used. They assumed that the ship domain is proportional to the ship’s length and analyzed the domain shape using intensity plots, that visualize the passing distances between ships. The shape of the domain roughly follows the results presented by Fuji and Tanaka [100] and Coldwell [102]. The drastic reduction of the parameters used to define the ship domain makes it an easily understandable approach to the ship domain. However, as it is based on empirical data for a specific area, the general applicability might not be as good.

Wang and Chin [109] presented an empirically-calibrated ship domain as a safety criterion for navigation in confined waters. They used two individual domains of an asymmetrical polygonal shape for both the own ship and the OV, and the domain size is assumed to be dynamically enlarged with increased ship speeds. It is another example of an empirical ship domain proposed for a particular water region, which is the Singapore port and strait in this case. It has been assumed that the domain’s size is a linear function of the ship’s length and a quadratic function of its speed, and the safe distance in each direction depends additionally on the polar angle measured clockwise from the ship heading. This model does however involve more parameters than the empirical model proposed by Hansen et al. [108], and they assume that the ship domains of both vessels should not encroach, meaning that both vessels’ lengths and speeds impact the effective spacing. Wang and Chin claim the superiority of their approach comes from the free-form polygonal shape, but this is debatable, as stated in [8]. Firstly, the resulting polygon is quite close to an ellipse – a shape suggested by past works. Secondly, the criterion of not overlapping used here makes it hard to compare the effective spacing between ships with that resulting from using other domains. Also, differences in results can be partly attributed to different water regions that provided data sets.

Namgung et al. [110] attempted to create a domain for their application that would be most suitable for the general operations of autonomous vessels. They rightfully point out that the research of Fuji and Tanaka [100] only applies the ship length as the variable for the domain determination, and is thus regardless of the change in velocity. They attempted to combine the approach presented by Bakdi et al. [105] with the approach of Fuji and Tanaka, to extend this and make the domain dimensions dependent on the change in velocity. Namgung et al. identified that at a speed of 10 knots, the domain proposed by Bakdi et al. is similar to the domain proposed by Fuji and Tanaka, and they defined a ship domain according to the length of the considered vessel and the changes in velocity through the proportional expression. The centered ship domain leads to a great increase in the simplicity of the model. This approach brings a good balance between simplicity and general applicability of the ship domain. A tabular overview of the reviewed literature regarding the ship domain can be seen in Table 4.2. This overview displays the shape of the ship domain that has been proposed, whether the domain is adjustable based on the velocity, and whether the vessel is shifted within the domain, or if it is located in the exact center.

Table 4.1: Literature review of the considered ship domains

Reference	Shape	Dependent on velocity y/n	Centered y/n
Bakdi et al. [105]	Polygonal	Yes	No
Kijima et al. [104]	Elliptical	Yes	No
Szlapczynski et al. [106]	Elliptical	No	No
Rawson et al. [103]	Pentagonal	Partly	Yes
Wang [107]	Diamond	Yes	No
Hansen et al. [108]	Elliptical	No	No
Wang et al. [109]	Polygonal	Yes	No
Namgung et al. [110]	Elliptical	Yes	Yes

4.3. Domain determination

Creating a refined ship domain for this research is a challenging yet crucial task. In defining the domain dimensions, it is of the utmost importance that the dimensions are neither too small nor too big. Selecting dimensions of the ship domain that are too large and therefore too cautious could lead to undesired alterations of the ASV. This could lead to suboptimal motion of the ASV, potentially leading to unnecessary, avoidable additional encounter situations. Selecting dimensions of the ship domain that are too lenient could lead to close-call encounter scenarios that are per definition undesired according to the COLREGs, and should therefore be avoided. As was mentioned in the introductory chapter, the approaches for determining ship domains can roughly be divided into those determined through theoretical analysis, experts' knowledge, and empirically determined ship domains. although these are not mutually exclusive [8]. For this research, the ship domain is determined to be the area around the ASV that needs to be kept clear of other vessels no matter the circumstances. If neither vessel violates the OV's ship domain in the respective encounter situation, it is assumed to be a case of safe passing and it is assumed that collision has been successfully avoided.

For this research, the shape of the ship domain was chosen based on existing literature, consideration of COLREG compliance, and the desired simplicity of the model. Circular ship domains are convenient, easily implementable, and have proven successful in previous research. Circular ship domains provide the easiest approach, but using a circular domain implies that the accepted safety zone is of equal size in all directions, which is counter-intuitive. No distinction would be made between the different types of encounter scenarios and the same passing distance would be assumed to be acceptable towards all sides. At the other extreme of the spectrum, as has been pointed out in existing research [8], selecting very complex polygonal shapes for the ship domain might not be desirable, and using a large number of parameters in the domain calculation could prove to be incredibly inconvenient if these parameters need to be updated regularly. It is also all but guaranteed that making the domain more complex leads to a more 'desired' domain, which the complex models of [107] and [49] display. Elliptical ship domains offer a comprehensive middle ground between simple and complex shapes of the ship domain. The advantages of the simplicity of a circular domain are largely maintained in an elliptical domain, while the disparity in encounter scenarios is also accounted for. Several data-driven approaches have also shown that the passing distances generally assumed to be safe lead to an elliptical shape around the vessel [102] [108]. These arguments have led to the decision to use an elliptical shape for the ship domain in this research.

Most existing literature assumes invariable dimensions of the ship domain that are simply multiplications of the ASV's length, disregarding the ASV's maneuverability and velocity. This research attempts to incorporate the ASV's stopping ability and velocity in calculating the dimensions of the ship domain.

In this research, the size of semi major-axis D_a and semi minor-axis D_b consist of 2 components: D_0 and D_1. Component D_0 defines a buffer distance independent of the velocity and the maneuverability. This component is necessary to ensure the size of the D_b never gets below a certain minimum value. This component D_0 defines the safe passing distance between 2 vessels passing each other head-on. D_0 strictly depends on the length of the ASV, as it is assumed that the safe passing distance in a head-on encounter situation would be independent of the velocity of the vessels. The expression for D_0 is set as 2 times the length of the ASV, which is a number that is taken as an average of the length of the semi minor-axis in existing research, where this value varies in the range of 1.5 times the length up to 2.5 times the length of the ASV.

The other component of the domain dimensions, D_1, considers the stopping ability and velocity of the ASV. The maximum reverse force that the thrusters can exert and the mass of the ASV are used to determine the stopping ability. Assuming constant deceleration of the ASV is possible, the required stopping time of the ASV can be calculated for the current surge velocity. A certain buffer time is implemented, representing the time the ASV needs to go from current surge velocity to maximum reverse thrust and thus maximum deceleration. The overall formulas for the components of the dimensions of the ship domain are as follows:

$$D_0 = 2L \tag{4.1}$$

$$D_1 = u_{avg,br} \cdot t_{brake} + u \cdot t_{buf} \tag{4.2}$$

Where L is the length of the ASV, $u_{avg,br}$ is the average surge velocity during the braking of the ASV, t_{brake} is the total time required for the ASV to come to a halt, u is the current surge velocity of the ASV and t_{buf} is the buffer time that the ASV needs to go from the current sailing surge velocity to a maximum reverse thrust. The formulas that present the dependency of the semi-minor- and major axis on D_0 and D_1 are as follows:

$$D_a = D_0 + D_1 = 2L + u_{avg,br} \cdot t_{brake} + u \cdot t_{buf} \tag{4.3}$$

$$D_b = D_0 = 2L \tag{4.4}$$

A schematic overview of the ship domain and its semi-major and semi-minor axes D_a and D_b can be seen in Figure 4.2.

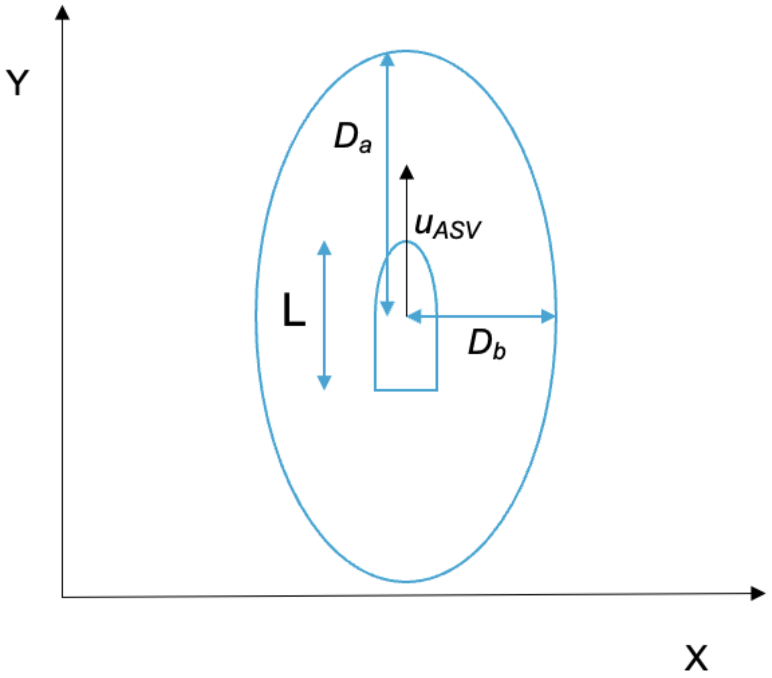


Figure 4.2: A graphical overview of the semi-major and semi-minor axis of the ship domain

4.4. Conclusion

This chapter has provided a thorough answer to the second research question: *What is the role of the ship domain and what are the primary factors influencing the definition of the ship domain?* This chapter provided a refined definition of the concept of the ship domain and discussed existing research where this concept is applied and the background behind the concept. The reason for picking an elliptical shape for the domain was provided and the exact approach to determining the domain dimensions was presented. The next chapter shifts the focus toward the ship arena. The concept of the ship arena is provided, existing research using the concept of a ship arena or a similar concept is discussed and the way of determining the arena properties in this research is presented.

5

Ship Arena

5.1. Concept of the ship arena

The ship arena represents a certain 'alarm area' around the ASV that provides a warning about risk of collision with the OV once the OV has entered the corresponding ship arena. Upon the OV entering the ship arena, the encounter situation is analysed to establish what kind of alteration the ASV needs to perform to avoid collision while complying with COLREGs. The ship arena provides a dynamic and precise approach to collision avoidance for ASVs. The timing of collision avoidance manoeuvres of ASVs has always been challenging, as the COLREGs provide little elaboration on when manoeuvres should be performed and vessels are typically slower than UAVs or AGVs. The ship arena provides a comprehensive approach that takes the vessel's manoeuvrability into account and realises the appropriate point of action based on the respective velocity components of both vessels. This prevents the ASV from performing premature alterations, while also guaranteeing the ASV takes action well before any potential danger could occur.

The ship arena is still a fairly new and unknown concept. As is the case for the ship domain, there is very little existing research applying the ship arena. However, the number of existing reports providing a thorough analysis of the ship domain is much larger than that of the ship arena. A few applications that consider a concept similar to the ship arena are now mentioned, and this overview is used to obtain the apparent gaps in the existing research regarding the ship arena. These gaps help bridge this research, presenting a more sophisticated model to define the ship arena and its dimensions.

5.2. Existing approaches

The first research that was performed on the potential usage of the ship arena was published by Davis et al. [51] and Colley et al. [111], which was largely an extension of the work from Davis et al. Davis et al. defined the arena as the 'area around the domain which when infringed causes the mariner to consider whether to make a collision-avoidance manoeuvre'. Davis et al. simply used different arbitrary values for the size of the circular ship arena and did not attempt to consider the velocity of the own ship and the OV in the determination of the size. Colley et al. rightfully noticed this and attempted to extend the work of Davis et al. by including the relative velocity between the vessels in their approach. They also pointed out that Davis et al. did not compensate for any speed loss during a manoeuvre. They created a circular arena where the dimensions were dependent on the relative velocity between the 2 vessels. As this is a very old model, however, the COLREGs were not considered and any potential prioritization for a manoeuvre towards a certain side was not accounted for. These models provided a promising starting point for the research towards ship arenas but did not contain any widely applicable refined approaches.

Dinh and Im [50] use a so-called 'action area' in their research, that is applied to prevent alterations from being performed too early, which could potentially lead to meaningless alterations due to the newly changed course of the OV. They propose a circular arena that increases in radius based on the front dimension of the ship domain and the relative velocity between the OV and the ASV. They created this action area based on the TCPA that navigators feel comfortable with, but the simplified model disregards any potential manoeuvrability limitations of the vessel.

Zhang et al. [112] present a distributed anti-collision system that is compliant with COLREGs, and they use a circular equivalent to the ship arena. It is a sort of safety ring around the vessel, here called the ‘action range’, that is set to an arbitrary value of 6 NM. It is based on CPA and is heavily dependent on this, but Zhang et al. end up simply assuming a value based on when navigators tend to want to take action, disregarding the dynamics of the ASV and the OV, making the model generally inapplicable to other cases.

Stankiewicz et al. [95] proposed a ship arena design to estimate the appropriate action quantification. They define the arena as ‘the area around the own ship where the mariner should begin manoeuvring if collision risk exists’. This allows the ASV to take action well before the domain could potentially be violated. They rightfully point out that enlarging the arena size towards the fore and starboard sides compared to the abaft and port sides of the domain leads to earlier notice of OV in situations where the ASV would be forced to give way, rather than situations where the ASV is the stand-on vessel. However, they set the size of the arena arbitrarily and simply enlarged the ship domain to design the arena. They rightfully pointed out that future research should guide the world into a more generally applicable way of designing the ship arena, that could be applied to multiple different kinds of vessels.

Heiberg et al. [113] proposed a risk-based implementation of COLREG compliance for autonomous vessels using deep reinforcement learning. They used the concept of the ship domain and arena as part of the implementation and used CPA and DCPA as benchmarks in calculating the arena dimensions. However, they implemented the arena as a predefined scaling of the ship domain, which is not a concise and well-analysed way of designing a collision avoidance algorithm. A tabular overview of the reviewed ship arena approaches is presented in Table 5.1.

Table 5.1: Literature review of the considered ship arenas

Reference	Shape	Dependent on velocity y/n	Centered y/n
Davis et al. [51]	Circular	No	No
Colley et al. [111]	Circular	Yes	No
Dinh and Im [50]	Circular	Yes	Yes
Zhang et al. [112]	Circular	No	Yes
Stankiewicz et al. [95]	Elliptical	No	No
Heiberg et al. [113]	Elliptical	Yes	No

The literature review of the existing research where the ship arena is applied displays some obvious limitations. Most existing models either failed to consider the COLREGs in the implementation or failed to include the relative velocity between the ASV and the OV in the approach. Thus far, there has not been a widely applicable approach towards the ship arena that correctly accounts for the velocity difference between the own ship and the OV while also taking the manoeuvrability of the ASV into account. This research presents a more refined approach to determining the dimensions of the ship arena, taking into account the differences in velocity between the ASV and the OV, factoring in their differences in heading, accounting for the manoeuvrability of the ASV and factoring in some standard ship parameters, such as the mass and the maximum braking force. The exact way of determining the arena sizes for this research is now provided.

5.3. Arena determination

Creating a concise and effective ship to apply in this research is another important aspect of this research. The implementation of the ship arena into the framework allows collision avoidance to be performed proactively, but this can only be realised if the arena dimensions are neither too strict nor too conservative. If the dimensions of the arena are too big, the algorithm performs potential collision avoidance alterations too early, which could lead to confusion and unclear traffic situations. If the dimensions of the arena are too small, potentially dangerous situations could arise if the OV assumes the ASV is not taking any action to avoid a collision even though it is the give-way vessel in the encounter situation. Ignoring the velocity dependency in the arena determination could again lead to ineffective and insufficient models, especially when very high and very low velocities are considered. Whenever OV_i violating ship arena A^i, risk of collision is deemed to exist and a collision avoidance alteration needs to be performed. If OV_i never enters the according arena A^i, the passing distance is assumed to be sufficient and there is no risk of collision. Most of the existing research uses the ship arena as an alert zone, where OV_i violating A^i tells the controller that a collision avoidance manoeuvre *might* need to be performed [95] [112]. However, this research aims to remove this vague definition, so the controller knows an alteration must be performed when OV_i violates A^i. The ship arena is a hard boundary that tells the control algorithm when collision avoidance needs to be performed, regardless of the traffic role, as the difference between stand-on and give-way encounter situations is accounted for in the arena boundaries.

Choosing an adequate method to determine the size and shape of the ship arena is not easy. In existing research, circular and elliptical shapes have mainly been used. The circular ship arena would be the easiest to implement, similar to the ship domain. However, using a circular ship arena would mean there is no distinction between the different sides an OV can be approaching from. This would imply that the controller would be alerted at the same time regardless of where the OV is approaching from. This is counter-intuitive, as the approaching direction of the OV is crucial for the traffic role assigned to the ASV. Complex shapes have not yet been applied for the concept of the ship arena in existing research, but it is assumed that picking a more complex shape would lead to unnecessary complications, that would not weigh up to the potential benefits. These are the main reasons why an elliptical ship arena is applied in this research.

In a lot of existing literature where the concept of the ship arena has been applied, the velocity of the ASV is ignored in the determination of the arena size [51], [112], [95], which can lead to sub-optimal arena dimensions. When the ASV's and the OV's manoeuvrability and surge velocity are ignored, the arena size would not be optimised for most encounter situations. For this research, the relative velocity of the OV concerning the ASV is implemented in determining the arena size. By using the relative velocity in the body frame of the ASV, the arena dimensions can be constructed precisely and adequately.

The dimensions of the ship arena are based on the relative velocity components of OV_i and the ASV in the body-fixed frame of the ASV, as was pointed out earlier. The length of the semi-major axis and semi-minor axis D_a and D_b of the ship domain are used as base components of the ship arena, which is done to avoid the arena being smaller than the ship domain. Using the relative velocity components in the body-fixed frame of the ASV allows the arena to constantly be updated to adequately resemble the required alarm area around the ASV, which is crucial to perform collision avoidance manoeuvres in time. The semi-major axis and semi-minor axis of the ship arena are constructed as follows, where firstly the arena size to the forward, aft, starboard and port sides are determined:

$$A_F = D_a + t_{crit}(u - u^i \cdot cos(\psi_r^i)) \tag{5.1}$$

$$A_A = D_a + t_{crit}(u^i \cdot cos(\psi_r^i) - u) \tag{5.2}$$

$$A_S = D_b + t_{crit}(u^i \cdot sin(\psi_r^i)) \tag{5.3}$$

$$A_P = D_b + t_{crit}(\frac{u^i \cdot sin(\psi_r^i)}{2}) \tag{5.4}$$

Here, D_a and D_b embody the semi-major- and minor axes of the ship domain, t_{crit} defines a certain critical time until the vessels would collide, u defines the surge velocity of the ASV and u^i defines the surge velocity of the OV. ψ_r^i defines the relative heading between the ASV and OV_i, translating the velocity components to the body-fixed frame of the ASV. This is a logical approach, as the dimensions of the arena are also determined in the body frame of the ASV. After computing these components of the arena, the finalized formulas for the size of the semi-major- and minor axis of the arena are obtained by taking the average of the arena components:

$$A_a = \frac{A_F + A_A}{2} \tag{5.5}$$

$$A_b = \frac{A_S + A_P}{2} \tag{5.6}$$

To acknowledge the COLREGs in the arena determination, the position of the ASV within the arena is shifted to the bottom left side of the arena, contrary to the ship domain where it was centred. In situations where the ASV would be forced to give way, OV_i would violate the arena from the fore or starboard direction, which is the case for head-on, overtaking and starboard crossing situations. By shifting the ASV to the bottom left of the arena, OVs that violate the domain from the fore or starboard direction are observed earlier, which leads to timely manoeuvres, desired by the COLREGs. The formulas for the shifts of the ASV within the ship arena are as follows:

$$\Delta a = A_F - A_a \tag{5.7}$$

$$\Delta b = A_S - A_b \tag{5.8}$$

A graphical overview of the ship arena including the semi-major- and minor-axis A_a and A_b can be seen in Figure 5.1.

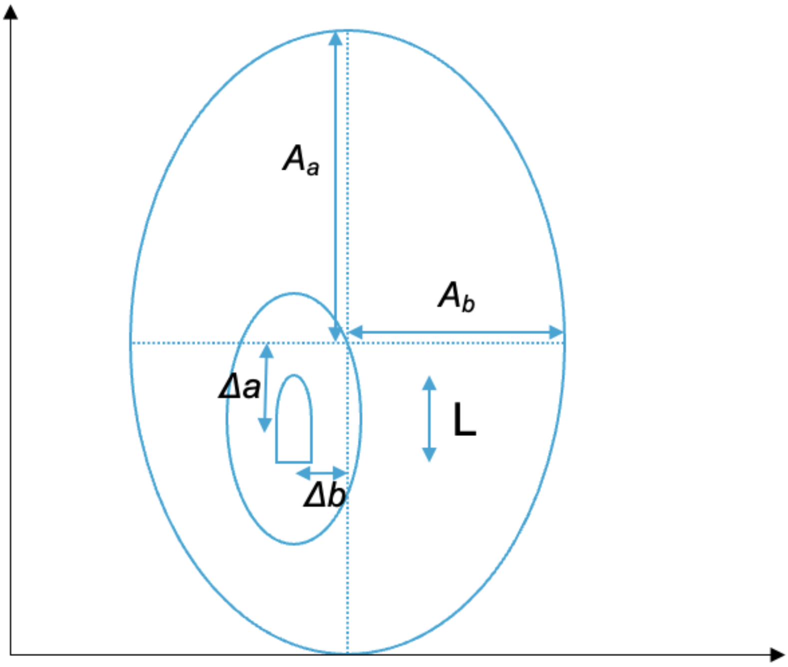


Figure 5.1: A graphical overview of the semi-major and minor axes of the ship arena

A separate ship arena is generated for every OV, to ensure the collision risk is appropriately analyzed with every OV individually. As the dimensions of the ship arena are partly dependent on the relative velocity, this makes for different distances at which risk of collision is deemed to exist. A graphical overview of two different OV's violating the according ship arena's is displayed in Figure 5.2.

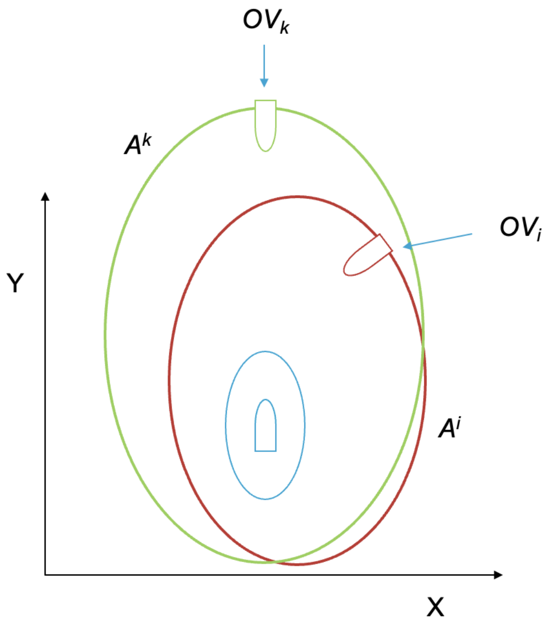


Figure 5.2: A graphical overview of two OV's violating the corresponding ship arena

5.4. Conclusion

This chapter has provided an extensive answer to the third research question: *What is the role of the ship arena and how does it impact ASV collision avoidance?* The concept of the ship arena and its role in collision avoidance have been analyzed in this chapter. Existing research applying the ship arena or a similar concept has been analyzed to obtain the possibilities for this research. The reasoning behind the selected shape has been provided and the formulas that are applied to determine the arena dimensions have been explained. The next chapter shifts the focus to the methods that have been applied to evaluate the performance of the designed control algorithm. The type of performed simulations are presented and the key performance indicators to gauge the effectiveness and reliability of the algorithm are provided.

6

Proposed Method

The previous chapters have presented the building blocks for the applied control method. The existing research was analysed to obtain possibilities for this research. The COLREGs were analysed individually and the encounter situation classification was presented. The ship domain and the ship arena were extensively covered and a comprehensive approach to create the velocity-dependent dimensions and shape of the domain and arena was presented. This chapter explains the different methods applied to realize collision avoidance using the ship domain and arena. The simulation setups are presented and pseudocode is supplied to demonstrate the algorithm. Chapter 7 contains the results and analysis of the performed methods.

6.1. The velocity obstacle algorithm

The VO algorithm provides a foundation for this research, presenting the mathematical notations. Let's start with the λ, which represents a ray going from the position of the ASV into the direction of the velocity of the ASV:

$$\lambda(\mathbf{p}, \mathbf{v}) = (\mathbf{p} + t\mathbf{v} | t \geqslant 0) \tag{6.1}$$

The following equations are used to express the Minkowski sum (6.2) and the reflection (6.3) used in the VO algorithm [2]:

$$A \oplus B = (\mathbf{a} + \mathbf{b} | \mathbf{a} \in A, \mathbf{b} \in B) \tag{6.2}$$

$$-A = (-\mathbf{a} | \mathbf{a} \in A) \tag{6.3}$$

Then, considering the shape of the ship domains $\mathbf{D^A}$ and $\mathbf{D^B}$ of the ASV and OV_B, the VO generated by OV_B in the velocity space of the ASV A is given by:

$$VO_B^A(\mathbf{v_B}) = (\mathbf{v_A} | \lambda(\mathbf{p_A}, \mathbf{v_A} - \mathbf{v_B}) \cap (\mathbf{D^A} \oplus -\mathbf{D^B}) \neq \varnothing) \tag{6.4}$$

Where $\mathbf{p}_A$ and $\mathbf{p}_B$ represent the position of the ASV and OV_B and $\mathbf{v_A}$ and $\mathbf{v_B}$ represent their velocity vectors. As Kuwata et al. pointed out, a simple representation of this equation is that the ray starting from the ASV and going in the direction of the relative velocity ($\mathbf{v_A} - \mathbf{v_B}$) intersects OV expanded by the ship domain $\mathbf{D^A}$ of the ASV. As long as the selected velocity lies outside the cone that is generated from the VO, it will not collide with OV_B, assuming the velocities stay constant over time. If the velocities change, the algorithm provides an updated plan using the latest information it has received. When multiple OVs are involved, a set of constraints is created by taking a superposition of the separate VO's. A schematic overview of the Velocity Obstacle algorithm as presented by Van den Berg et al. [9] is presented in Figure 6.1.

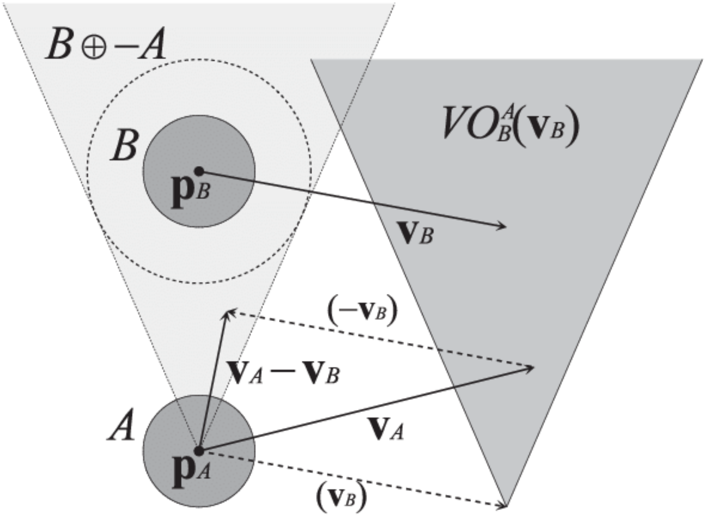


Figure 6.1: A graphical interpretation of the VO algorithm [9]

The collision cone $\mathbf{C^i}$ is constructed separately for every OV_i. In multi-vessel situations, the different collision cones are combined to create a set of velocities blocked out by the algorithm. To construct the edges of the collision cone, lines are drawn from the position of the ASV that pass through the tangent points with circle $\mathbf{T^i}$ that encircles the irregular shape that consists of the Minkowski sum $\mathbf{D} \oplus \mathbf{D^i}$ of the ship domain of the ASV and the ship domain of OV_i. One edge starts at the position of the ASV, $\mathbf{Q_1}$, and goes through $\mathbf{Q_2}$, one of the tangent points. The other edge also starts at $\mathbf{Q_1}$ but passes through the other tangent point, $\mathbf{Q_3}$. The cone is then shifted based on the velocity of OV_i, corresponding to the traditional VO algorithm. A visual representation of how these collision cones are created can be seen in Figure 6.2.

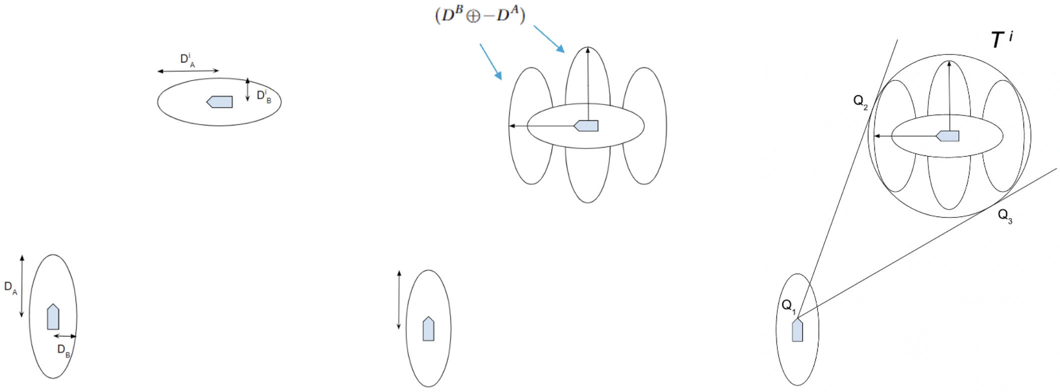


Figure 6.2: The determination of the corner points of the collision cone

6.2. ASV Control

6.2.1. Vessel model

The vessel model is important in achieving successful collision avoidance for ASVs. Information is gathered via onboard sensors and the information of the OV is gained through AIS data. The proposed reference control output is sent to the physical system based on ASV's and OV's states. The control output of the ASV is the measured position, the required thruster force, and the angle of thrust output. The ASV is assumed to move in a planar workspace $\mathbf{W} = \mathbb{R}^2$, where the x- and y-position combine to represent the position of the ASV. The state of the ASV is denoted with $\boldsymbol{\eta} \in \mathbf{H} \subseteq \mathbb{R}^{3x1}$ and the control input is denoted by $\boldsymbol{\tau} \in \mathbf{T} \subseteq \mathbb{R}^{3x1}$. Planar motion is also assumed for the OVs and the state of OV_i, $\boldsymbol{\eta_i}$, is known to sufficient precision through AIS data. A 3-degree-of-freedom kinematic model is adapted for the ASV, that contains the position in x- and y-direction as well as the orientation in the North-East-Down (NED) coordinate system: $\boldsymbol{\eta} = (x, y, \psi)^T$. Figure 6.3 displays a graphical overview of the state of the ASV.

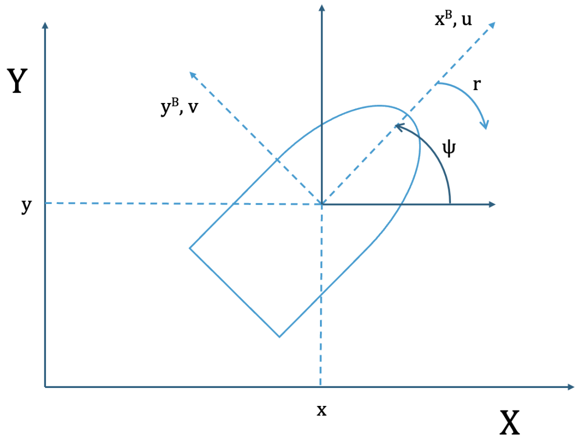


Figure 6.3: The position of the ASV represented in the NED frame, and the velocity expressed in the body frame

The state of the OV is represented similarly: $\boldsymbol{\eta_i} = (x^i, y^i, \psi^i)^T$, where i represents the number of OVs. The control input $\boldsymbol{\tau}$ is denoted as $\boldsymbol{\tau} = (u, 0, r)^T$, where u represents the surge velocity and r represents the yaw velocity. The sway velocity is assumed to be 0, which is a commonly applied simplification for ASVs [98].

The evolution of the state of the ASV throughout the simulations is determined from the control outputs produced at every iteration. The kinematic equation that displays the evolution of the state of the ASV is as follows:

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\tau} \tag{6.5}$$

Where $\mathbf{R}(\psi)$ represents the rotation matrix to convert a position or velocity vector from the body-fixed frame to the inertial frame:

$$\mathbf{R}(\psi) = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{6.6}$$

6.2.2. Shared information

To obtain the reference output $\boldsymbol{\tau}_{ref}$, the controller of the ASV needs sufficient information about the state of the ASV $\boldsymbol{\eta}$ and the state of OV_i $\boldsymbol{\eta_i}$ in the vicinity. $\boldsymbol{\eta_i}$ and $\mathbf{v_i}$ are assumed to be available through AIS data and $\boldsymbol{\eta}$ is assumed to be sufficiently available through onboard sensors. The motion controller receives $\boldsymbol{\eta}$ and $\boldsymbol{\eta_i}$ and generates the reference control output $\boldsymbol{\tau}_{ref}$. Figure 6.4 presents a schematic overview of this process.

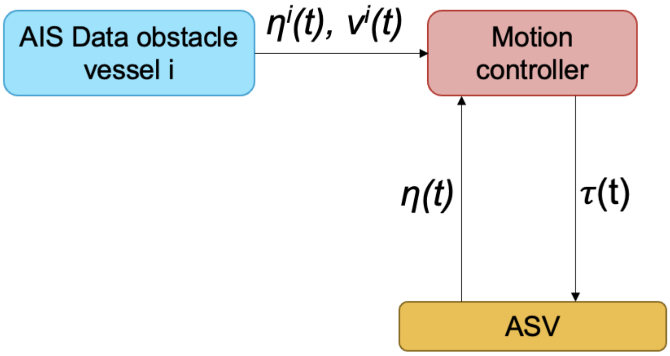


Figure 6.4: The control hierarchy of the ASV motion control

6.2.3. Preferred passing side

Determining what side the ASV should pass OV_i on is an important distinction within the COLREGs. The COLREGs explicitly state what alteration is preferred for the different encounter situations. The ASV should pass OV_i while seeing it on its own port side for head-on, starboard crossing, and emergency crossing scenarios. For overtaking scenarios, the COLREGs do not explicitly state at what side the ASV should pass OV_i For this research, a distinction has been made between port and starboard overtaking, as was briefly touched upon in chapter 3. To avoid further complications that could lead to a new crossing scenario between the vessels, the ASV always overtakes towards the side of OV_i that the ASV's target position is on. This is implemented to ensure the ASV never has to cross ahead of OV_i after it has overtaken OV_i. If the ASV is getting overtaken by OV_i, but OV_i fails to take substantial action to avoid collision, a similar argumentation is used to determine the passing side. If OV_i was supposed to pass the ASV on the ASV's port side, the ASV would alter to starboard in an emergency situation. Simultaneously, if OV_i was meant to pass the ASV on the ASV's starboard side, the ASV alters to port to ensure collision is avoided.

To summarize, for head-on, starboard crossing, starboard overtaking, emergency port crossing, and emergency port overtaking scenarios, the ASV passes OV_i while seeing it on its own port side. In port overtaking and emergency starboard overtaking, the ASV passes OV_i while seeing it on its own starboard side. To ensure the ASV passes OV_i on the correct side, an approach similar to Kuwata et al. [2] is implemented. Each velocity candidate that would lead to COLREG noncompliance is blocked, and the remaining COLREG-compliant velocity candidates remain available for the algorithm to choose from. To find all candidates that need to be blocked out, the cross product between the relative position and the candidate velocity of the ASV and OV_i is calculated:

$$(\mathbf{p_i} - \mathbf{p_{ASV}}) \times (\mathbf{v_c} - \mathbf{v_i}) < 0 \tag{6.7}$$

If equation 6.7 is indeed smaller than 0, the ASV passes OV_i while seeing it on its starboard side. As was mentioned earlier, this is undesired for head-on, starboard crossing, and starboard overtaking scenarios. Consecutively, all velocity candidates that lead to a negative value for this cross product are blocked out for these encounter situations, ensuring no COLREG-incompliant velocity candidate is selected. The remaining velocity candidates are run through an objective function to find the optimum velocity at that point in time. This cost function is presented later on in this chapter.

6.2.4. Control output

Before the algorithm finds $\boldsymbol{\tau}_{opt}$, 640 potential velocity candidates $\mathbf{v_c}$, consisting of an x- and y-velocity, are generated at every time step. These velocity candidates are constructed from 20 possible surge velocities, evenly distributed from 0 to 3 meters per second, and 32 possible heading angles, ranging from 0 to 360 degrees. By combining the surge velocity candidates with the heading angle candidates and converting from the body frame to the global frame, 640 potential combinations of x- and y-velocities are formed. Afterward, the optimal velocity is added as the 641st option, to ensure the algorithm can select this if it is not blocked out. Matrix A is a matrix of size $i \times 641$ that contains all $\mathbf{v_c}$. i equals the number of OVs for a certain encounter scenario.

In the process of selecting $\boldsymbol{\tau}_{opt}$, the COLREG incompliant $\mathbf{v_c}$ are blocked out at the first step. The preferred passing side for the different encounter situations was explained shortly before. A matrix B of size $i \times 641$ is filled with Boolean variable $Bool_{side}$, where the number of rows i equals the number of OVs and the number of columns equals the number of candidate velocities. For every element $B_{i,j}$ of this matrix, it is checked whether candidate velocity j leads to an incompliant passing side with OV_i. If the velocity candidate j leads to a breach of the COLREGs with OV_i, the according element of the matrix $B_{i,j}$ takes the value 1. Once every candidate velocity j is run through equation 6.7, all columns that contain at least one nonzero input are blocked out, and the columns that only contain zeroes remain. By doing this, every $\mathbf{v_c}$ is inspected on COLREG compliance with every OV_i. This ensures that the final control output leads to complete COLREG-compliant maneuvers with all OVs in the vicinity.

After the columns of matrix A containing nonzero inputs of $Bool_{side}$ have been blocked off, a matrix E of size $i \times L$ remains. The number of rows of this matrix again depends on the number of OVs i, and the number of columns represents the remaining $\mathbf{v_c}$ after the COLREG-incompliant candidates have been blocked off. The remaining velocity candidates are checked on collision risk with all OVs.

Matrix F is filled with Boolean variable $Bool_{col}$, where the size is equal to matrix E, $i \times L$. Variable L represents the remaining number of available velocity candidates after the COLREG incompliant velocities have been blocked out and i represents the number of OVs. If the respective $\mathbf{v_c}$ lies within the set of velocities $\mathbf{v_{ASV}} \in VO_i^A(\mathbf{v_i})$, it will lead to a collision with OV_i. If this is the case, the matrix element $F(i,j)$ that belongs to this candidate velocity takes the value 1 in the row representing OV_i. To obtain the velocity candidates that guarantee collision avoidance with every OV_i, each column with at least one nonzero value is blocked off, and each column only containing zeros remains. After this process has been performed, the only remaining $\mathbf{v_c}$ are the ones that guarantee COLREG compliance and collision avoidance with every OV_i in the vicinity. The remaining available $\mathbf{v_c}$ are stored in matrix G, which has size $i \times M$. Figure 6.5 presents a schematic overview of this process.

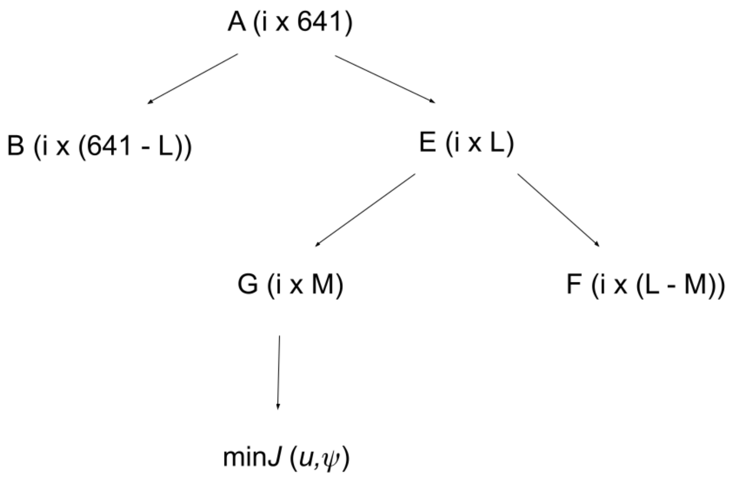


Figure 6.5: The process in eliminating unsafe and COLREG incompliant velocity candidates

To ensure the optimum $\mathbf{v_c}$ is selected at every iteration, objective function J is minimized for every iteration. The remaining candidate x- and y-velocities are converted to a set of surge velocities and heading angles. This step is performed due to COLREG 8 stating that if possible, altering speed should only be performed if necessary to avoid collision, but if strictly altering the course is enough to avoid collision, this is preferred. The objective function J that is minimized to ensure a change in heading is preferred to a change in surge velocity is:

$$\underset{u,\psi}{\text{minimize}} \quad \mathbf{J}(u,\psi) = w_1||u_d - u|| + w_2||\psi_d - \psi|| \tag{6.8a}$$

$$\text{subject to} \quad \boldsymbol{\eta} \in \mathbf{H} \in \mathbf{H^R}(\boldsymbol{\eta_0}), \tag{6.8b}$$

$$\boldsymbol{\tau} \in \mathbf{T} \tag{6.8c}$$

The solution to the presented discrete optimization problem is $\boldsymbol{\tau}_{opt}$ that minimizes cost function 6.8a under state constraints 6.8b and input constraints 6.8c. $\mathbf{H^R}$ provide the set of reachable states $\boldsymbol{\eta}$ depending on the current state $\boldsymbol{\eta_0}$ and $\mathbf{T}$ presents the constraints on the control output $\boldsymbol{\tau}$. Cost function J 6.8a is designed such that the ASV prioritizes minimizing deviation to the optimal surge velocity over minimizing deviation to the optimal heading angle, which is desired according to COLREG 8. Variables u_d and ψ_d are the desired surge velocity and heading, and by assigning a significantly higher value to w_1 than w_2, the algorithm applies this prioritization. As the surge velocity ranges from 0 to 3 meters per second and the heading angle ranges from 0 to 360, an initial scaling of 120 is needed to level their importance in the cost function. On top of this, $w_1 = 5 \cdot w_2$, to ensure the algorithm prioritizes the desired velocity over the desired heading. This concludes the process of finding the optimum control output, guaranteeing collision avoidance and COLREG-compliant maneuvers.

Down below, the pseudocode that belongs to the designed algorithm is presented. The algorithm checks for every iteration whether OVs are present in the vicinity. If OV_i enters the correspondent ship arena $\mathbf{A^i}$, the encounter situation is analyzed and the responsibility is obtained. Afterward, the ship domain is shifted to the position of OV_i, and the tangent points of the rotated and shifted elliptical domain are used as corner points of the Velocity Obstacle.

Algorithm 2 Reciprocal Velocity obstacle with ship domain and arena

```
Result: Calculate the path that minimizes the total cost $\sum J$ while guaranteeing collision avoidance
Obtain the ASV's starting position(X, Y), target position (X, Y) and initial velocity(u, r)
while target position has not been reached do
    Generate velocity candidates that the algorithm can select
    Obtain a list of obstacle vessels
    for every target ship i in the vicinity do
        if $r^i < A^i(\beta_r)$ then
            Obtain $\beta_r^i$ and $\psi_r^i$ to analyse the encounter scenario
            Responsibility $\alpha$ is determined based on encounter situation
            if ASV is forced to give way then
                Obtain $\mathbf{D^i}$ and the Minkowski sum of $\mathbf{D}$ and $\mathbf{D^i}$
                if state = 2||3||5||6||8 then
                    Pass obstacle vessel $i$ on its starboard side
                else
                    Pass obstacle vessel $i$ on its port side
                end
                Obtain according $VO^i(\mathbf{v^i}) = \{\mathbf{v} | \lambda(\mathbf{p}, \mathbf{v} - \mathbf{v^i}) \wedge (\mathbf{D} \bigoplus -\mathbf{D^i}) \neq \emptyset\}$
            end
        end
        Find the optimal velocity that guarantees collision avoidance through minimization of the cost function $\sum J$
    end
    Move to the next decision node
end
```

6.3. Conclusion

This chapter has provided the first part of the answer to the research question: *How does the integration of the ship domain and arena influence the performance of the VO collision avoidance algorithm?* This chapter combined the different building blocks of the previous chapter to present the defined algorithm. The baseline Velocity Obstacle algorithm was presented and the control of the ASV was further elaborated. The preferred passing side was explained and the process of finding the optimal control output through the minimization of the objective function was presented. The next chapter presents the setup of the performed simulations and the results of the according simulations using the newly developed algorithm and the algorithm of Thyri et al. [1].

7

Results of the performed simulations

This chapter concludes the experimental assessment of the developed algorithm. The batch simulations that have been performed to display the performance of the designed algorithm in different vessel-to-vessel encounters are analyzed and a thorough comparison to the state-of-the-art is elaborated. Afterward, the results of the complex scenarios are presented to display the wide applicability of the algorithm.

7.1. Simulation Setup

To evaluate the performance of the algorithm, several simulations are performed. To display the effectiveness of the algorithm and to prove the contribution to the state-of-the-art, a comparative analysis is performed with the work of Thyri and Breivik [1], which is considered to be the latest implementation of the velocity obstacle algorithm in the collision avoidance of ASVs. After this comparative study is performed, the algorithm is applied to complex, multi-vessel scenarios. This will help validate the versatility and robustness of the algorithm. The system described thus far is simulated using MATLAB and the set of general parameters used throughout the simulations are shown in Table 7.1.

Table 7.1: General parameters used in the simulations

Parameter	Value	Comment
Dt	0.1 s	Step size in seconds
Nv	20	Amount of sample surge velocities
Nh	32	Amount of sample heading angles
W1	5	Weight factor for surge velocity deviation
W2	1	Weight factor for heading angle deviation
M	29 Kg	Mass of the ASV
F_T	19.88 N	Maximum reverse thruster force
L	1.3 m	Length of the ASV
t_{crit}	30 s	Critical time to scale arena size
t_{buf}	3 s	Buffer time to account for thruster motion
t_{exit}	-10 s	Exit TCPA value of the FSM
D_{exit}	50 m	Exit DCPA value of the FSM

7.1.1. Key performance indicators for collision avoidance ASVs

The key performance indicators (KPIs) that are generally used to verify the effectiveness of VO implementations are collision rate or minimum inter-distance between ASVs to display safe navigation [1] [79] [77], the time to goal [97], and the rate of COLREG compliance [2] [78] [80]. The collision rate displays how successful an algorithm is at avoiding collision with OVs, where the minimum inter-distance shows there have been no dangerous encounters with OVs while safely solving the give-way encounter scenario. The time to goal shows how fast the developed algorithm manages to guide the ASV to its target position while safely avoiding collision. The rate of COLREG compliance shows how well the developed algorithm does at complying with the navigational rules in certain encounter situations. To contribute to the state-of-the-art, it has been attempted to improve on the reactive nature of the algorithm. The KPI that is measured to display this is the change in heading of the ASV throughout a simulation, where a smaller change in heading to reach the target position indicates that the ASV has fewer oscillations in its movement, indicating a more proactive approach.

7.2. Batch simulations

The results of the different vessel-to-vessel batch simulations that have been performed are now provided. These batch simulations have been run using both the developed algorithm and the algorithm of Thyri et al. [1], which has been considered state-of-the-art, as mentioned before. Therefore, the constructed algorithm is compared to theirs using the predetermined KPIs and the overall performance of the algorithms. In the provided vessel-to-vessel simulations, the ASV runs the proposed algorithm and OV_i keeps a constant velocity and heading throughout the simulation. A set of trajectories is generated for the ASV, where the encounter situation is similar for each batch, but a 10-meter separation is implemented to display the algorithm's flexibility. OV_i keeps the same trajectory for every simulation and the ASV will have give-way obligations in every encounter. Evidently in head-on scenarios, both vessels are meant to perform collision avoidance maneuvers, but because the goal is simply to display the effectiveness of the algorithm in different encounter situations, only the ASV will be giving way. The overall parameters of the different batch simulations that have been performed are displayed in Table 7.2, which provides a comprehensive overview of the simulations.

Table 7.2: Encounter specific parameters used in the simulations

	Encounter situation		
Parameter	Head-on	Crossing	Overtaking
ASV starting xpos	[200]	[-90 to 90]	[-60 to 60]
ASV starting ypos	[-60 to 60]	[-100]	[-100]
ASV goal xpos	[-200]	[-90 to 90]	[60 to -60]
ASV goal ypos	[-60 to 60]	[200]	[200]
Obstacle vessel starting xpos	[-200]	[200]	[0]
Obstacle vessel starting ypos	[0]	[100]	[0]
Obstacle vessel goal xpos	[200]	[-100]	[0]
Obstacle vessel goal ypos	[0]	[100]	[150]
ASV surge velocity [m/s]	3	3	3
Obstacle vessel surge velocity[m/s]	3	3	1.5

Head-on encounters

COLREG 14 covers head-on encounter situations, elaborated in chapter 3. A set of head-on simulations are performed to display the algorithm's compliance with this rule. The starting and target y-position of the ASV is shifted by 10 for every simulation. The target y-position is the same as the starting y-position for these simulations, to guarantee the relative heading between OV_i and the ASV is in line with a head-on situation. OV_i moves from [-200,0] to [200,0] with the same velocity as the ASV but does not run the presented algorithm. These simulations also provide a concise overview of the arena's impact, as the arena's dimensions determine whether or not the ASV needs to take action to avoid collision in a certain scenario. This provides a clear argument for how the arena is not too conservative but still guarantees safe navigation.

Figure 7.1 displays the superimposed simulations of a head-on vessel-to-vessel encounter where the ASV moving from the right to the left runs the presented algorithm. After approximately 151 seconds, the ASV has reached the desired target position while guaranteeing appropriate collision avoidance with OV_i for each simulation. For the simulations beginning at y = ± 40 until y = ± 60, it can be observed that the ASV does not take any action and simply continues its journey in a straight line. This happens due to the definition of the dimensions of the ship arena. The OV_i never enters arena $\mathbf{A^i}$, sequentially the finite state machine does not transition to the head-on state and no collision avoidance maneuver needs to be performed. COLREG 14 discusses head-on situations and points out that to pass an obstacle vessel head-on, a vessel should always alter to starboard and pass at a safe distance. As can be seen in Figure 7.1, the algorithm always performs a safe maneuver that is compliant with this statement.

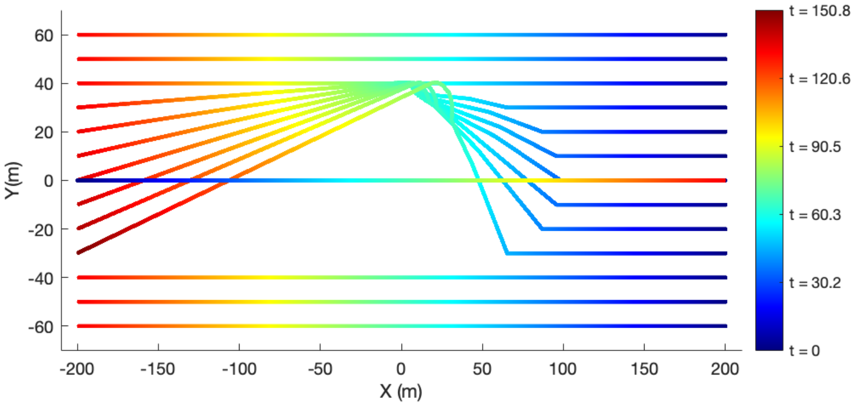


Figure 7.1: A set of head-on encounter simulations where the ASV maneuvers from right to left while avoiding collision

To guarantee collision avoidance and safe navigation throughout these simulations, the inter-distance between the ASV and OV_i throughout 3 of the head-on simulations is displayed in Figure 7.2. These lines represent the inter-distance in the simulations starting at y = 0, y = 10, and y = -10, to display safe navigation for any starting y-position. As can be seen in this figure, the ASV manages to maintain a safe distance to OV_i that is greater than the minimum required distance, which is represented by the red line. This minimum required inter-distance is composed of the Minkowski sum of the ship domain of the ASV and OV_i, as was elaborated in a previous chapter.

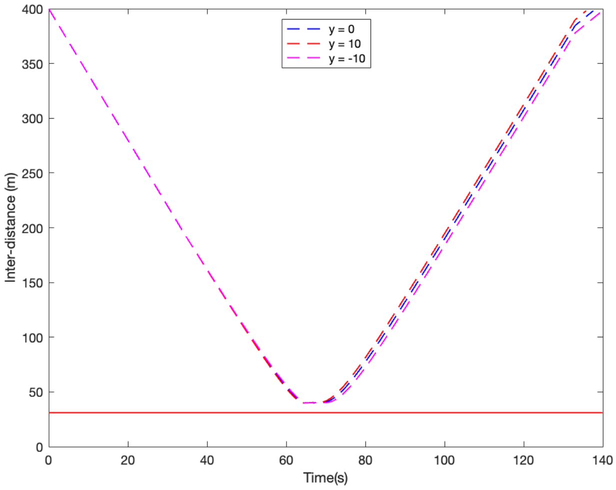


Figure 7.2: The inter-distance between the ASV and OV_i in 3 of the head-on scenarios, showing safe navigation

Crossing encounters

COLREG 15 covers crossing situations, where the vessel seeing the other vessel on its starboard side is the give-way vessel. To display compliance with this rule, a set of crossing situations are performed. The starting and the target x-position of the ASV are shifted by 10 for every simulation, again to show the flexibility of the algorithm and how the algorithm handles encounter situations requiring a larger maneuver to ensure safe navigation. The target x-position is the same as the starting x-position for every simulation to ensure the relative heading correlates with a crossing scenario. OV_i moves from [200,100] to [-100,100] at the same velocity as the ASV.

Figure 7.3 displays the set of superimposed simulations of a crossing vessel-to-vessel simulation where the ASV moving from the bottom to the top is running the proposed algorithm. OV_i keeps the maximum allowed surge velocity throughout the entirety of every simulation. After approximately 118.4 seconds, the ASV has reached the target position for every performed simulation while guaranteeing collision avoidance with OV_i. For the simulations starting at x = -90 and x = -80, the algorithm does not perform a collision avoidance maneuver. This is again because OV_i never violates the generated arena and thus the state of the finite state machine never switches from standing on. With this, the designed algorithm assumes the ASV crosses sufficiently far ahead of OV_i. The simulations also show that the algorithm does not take any action to avoid collision for the simulations starting at x = 40, x = 50 and x = 60. This is not because OV_i does not violate the arena, but it is because the ASV can still adequately avoid collision and guarantee a big enough passing distance to OV_i without performing any alteration. COLREG 15 covers crossing simulations and this rule states that the vessel that has the other vessel on its starboard side should be giving way and should avoid crossing ahead of OV_i. Figure 7.3 displays that the algorithm always comes up with a safe maneuver that is compliant with COLREG 15.

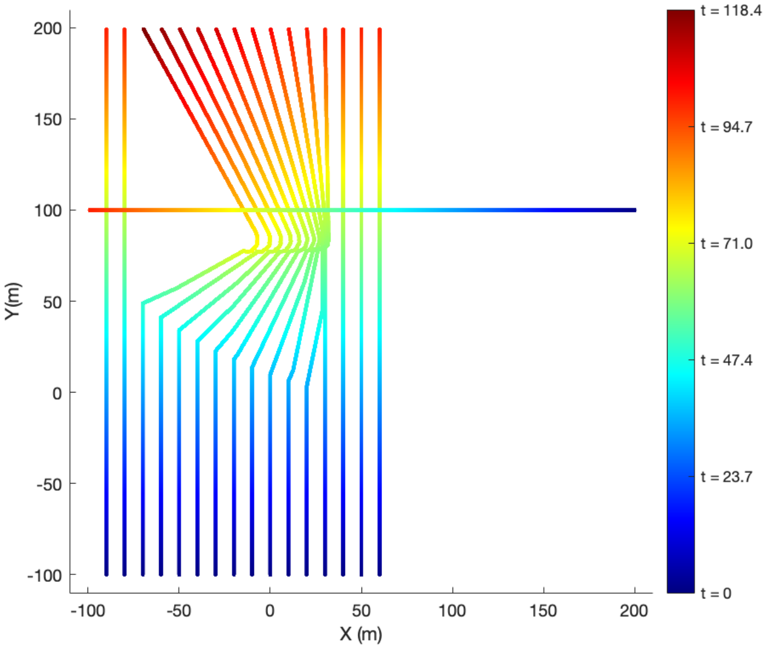


Figure 7.3: A set of crossing encounter simulations where the ASV moves upwards from y = -100 and maneuvers behind the OV

The inter-distance between the ASV and OV_i throughout 3 of the crossing simulations is displayed in Figure 7.4. These lines represent the inter-distance in the simulations starting at x = 0, x = 10, and x = -10, to display safe navigation for any starting x-position. As can be seen in this figure, the ASV manages to maintain a safe distance to OV_i that is greater than the minimum required distance, again represented by the red line.

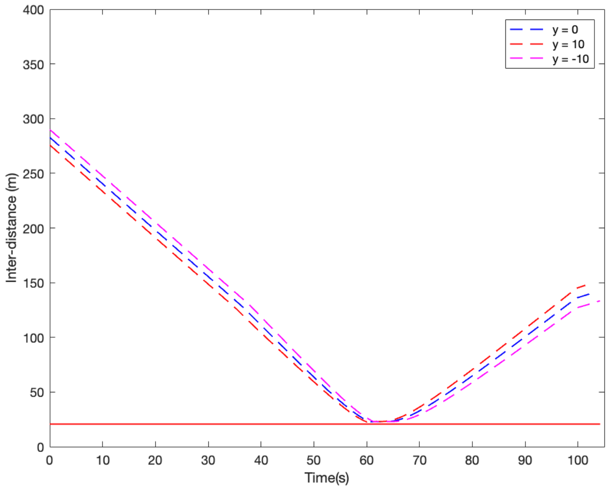


Figure 7.4: The inter-distance between the ASV and OV_i in 3 of the crossing simulations, displaying safe navigation is maintained

Overtaking encounters

COLREG 13 covers overtaking scenarios, and this rule states that the overtaking vessel has give-way compliance to the vessel being overtaken. The ASV overtakes OV_i, and the starting- and target- x-coordinate are shifted by 10 meters for every simulation. For the starting position [-60,-200], the target position is [60,200], for the starting position [-50,200] the target position is [50,200], and so on. OV_i moves from [0,0] to [0,150] with half the velocity of the ASV, to guarantee the ASV has to overtake it. This set of overtaking scenarios displays compliance with COLREG 13 (a) and (b), but it also shows compliance with part (d) of COLREG 13, stating that an alteration of the bearing between the vessels does not make the overtaking vessel a crossing vessel and relieve it from its duties. The algorithm accounts for this by assigning a different role for port/starboard overtaking, further displayed in the chapter presenting the results.

Figure 7.5 displays a set of superimposed vessel-to-vessel overtaking scenarios, where the ASV overtakes OV_i while running the proposed algorithm. After approximately 107.5 seconds, the ASV has reached the designated target position for each of the simulations running the proposed algorithm, while guaranteeing collision avoidance with OV_i. For the simulations starting at x = 50, x = 60, x = -50, and x = -60, the ASV does not make any drastic maneuvers in the overtaking of OV_i, which is again because it can maintain an appropriate inter-distance to OV_i while reaching its goal. COLREG 13 does not explicitly state towards what side the overtaking vessel needs to maneuver to avoid collision. However, COLREG 13 does state that the overtaking vessel maintains the give-way vessel until the situation is fully resolved. To avoid complicated situations where the ASV would need to cross ahead of OV_i after it has overtaken it, the side at which the ASV passes OV_i is dependent on the relative heading. The relative heading helps indicate towards which side the target position of the ASV is, which ensures that potential dangerous crossing situations right after the overtaking maneuver has been performed are avoided at all costs.

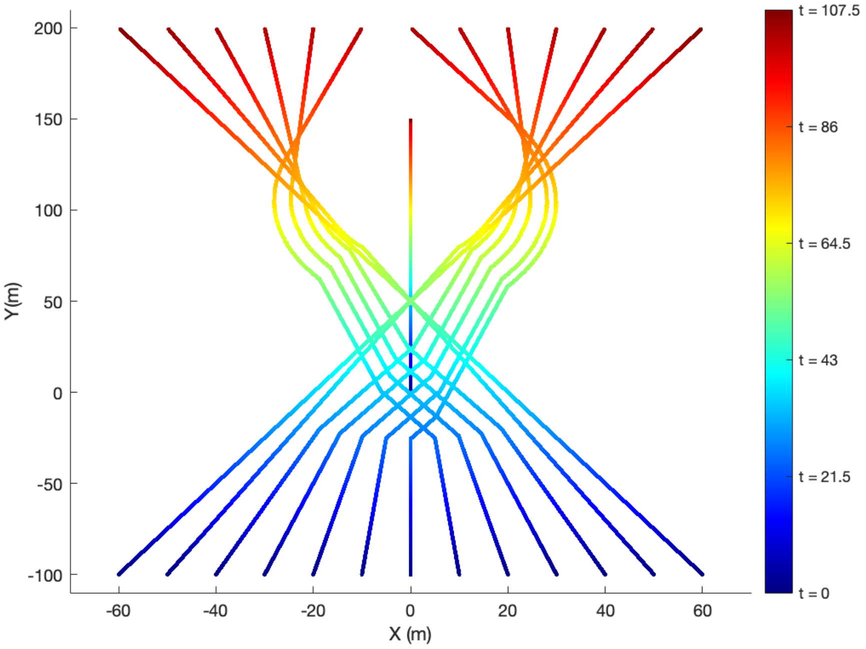


Figure 7.5: A set of overtaking encounter simulations where the ASV overtakes OV_i to both sides, depending on the target position

The inter-distance between the ASV and OV_i throughout 3 of the overtaking simulations is displayed in Figure 7.6. The lines represent the inter-distance throughout the performed simulations starting at x = 0, x = 10, and x = -10. This figure displays that the ASV maintains a safe inter-distance to OV_i for each of these simulations while moving towards its target position. The results of the simulations where the algorithm of Thyri et al. is run are displayed shortly, after which a proper comparison is performed.

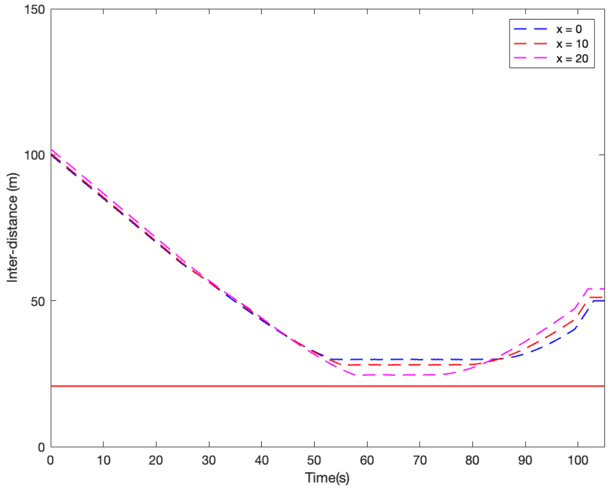


Figure 7.6: The inter-distance between the ASV and OV_i in overtaking scenarios, displaying the minimum inter-distance is never violated

Figure 7.7 displays the simulation results of the presented head-on, crossing, and overtaking simulations where the algorithm of Thyri et al. [1] is run. As can be seen from these figures, the algorithm developed by Thyri results in safe navigation in these vessel-to-vessel scenarios. The maneuvers that are performed by the ASV are COLREG compliant, as the ASV passes OV_i while seeing her on her own port side for all of the simulations. The most notable difference between the simulations that were performed running the developed VO algorithm and the work of Thyri et al. is in the overtaking scenarios. A more thorough comparison is hereafter provided.

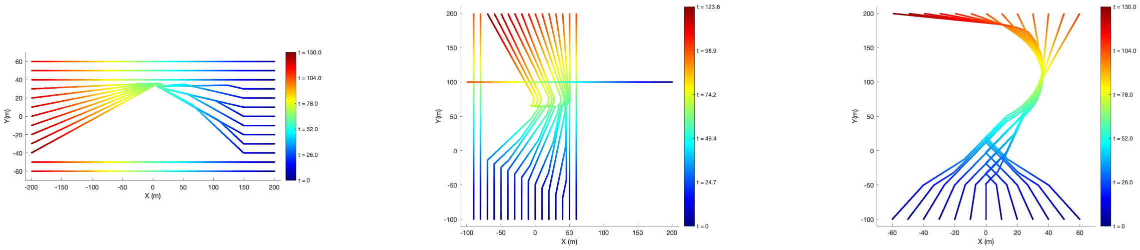


Figure 7.7: The results of the same head-on, crossing and overtaking simulations running the algorithm of Thyri et al. [1]

7.2.1. Overtaking scenario comparison

Figure 7.8 presents a side-by-side comparison of the results of the overtaking simulations running the developed VO algorithm and the algorithm of Thyri et al. The left figure shows the simulations where the proposed algorithm is run, and the figure on the right shows a set of overtaking simulations running the algorithm of Thyri. Running the algorithm of Thyri et al., the target position is reached after approximately 128.9 seconds for every simulation. COLREG 13 considers overtaking situations, and this rule states that the vessel that is overtaking always has to give way to the vessel being overtaken and it maintains the give-way role until the encounter situation is completely resolved. For the newly developed VO algorithm, β_r and ψ_r are used to distinguish port and starboard overtaking. This distinction is made to specifically ensure that further dangerous situations are avoided after the ASV has overtaken OV_i. As can be seen in the right figure of 7.8, the algorithm of Thyri does not make this distinction. Regardless of the relative heading and the target position, the ASV overtakes towards starboard side. This does however lead to the ASV crossing ahead of OV_i if the target position is to the left of the target position of OV_i. Usually in this crossing scenario, OV_i would be the give-way vessel, but as it has just been overtaken by the ASV, the ASV still has the give-way responsibilities in this situation. The ASV fails to fulfill this role in these overtaking situations and creates an unnecessary and unsafe encounter situation with OV_i.

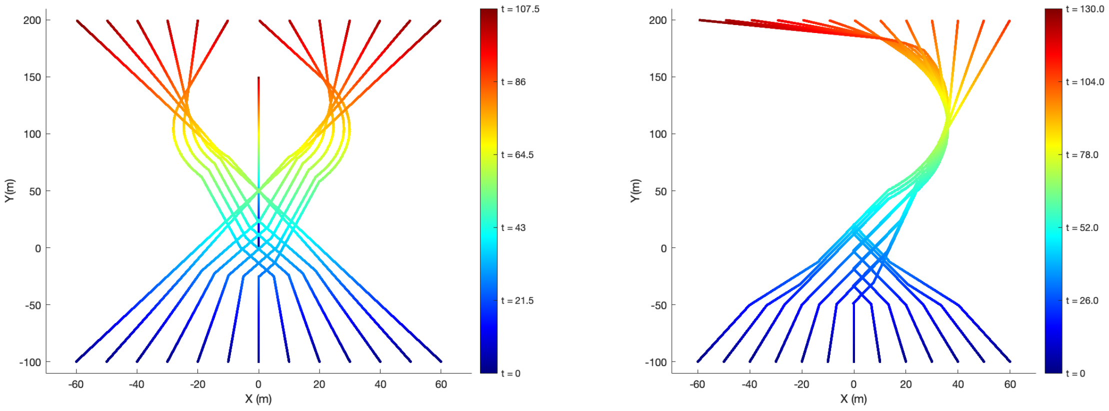


Figure 7.8: The performed overtaking simulations running the proposed algorithm (left) and the algorithm of Thyri et al. [1] (right), showing that the developed algorithm makes a clear distinction in passing side

7.2.2. Time to goal

The time that the ASV needs to reach the target position for the different simulations is a valuable KPI. An algorithm that averages a shorter time to goal while guaranteeing COLREG compliance and safe navigation can be considered more efficient than another algorithm. The time-to-goal KPI shows the ability of the algorithm to plan and make adequate decisions while avoiding collision. Table 7.3 shows the time to goal of the performed head-on, overtaking, and head-on scenarios running the newly proposed algorithm. Table 7.4 displays the time to goal of the same simulations performed using the algorithm of Thyri et al.

Table 7.3: Time to goal for different starting positions running the developed VO algorithm

Encounter situation	Head-on	Crossing	Overtaking
x/y = -90		99.8	
x/y = -80		99.8	
x/y = -70		118.4	
x/y = -60	133.1	115.6	107.5
x/y = -50	133.1	113.0	105.3
x/y = -40	133.1	110.6	103.6
x/y = -30	150.8	108.3	102.5
x/y = -20	143.6	106.2	102.0
x/y = -10	140.0	104.3	102.3
x/y = 0	137.7	102.7	103.1
x/y = 10	135.9	101.5	102.3
x/y = 20	134.7	100.6	102.0
x/y = 30	133.9	100.0	102.5
x/y = 40	133.1	99.8	103.6
x/y = 50	133.1	99.8	105.3
x/y = 60	133.1	99.8	107.5

Table 7.4: Time to goal for different starting positions running the algorithm of Thyri et al.

Encounter situation	Head-on	Crossing	Overtaking
x/y = -90		99.8	
x/y = -80		99.8	
x/y = -70		123.4	
x/y = -60	133.1	120.8	108.5
x/y = -50	133.1	118.4	106.6
x/y = -40	144.8	114.8	105.0
x/y = -30	142.2	112.6	103.9
x/y = -20	139.6	110.6	103.6
x/y = -10	137.8	107.2	103.8
x/y = 0	136.3	105.1	104.7
x/y = 10	134.9	103.5	107.8
x/y = 20	134.1	102.1	111.7
x/y = 30	133.9	101.2	115.8
x/y = 40	133.1	100.6	120.5
x/y = 50	133.1	99.8	125.2
x/y = 60	133.1	99.8	130.0

7.2.3. Heading angle deviation

As was repeatedly mentioned throughout the introductory part of this paper, one of the major downsides of implementing the Velocity Obstacle algorithm in collision avoidance of ASVs is the reactive nature of the algorithm. Implementing an appropriately designed approach of the ship arena into this framework has been done to help overcome this shortcoming and to make the algorithm more proactive. The KPI used to demonstrate this, is the deviation of the heading angle throughout the simulations. As these simulations are performed without any limitations in the change in heading of the ASV, this is a concise and effective KPI to test whether the developed VO algorithm is more proactive and requires less reactive maneuvers to avoid collision while navigating towards its target position. To demonstrate this, the change in heading angle throughout 3 head-on, crossing, and overtaking simulations is simulated and the overall deviation of the heading angle is compared. To avoid cluttered figures and because it is assumed that 3 simulations are enough to display the differences, only the heading angle of 3 encounter situations is shown. Figure 7.9 presents the heading angle of the ASV throughout the different scenarios of vessel-to-vessel encounters running the algorithm of Thyri et al [1].

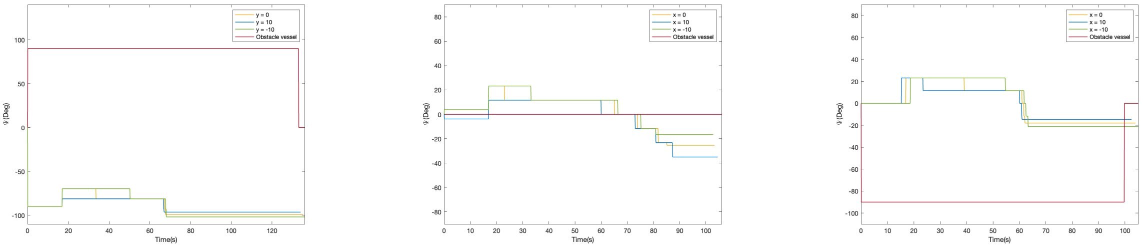


Figure 7.9: The heading angle of the ASV throughout the vessel-to-vessel simulations running the algorithm of Thyri et al. [1]

And Figure 7.10 presents the heading angle of the ASV throughout the same vessel-to-vessel simulations, using the developed VO algorithm.

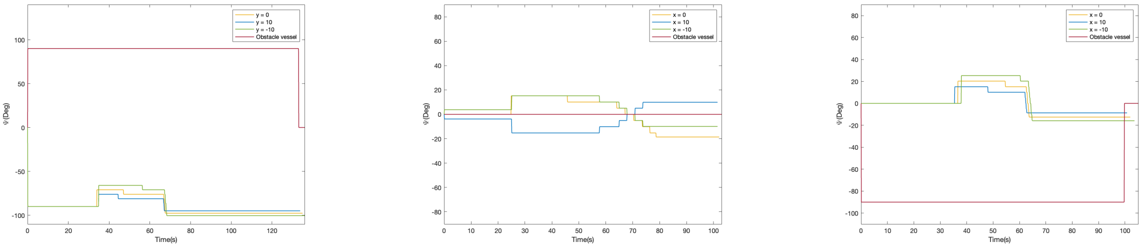


Figure 7.10: The heading angle of the ASV throughout the vessel-to-vessel simulations running the developed VO algorithm

7.3. Complex scenarios

Complex scenarios are simulated to display the wide applicability and give a more comprehensive assessment of the designed collision avoidance algorithm. These complex scenarios present how the developed algorithm deals with complex scenarios where failing to resolve these encounter situations could potentially have destructive consequences. These simulations display how well the algorithm adapts to different environments and how the algorithm deals with multiple encounter situations at once efficiently. The results of the performed complex scenarios running the developed algorithm are hereafter presented. These results show how the algorithm deals with the proposed scenarios.

7.3.1. Head-on and crossing scenario

Firstly, a scenario with 3 vessels where the ASV running the presented algorithm encounters an OV in a head-on encounter and sequentially encounters another OV in a crossing encounter. The bottom ASV, starting at [0;-50] and moving to target position [0;300], is running the proposed algorithm, but the top ASV, starting at [0;250] and moving to target [0;0], and the bottom right ASV, starting at [200;-50] and moving to target [-50;150], are not running the algorithm. The goal of this complex simulation is to display how the algorithm deals with sequential head-on and crossing encounter situations. The setup of this encounter situation is displayed in Figure 7.11. The ASV in red is the only vessel running the proposed algorithm and the other 2 obstacle vessels continue their journey without taking any action to avoid collision. The ASV first finds itself in a head-on scenario with the green OV and sequentially enters a crossing encounter with the blue OV. The algorithm manages to sufficiently avoid collision with each vessel while complying with COLREG 14 and 15. The trajectories of the different vessels throughout this simulation are presented in Figure 7.12. This figure shows that the ASV running the algorithm firstly gives way to the green ASV by altering to starboard, which is in line with COLREG 14. It then encounters the blue ASV in a starboard crossing encounter and alters even further to starboard to cross behind the OV, which is in line with COLREG 15.

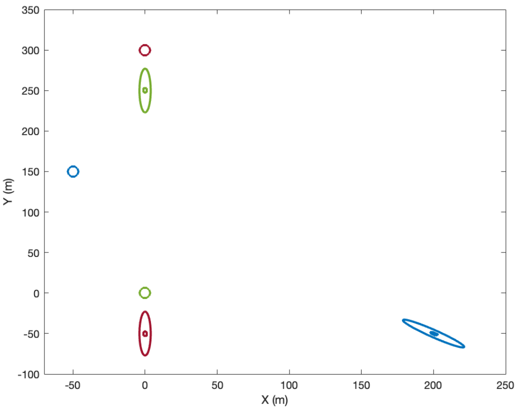


Figure 7.11: The setup of the complex head-on + crossing scenario, where the red ASV is the only one running the developed algorithm

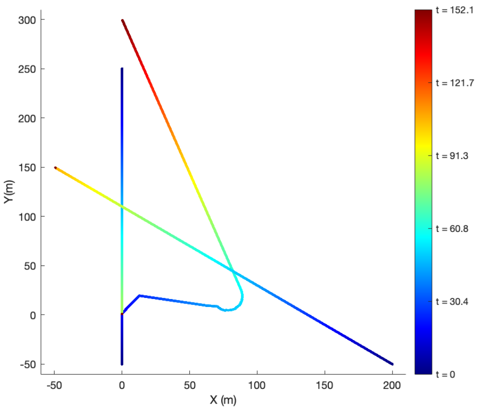


Figure 7.12: The trajectories of the ASVs in the head-on + crossing scenario

The inter-distance between the ASV running the proposed algorithm and the 2 obstacle vessels is presented in Figure 7.13, displaying proper collision avoidance throughout the simulations. The inter-distance between the ASV running the algorithm and the 2 obstacle vessels never gets below the threshold for safe passing, represented by the red line. The heading angle of each ASV is presented in Figure 7.14, showing good consistency while avoiding collision and reaching the target position.

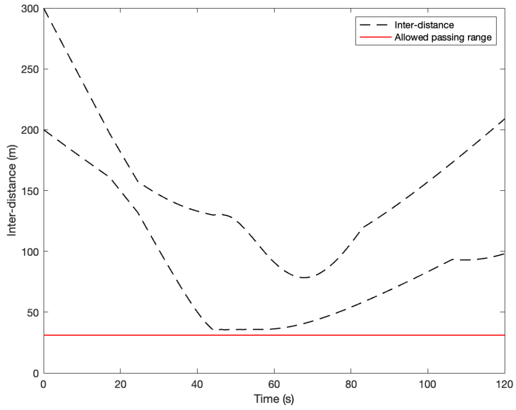


Figure 7.13: The inter-distance between the vessels throughout simulation

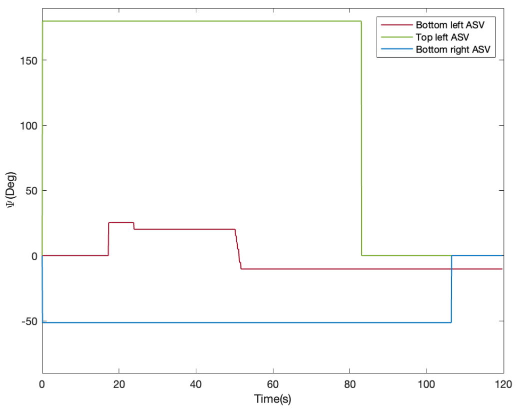


Figure 7.14: The heading angle of the vessels throughout the simulation

7.3.2. Head on and emergency port crossing

Secondly, another complex scenario with 3 vessels is simulated. The bottom left ASV, starting at [-100;-100] with target position [140;140], is running the proposed algorithm, and the top right ASV, starting at [100;100] with target position [-140;-140], is also running the proposed algorithm. The bottom right vessel, starting at [100;-100] with target position [-140;140], is not running the proposed algorithm and will therefore not take any action to avoid collision, even though COLREG 15 implies it has to give way to the top right vessel. The reason for not running the algorithm for the bottom right vessel is to present how the algorithm performs in emergency situations. Since the bottom right vessel is not performing any maneuvers to solve the starboard crossing encounter, the top right vessel finds itself in an emergency port crossing scenario with the bottom right vessel, while also solving a head-on encounter situation with the bottom left vessel. The setup of the simulation is displayed in Figure 7.15. The red and the blue ASV are running the algorithm and encountering each other head-on, but the blue ASV encounters the green ASV in a port crossing encounter where the green ASV was initially meant to give way but failed to take substantial action as it is not running the algorithm. The green ASV would be the give-way vessel in the encounter situation with the blue ASV, but as the goal of this simulation is to display the ability of the algorithm to deal with emergency situations, it is simply continuing its journey without taking action. The trajectories of the ASVs are shown in Figure 7.16, which displays how the blue ASV makes a 180-degree turn to ensure collision with the green ASV is avoided. Once the green ASV is truly past and clear, the blue ASV turns back and continues sailing towards the goal.

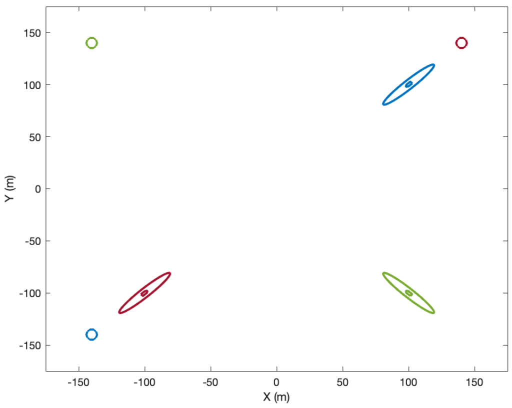


Figure 7.15: The setup of the complex head-on + emergency port crossing scenario with 3 vessels, where the red and blue ASV are running the developed VO algorithm

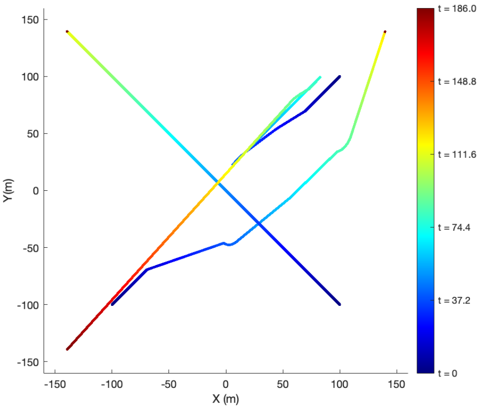


Figure 7.16: The trajectories of the ASVs in this complex head-on + emergency port crossing scenario

The inter-distance between each ASV throughout this simulation is presented in Figure 7.17, again displaying proper collision avoidance throughout this complex encounter scenario. The inter-distance between any of the vessels running the algorithm never gets below the minimum threshold for safe passing, represented by the red line. The heading angle of the ASVs throughout the simulation is presented in Figure 7.18, showing good proactive decision-making throughout this simulation.

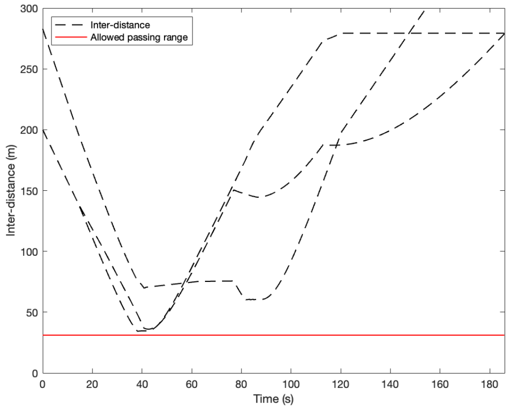


Figure 7.17: The inter-distance between the vessels throughout the head-on + emergency port crossing scenario

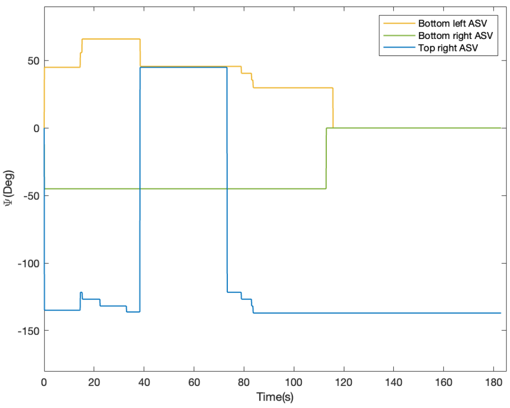


Figure 7.18: The heading angle of the vessels throughout the simulation

7.3.3. Encounter situation with 4 vessels

Finally, an encounter situation where 4 vessels move to the exact opposite of a grid from 4 different corner points is run. Each ASV runs the presented algorithm and starts at one of the corner points of a grid going from -100 to 100 in x- and y-direction. The target positions of the ASVs are in the opposite corner of a grid going from -140 to 140 in x- and y-direction. With each ASV having a target position exactly mirrored to the origin at [0,0], every ASV has to solve an encounter situation with the 3 OVs attempting to achieve a similar goal. The setup is displayed in Figure 7.19 and shows the different vessels starting from all corners of the grid. Each of the 4 vessels runs the proposed algorithm, so none of the vessels fails to take responsibility to avoid collision. Every ASV finds itself in a head-on encounter situation and a starboard crossing encounter simultaneously. The algorithm again manages to solve this situation and every ASV makes its way to its target position while complying with COLREGs and adequately avoiding collision with the other vessels. The trajectories of the ASVs are presented in Figure 7.20.

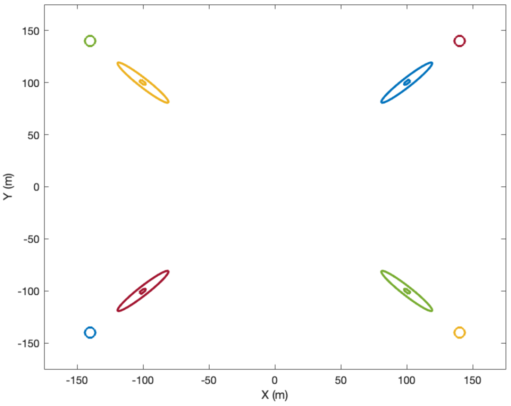


Figure 7.19: The setup of the complex scenario with 4 vessels moving across a grid

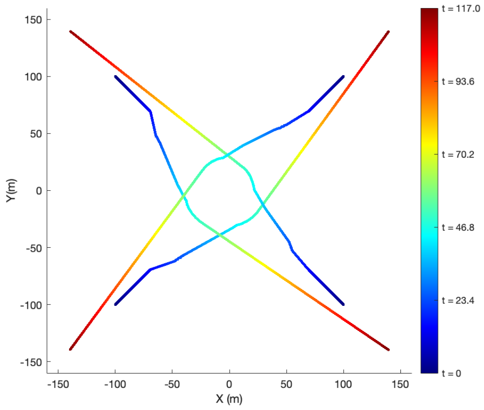


Figure 7.20: The trajectories of the ASVs in the developed complex scenario

The inter-distance between each of the ASVs running the algorithm in this scenario is presented in Figure 7.21. This figure shows that a safe inter-distance is maintained between any of the vessels throughout this simulation. The minimum inter-distance at every time point of the simulation is displayed with the blue line, and it can be seen that this minimum inter-distance never goes below the safe passing threshold, represented by the red line. The heading angle of the ASVs is presented in Figure 7.22, showing decisive decisions throughout these simulations.

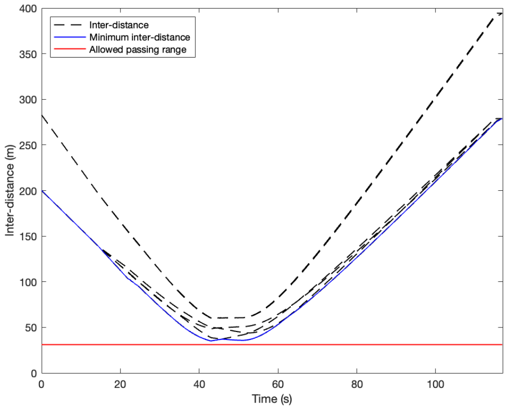


Figure 7.21: The inter-distance between the 4 vessels throughout the simulation, where the blue line represents the minimal inter-distance

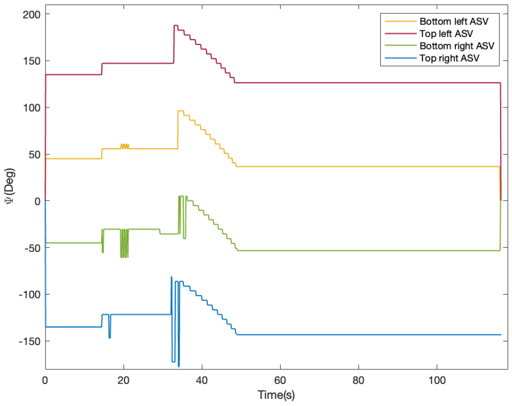


Figure 7.22: The heading angle of the vessels throughout the simulation

7.4. Conclusions on the performed simulations

In this chapter, the results of the performed simulations have been presented. In this section, conclusions are drawn from the obtained results and the performance of the algorithm is analyzed compared to the state-of-the-art.

7.4.1. Safe navigation

Safe navigation is the primary point of attention in a collision avoidance algorithm for ASVs. If safe navigation cannot be guaranteed, none of the other aspects of the algorithm matter. For each of the simulations, both the batch simulations and the complex, multi-vessel simulations, the inter-distance between the vessels was tracked throughout the entirety of the simulation. Figures 7.2, 7.4 and 7.6 provided the inter-distance between the ASV running the proposed algorithm and the OV for head-on, crossing, and overtaking scenarios. In each of these situations, the ASV ensured that a proper safe distance was kept to the ASV. In every case, the provided minimum safe passing distance was never violated. This minimum safe passing distance was obtained from the Minkowski sum of the ship domains, which was extensively explained in a previous chapter.

For the complex scenarios, the inter-distance between the vessels was also generated throughout the simulations. Figures 7.13, 7.17 and 7.21 provide the inter-distances between the different vessels throughout the different complex scenarios, again guaranteeing safe navigation. The red line, representing the minimum safe passing distance has remained respected throughout all of these simulations.

7.4.2. COLREG compliance

COLREG compliance is another vital aspect of the developed collision avoidance algorithm. To guarantee safe navigation and to ensure adequate decision-making, the COLREGs provide a concise rulebook describing each of the encounter situations. As there is no proper performance indicator to gauge COLREG compliance, the eye test is used to draw conclusions on this.

COLREG 13 through 15 are the main relevant COLREGs in implementing this algorithm. The head-on simulations, displayed in Figure 7.1, show how the algorithm implements COLREG 14, covering head-on scenarios. In head-on situations, the ASV is meant to maneuver to her own starboard side to avoid collision with the OV. These batch simulations show that for all cases where the OV violates the arena and the algorithm thus takes action to avoid collision, the ASV indeed maneuvers to starboard side and passes the OV while seeing it on its own port side, thus complying with COLREG 14.

The crossing simulations, displayed in Figure 7.3, show how the algorithm implements COLREG 15, covering crossing situations. In crossing situations, the vessel that has the other vessel on its starboard side is forced to give way, which is the ASV running the proposed algorithm for these simulations. Bar the simulations where the OV never violates the correspondent arena and the ASV continues moving in a straight line towards its target position, the ASV takes proper action for each of the simulations. A maneuver towards its starboard side is performed to guarantee that the ASV crosses behind OV_i, which is required according to COLREG 15. We can thus conclude that the algorithm complies with the rules in crossing situations.

The overtaking simulations, displayed in Figure 7.5, show how the algorithm implements COLREG 13, covering overtaking situations. COLREG 13 does not provide a clear obligation for which side the overtaking vessel should pass the OV on, but the overtaking vessel is always the give-way vessel in these encounters. The proposed algorithm makes a clear distinction in what side it passes OV_i on, based on the relative heading between the 2 vessels. This is to comply with part (d) of COLREG 13, stating that the overtaking vessel is not relieved of its duty of keeping clear until she is finally past and clear.

The complex scenarios also show proper COLREG compliance. In the head-on + crossing scenario, the ASV running the algorithm properly maneuvers to its own starboard side to avoid the head-on OV, after which it runs into the crossing encounter with the OV crossing from starboard. It further maneuvers to its own starboard side to ensure the ASV crosses behind the crossing OV, thus complying with COLREGs.

In the head-on + emergency port crossing scenario, the ASV running the proposed algorithm correctly maneuvers to its own starboard side to avoid collision with the head-on OV. Once the OV approaching from its own port side violates the arena and it becomes clear that the OV crossing from port has not taken appropriate action to avoid collision, the ASV turns away from the OV to ensure collision is avoided. COLREG 17 states that the stand-on vessel should not alter to port in an emergency port crossing situation, and the ASV complies with this while performing an emergency maneuver.

The complex scenario with 4 vessels moving across the grid from different corners displays how each of the ASVs deals with simultaneous head-on + crossing scenarios. The algorithm shows that this situation is solved properly, and each ASV takes the COLREG-compliant maneuvers to avoid collision with the ASVs it is forced to give way to. All of the ASVs pass the OVs they are meant to give way to on their port sides, which aligns with COLREG 14 and 15.

7.4.3. Time to target

The time that both the developed VO algorithm and the algorithm of Thyri et al. needed to reach the target position for the different batch simulations of the head-on, crossing, and overtaking encounters were presented in Table 7.3 and 7.4. The time to reach the target provides promising insight into the efficiency of the developed algorithm, which was cut down a decent bit for the crossing simulations, cut down significantly for overtaking simulations, and only slightly increased for head-on scenarios. Figure 7.23 displays the difference of the time to goal of the performed head-on, overtaking, and crossing simulations running the presented algorithm and the algorithm of Thyri et al. using boxplots. On average, the newly presented algorithm has a 6.8 % shorter time of elapse for overtaking scenarios, a 2.3 % shorter time of elapse for crossing situations, and a 0.36 % longer time of elapse for overtaking situations, which is nearly negligible. The developed algorithm also showed less deviation in the time the ASV needs to reach the target position, hinting at a more consistent and efficient result. Overall, the proposed algorithm provides a significant decrease in the time of elapse of the performed simulations, which is a promising result. This all while guaranteeing COLREG compliance for every vessel-to-vessel encounter situation, as was shown before this section.

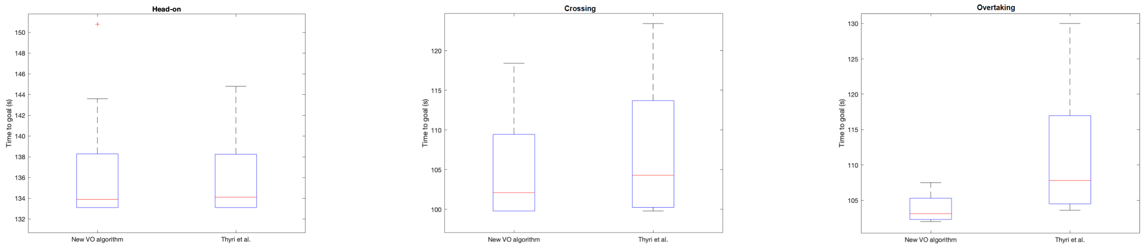


Figure 7.23: Comparison of the time time to goal of the simulations between the presented algorithm and the work of Thyri et al.

7.4.4. Heading angle deviation

To display the ability of the proposed algorithm to make adequate decisions and guarantee COLREG compliance more proactively, the heading angle deviation of the ASV throughout the different batch simulations was measured and compared to the algorithm of Thyri et al. The heading angle was tracked throughout 3 of each of the simulations, which is assumed to give sufficient insight. The developed VO algorithm shows a clear decrease in the heading angle change throughout these simulations. To further back up these claims, the overall changes in heading angle of the ASV throughout these simulations are presented in Tables 7.5 and 7.6, showing a clear decrease in the overall deviations in the heading angle throughout the performed simulations.

Table 7.5: Total heading deviations running the proposed algorithm

Encounter situation	Head-on	Crossing	Overtaking
x/y = -10	58.57 °	66.58 °	36.53 °
x/y = 0	45.74 °	53.04 °	49.04 °
x/y = 10	32.81 °	39.09 °	36.53 °

Table 7.6: Total heading deviations running the algorithm of Thyri et al.

Encounter situation	Head-on	Crossing	Overtaking
x/y = -10	52.51 °	67.65 °	59.28 °
x/y = 0	49.82 °	64.41 °	71.85 °
x/y = 10	23.83 °	61.09 °	62.05 °

7.5. Discussion on results

Some discussion points arise from the results presented in this chapter, which is done in this section. Firstly, the simulations have been run using parameters assumed from an existing autonomous surface vessel. The parameters have been assumed through the existing work on the Heron ASV [114], which was assumed to be a sufficient baseline to display the algorithm's effectiveness. The parameters used also heavily impact the dimensions of the ship domain and the arena, but the provided approach would scale appropriately to bigger-sized vessels with different dimensions.

An interesting point of discussion is the deviation of the heading angle throughout the performed simulations. The heading angle has looked relatively consistent throughout most of the performed simulations, but a few noteworthy exceptions can be observed. The proposed algorithm was implemented without limitations to the rotational velocity, meaning that the ASV could apply swift changes in heading if necessary. Especially in the complex, multi-vessel scenarios, the heading angle changes drastically throughout the simulation. In the head-on and emergency port crossing scenario, the ASV that performs an emergency maneuver to avoid a collision with an obstacle vessel crossing from port side performs a drastic turn to avoid collision, leading to an immediate change in the heading angle of 180 degrees. Such a drastic alteration is unrealistic for most vessels but has been assumed sufficient to display the algorithm's effectiveness. In the complex scenario with 4 vessels moving across a grid, some jitters can be seen in the heading deviation of 2 of the ASVs. This happens because the algorithm assumes a certain candidate velocity is safe and wouldn't lead to COLREG-incompliant behavior, but in reality, it would. The algorithm then quickly realizes this and adjusts the heading angle back to the previous value. This only happens because the algorithm can quickly change the heading angle, which would be unrealistic in a real-time application. This behavior is not assumed to be problematic for the overall performance of the algorithm and has no impact on the eventual COLREG-compliant and safe maneuvers.

7.6. Conclusion

This chapter has provided the second part of the answer to the research question: *How does the integration of the ship domain and arena influence the performance of the VO collision avoidance algorithm?* In this chapter, the results of the simulations using the designed collision avoidance algorithm have been presented. The results are analyzed and compared to the work of Thyri et al. [1], which is assumed to be state-of-the-art. The results look promising compared to the research work from the literature. The developed VO algorithm looks to perform better regarding proactive maneuvers and the time to target that the algorithm needs to take the ASV to its target position. In the next chapter, Chapter 8, general conclusions are drawn and recommendations for future research are presented.

8

Conclusions and Recommendations

In the previous chapters, a COLREG-compliant collision avoidance algorithm has been presented that uses the Velocity Obstacle algorithm combined with the concept of the ship domain and the ship arena, mainly presented in chapters 3 through 6. Chapter 1 introduced the subject and gave background information regarding autonomous vehicles, particularly autonomous surface vessels. Chapter 2 provided an extensive literature review of the existing research regarding collision avoidance of ASVs and other autonomous vehicles. The research on risk measurement was provided and gaps in the literature were obtained. By precisely defining the research questions of this research, the main research question:

How can the integration of the ship domain and arena improve the reactive nature of the Velocity Obstacle algorithm and guarantee COLREG-compliant collision avoidance?

has been answered and the elaboration on this is provided in this chapter. The research questions that were formed are answered one by one, after which recommendations for future research are provided to further bridge the gap towards fully autonomous surface vessels being deployed in real-life situations.

8.1. Addressing the Research Questions

The research questions composed in Chapter 2 have been answered throughout this research. A retrospect of this is now provided.

8.1.1. Sub Research Questions

How can the COLREGs be effectively classified and prioritized within the decision-making of ASVs to ensure robust and compliant collision avoidance?
Chapter 3 provided a step-by-step elaboration on how the COLREGs have been categorized in this research and implemented into the control framework. The COLREGs were first analyzed one by one to recognize which of the COLREGs needed to be considered in the collision avoidance framework of the ASV. A precise description of each COLREG was provided and the impact on the states of the ASV was provided.

After the relevant COLREGs were classified and it had been obtained which of the COLREGs needed to be implemented into the framework, the according criteria to distinguish the different encounter situations were obtained. The relative bearing β_r and the relative heading ψ_r were elaborated and the values of these classification criteria that were used to classify the different roles and encounter situations were decided. The approach used by Cho et al. [97] was extended to cover all potential different encounter situations fully. The concept of a finite state machine was explained and the different transition criteria based on the values of the relative bearing and heading were proposed.

What is the role of the ship domain and what are the primary factors influencing the definition of the ship domain?
Chapter 4 gave a thorough explanation of the concept of the ship domain and how the existing approaches using a similar concept have gone about doing so. The reasoning for the determination of the size and shape

of the ship domain for this research has been provided, and the argumentation for the need for velocity dependency in the size of the domain has been explained. Shortcomings of the state-of-the-art on the ship domain were highlighted and the newly developed approach has been developed to improve on these shortcomings and make the ship domain more generally applicable in collision avoidance of ASVs.

What is the role of the ship arena and how does it impact ASV collision avoidance?
Chapter 5 provided a precise approach to the determination of the ship arena in this research. Much like in Chapter 4, the existing approaches using a similar concept were highlighted and their shortcomings were mentioned. The existing research on the ship arena is a lot less than on the ship domain, as this is a newer concept in risk measurement of ASVs. The determination of the size and shape of the arena was also provided, where the dimensions are not only dependent on the dynamics of the ASV but also on the dynamics of the respective obstacle vessel. The shifts of the semi-minor- and major axes of the arena were mentioned, which is performed to incorporate COLREG-compliance into the arena dimensions.

How does the integration of the ship domain and arena influence the performance of the VO algorithm?
After all of the building blocks of the algorithm had been obtained in chapters 2 through 5, the finalized algorithm was presented. Chapter 6 covers the implementation of the algorithm, which starts with an explanation of the baseline Velocity Obstacle algorithm and elaboration on how the collision cones are generated for this research. It also provided a deep dive into the control of the ASV by showing the vessel model and the information shared between the different vessels throughout the simulations. The preferred passing side, which was obtained through the relevant COLREGs, was provided for the different roles that the ASV can take in an encounter situation. The candidate velocities were presented and the objective function that was minimized to obtain the optimized control output for every iteration was displayed.

To evaluate the performance of the proposed collision avoidance algorithm and to really see the impact of the ship domain and arena, key performance indicators (KPIs) were constructed based on commonly used KPIs in the literature. Several batch vessel-to-vessel simulations were presented to test the algorithm's performance when different COLREGs need to be applied. To focus on the proactive nature of the algorithm, the heading deviation and the time to target were introduced as additional KPIs for this research. Finally, complex scenarios were presented to display the algorithm's performance in tough situations, displaying the adaptability and robustness of the proposed algorithm.

The results of these simulations were presented in chapter 7, where the vessel-to-vessel batch simulations and the complex simulations were presented sequentially. The results of the batch simulations were given to compare to the work of Thryi et al. [1], which has been used to represent the state-of-the-art throughout this research. The proposed algorithm performed well in all of the batch simulations, showing COLREG compliance for each of the encounter situations and confirming safe navigation through the measured interdistance to the obstacle vessel for each of the simulations. The developed algorithm showed a clear improvement in the time to goal for the batch simulations of the ASV, showing an improvement of 6.8 % for overtaking scenarios, 2.3 % for crossing scenarios, and a 0.36 % decrease for head-on scenarios. The total heading deviation of the ASV throughout these simulations also showed severe improvement in most of the simulations of the developed VO algorithm compared to the work of Thyri et al. All in all, these were promising results of the batch simulations.

The complex scenarios showed that the algorithm does well at dealing with multiple encounter situations at once. A head-on + crossing scenario was displayed and the simulations of the 4 vessels each maneuvering to the opposite corner showed the versatility of this algorithm. The head-on + emergency port crossing simulation showed how the algorithm solves emergency situations and guarantees safe navigation above all else.

8.1.2. Main Research Question

Throughout this thesis, a collision avoidance algorithm using the velocity obstacle algorithm alongside the concept of the ship domain and arena has been presented. The different COLREGs were analyzed and implemented in the decision-making of the proposed algorithm. A comparison to the work done by Thyri et al. [1] was performed to display the contribution to the state-of-the-art and complex scenarios were presented to display the effectiveness and robustness of the algorithm. All of this was done to answer the main research question:

How can the integration of the ship domain and arena enhance collision avoidance of ASVs to guarantee proactive and COLREG-compliant collision avoidance?

The variety of results has clearly shown that the algorithm manages to guarantee COLREG compliance in different encounter situations. The comparative study that was performed displays how the newly developed VO algorithm shows an increase in efficiency regarding the time to goal and shows a decrease in heading angle deviations, pointing to less reactive decision-making and a more proactive algorithm.

8.2. Recommendations for future research

This section provides some recommendations for future research to bridge the gap to a fully autonomous waterway:

1. **Safe passing distance**
   Not much attention has been given to the safe passing distance between the vessels or how freely the vessels could maneuver throughout this research. In certain waterways, where the water is more condensed and the ASVs can't move as freely, the maneuvers would be different and the safe passing distance, generated by the ship domain, should be adjusted.

2. **Limitations of the ASV movement**
   Throughout this research, no limitations have been applied to the movement of the ASV. For every iteration, a certain set of velocity candidates have been generated, but the current heading angle and surge velocity of the ASV were not accounted for in the process of generating these velocity candidates. To get closer to a realistic approach, the acceleration limitations of the ASV should be accounted for.

3. **Disturbances**
   Potential disturbances have largely been ignored throughout this research. Of course, ASVs sailing on a waterway come with a lot of natural disturbances and the data on obstacle vessels won't always be precisely known. In the future, more attention should be drawn to overcome these potential liabilities.

4. **Interaction with human operated vessels**
   On the road to the implementation of ASVs onto waterways, there needs to first be a hybrid approach, where waterways contain ASVs as well as human-operated vessels. The interaction between ASVs and human-operated vessels onto waterways is still a very unknown area and the desired behavior of ASVs when interacting with human-operated vessels should be researched.

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A

Scientific research paper

Collision avoidance of autonomous surface vessels considering proactive COLREG compliance

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Abstract—**This paper presents a COLREG-compliant collision avoidance and detection algorithm for the safe navigation of autonomous surface vessels. The method builds upon the Velocity Obstacle algorithm and implements the concept of the ship domain and the ship arena into the framework. The International Regulations for Preventing Collision at Sea – the COLREGs – are analyzed individually and incorporated in the designed collision avoidance algorithm. The COLREGs were used to determine the preferred passing side and optimized motion for every possible encounter situation with an obstacle vessel. The ship domain and arena help to perform proactive alterations when required, improving on the apparent shortcomings of the VO algorithm. This framework leads to a more proactive collision avoidance algorithm that guarantees COLREG compliance and safe navigation in mixed-traffic environments. The robustness and wide adaptability of the developed algorithm are validated in different encounter situations, ranging from vessel-to-vessel batch simulations to complex, multi-vessel scenarios.**

Index Terms—**Autonomous Surface Vessels, COLREGs, Velocity Obstacle, Collision avoidance, Ship domain, Ship Arena**

I. INTRODUCTION

The number of applications of autonomous machines and the desire to automate certain tasks and applications have been increasing rapidly in recent decades. Automated, unmanned systems are becoming integral in everyday life, typically employed to perform repetitive, tedious tasks. The number of implementations of autonomous vehicles has been increasing in different applications, such as unmanned aerial vehicles, autonomous ground vehicles, and autonomous underwater vehicles. While the maritime industry might not be as close to implementing autonomous vehicles onto waterways, the shift towards autonomy is happening swiftly. This drive to move towards autonomous vessels has been motivated by many factors, such as increased efficiency, reduced operational costs, and increased safety. Considering that around 75-96 % of marine casualties are related to human error (Celik and Cebi, 2009) and the number of marine accidents is continuously increasing (EMSA, 2018), autonomous navigation has the potential to drastically reduce the risk of collision, and with that reduce human casualties and environmental damage.

The process of implementing the International Regulations for Preventing Collision at Sea (COLREGs) into motion planning algorithms of autonomous surface vessels (ASVs) has proven to be challenging. The COLREGs were adopted in October 1972 and fully implemented by July 1977. The COLREGs set out the navigation rules that every seagoing vessel has to follow to avoid collision. It goes without saying that ASVs are also obligated to comply with these rules to avoid collision with other vessels. The COLREGs are classified into sections A to F, which cover different aspects of the rules. Section A elaborates on some general rules that explain the application of the COLREGs, some general definitions, and the responsibility of vessels concerning other vessels. Section B presents steering and sailing rules, which also cover rules regarding vessels in sight of one another and limited visibility. Section C elaborates on the rules regarding the lights and shapes of different types of vessels. Section D presents some rules on sound signals and Section E displays some exemptions to the rules. Lastly, section F presents the verification of compliance with the provisions of the convention. The COLREG classification is an essential part of collision avoidance of ASVs, as the COLREGs lay the foundation for the desired maneuvers in different give-way encounter situations. The COLREGs contain a lot of subjective terms such as ‘early’, ‘action that will be best to avoid collision’, and ‘as soon as it becomes apparent’, making it a challenging task to implement these rules into the control framework of ASVs.

Several control methods have been applied in existing research, such as the Artificial Potential Fields method (Wang et al., 2017). This algorithm is of low complexity but is highly reactive and difficult to combine with the COLREGs, often leading to rule violation. Search-based methods, such as the A* (He et al., 2022) and the Rapidly Exploring Random Tree (RRT) (Enevoldsen et al., 2021) algorithm have also been implemented in collision avoidance of ASVs. These algorithms search for a feasible path in a time-state space by creating obstacles in the discrete grid map to resemble compliant actions. However, these methods are not readily applicable to represent the complete set of regulations and often ignore part of the rules. Model Predictive Control (MPC) and its extensions are popular among collision avoidance applications. Kufoalor et al. (2020) presented an approach using automatic identification system (AIS) data from other vessels and applied model predictive control for safe navigation and collision avoidance. Tsolakis et al.

(2022) presented an approach based on Model Predictive Contouring Control, where the COLREGs are implemented. Safe navigation is guaranteed in mixed-traffic conditions and they implemented the COLREGs into the control framework. MPC can combine constraints of different natures, which is convenient for ASV motion control. However, MPC has high computational demands and is prone to deadlocks.

The Velocity Obstacle (VO) algorithm is among the most popular collision avoidance applications due to its simplicity and low complexity. Shaobo et al. (2020) incorporated a modified VO algorithm to handle the dynamic behavior of obstacle vessels (OVs). Kufoalor et al. (2018) used a dynamic reciprocal VO algorithm to incorporate the behavior of the obstacle vessel and deal with the uncertainty in the motion. Huang et al. (2019) presented a generalized VO algorithm to visualize the changes in the course and speed to adequately avoid collision. The VO algorithm is very fast to compute and of high performance, but its reactive nature makes it difficult to combine with the traffic regulations.

This work attempts to improve on the shortcomings of the VO algorithm by incorporating the concept of the ship domain and the ship arena into the framework. By defining precise dimensions for the ship arena, the collision avoidance of the ASV can be performed more adequately and effectively. The COLREGs are precisely defined and implemented through a finite state machine to guarantee concise collision avoidance maneuvers are maintained until the encounter situation has been resolved. The boundaries of the collision cone of the VO algorithm are composed through the Minkowski sum of the ship domain of the ASV and the obstacle vessel, which ensures a suitable minimum passing distance is maintained throughout the collision avoidance alterations. The developed method is demonstrated through several vessel-to-vessel batch simulations, where the algorithm's performance is compared to the work of Thyri and Breivik (2022), which is assumed to be state-of-the-art in this field. The remainder of this paper is structured as follows: In section 2, the concepts of the ship domain and ship arena are explained and the determination of the shapes and dimensions are provided. In section 3, the implemented algorithm is displayed and the COLREG classification is presented. Section 4 shows the results of the performed simulations and section 5 draws conclusions and shows some angles for future work.

II. THE SHIP DOMAIN AND SHIP ARENA

The ship safety domain, or ship domain in short, represents a safe distance around a vessel that is meant to be kept clear of obstacle vessels at any time. The ship domain of the ASV is denoted $\mathbf{D}$ and the ship domain of OV_i is denoted $\mathbf{D^i}$. Selecting a convenient shape and appropriate domain dimensions is crucial in incorporating the domain into the collision avoidance framework of ASVs. Circular ship domains have mostly been applied in existing research, but assuming an equal safe distance in all directions of the ASV is counter-intuitive. An elliptical shape is chosen in this work to maintain simplicity in the implementation while accounting for differences in the accepted safe passing distance in different encounter situations. In this work, the size of semi major-axis D_a and semi minor-axis D_b consist of 2 components: D_0 and D_1. Component D_0 defines a buffer distance independent of the velocity and the maneuverability. This component is necessary to ensure the size of the D_b never gets below a certain minimum value. This component D_0 defines the safe passing distance between 2 vessels passing each other head-on or in an overtaking encounter. D_0 strictly depends on the length of the ASV, as it is assumed that the safe passing distance in a head-on and overtaking encounter situation would be independent of the velocity of the vessels. The expression for D_0 is set as 2 times the length of the ASV, which is a number that is taken as an average of the length of the semi minor-axis in existing research, where this value varies in the range of 1.5 times the length up to 2.5 times the length of the ASV. The other component of the domain dimensions, D_1, considers the stopping ability and velocity of the ASV. The maximum reverse force that the thrusters can exert and the mass of the ASV are used to determine the stopping ability. Assuming constant deceleration of the ASV is possible, the required stopping time of the ASV can be calculated for the current surge velocity. A certain buffer time is implemented, representing the time the ASV needs to go from current surge velocity to maximum reverse thrust and thus maximum deceleration. The dimensions of the semi-major axis D_a and the semi-minor axis D_b are defined as

$$D_a = D_0 + D_1 = 2L + u_{avg,br} \cdot t_{brake} + u_{ASV} \cdot t_{buf} \quad (1)$$

$$D_b = D_0 = 2L \quad (2)$$

where L is the length of the ASV, $u_{avg,br}$ is the average surge velocity during the braking of the ASV, t_{brake} is the total time required for the ASV to come to a halt after the breaking has been initiated, u_{ASV} is the current surge velocity of the ASV and t_{buf} is a buffer time that the ASV needs to go from the current sailing surge velocity to a maximum reverse thrust, as it is assumed that the breaking motion cannot be initiated immediately. A graphical overview of the ship domain and its components can be seen in Figure 1.

The ship arena provides an 'action area' around the ASV that warns the controller that risk of collision exists once OV_i has violated the correspondent ship arena $\mathbf{A^i}$. The timing of collision avoidance maneuvers has always been a difficult problem in ASV navigation, but the ship arena provides a comprehensive approach. A separate ship arena is constructed for every obstacle vessel in the vicinity, and risk of collision is only deemed to exist with a specific obstacle vessel once that obstacle vessel has violated the correspondent ship arena. Figure 2 shows a graphical overview of different obstacle vessels violating their corresponding ship arena.

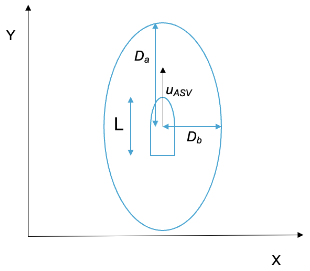

Fig. 1. A graphical overview of the semi-major and minor axes of the ship domain

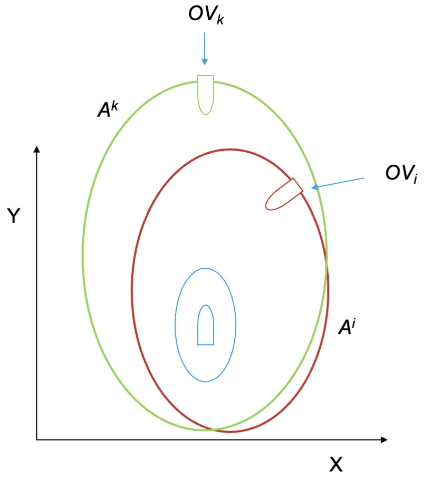

Fig. 2. A graphical overview of how multiple arenas are constructed in multi-vessel encounters

Circular ship arenas have often been applied in existing research, but circular ship arenas cannot distinguish between head-on, crossing, and overtaking encounter situations. An elliptical ship arena can help apply the COLREGs more efficiently. According to the COLREGs, it is desired that whenever the ASV is the give-way vessel in an encounter situation, OV_i is observed early and in ample time. To guarantee adequate distinguishing between different encounter situations and to ensure early maneuvers are performed, an off-centered, elliptical ship arena is implemented in this research. The dimensions of the semi-major axis A_a and semi-minor axis A_b are defined as

$$A_a = \frac{A_F + A_A}{2} \tag{3}$$

$$A_b = \frac{A_S + A_P}{2} \tag{4}$$

where the dimensions in fore (F), abaft (A), starboard (S), and port (P) directions are defined as

$$A_F = D_a + t_{crit}(u_{ASV} - u^i \cdot cos(\psi_r^i)) \tag{5}$$

$$A_A = D_a + t_{crit}(u^i \cdot cos(\psi_r^i) - u_{ASV}) \tag{6}$$

$$A_S = D_b + t_{crit}(u^i \cdot sin(\psi_r^i)) \tag{7}$$

$$A_P = D_b + t_{crit}(\frac{u^i \cdot sin(\psi_r^i)}{2}) \tag{8}$$

where D_a and D_b embody the semi-major- and minor axes of the ship domain, t_{crit} defines a certain critical time until the vessels would collide, u_{ASV} defines the surge velocity of the ASV and u^i defines the surge velocity of OV_i. Variable ψ_r^i defines the relative heading, which converts the relative velocity components of OV_i to the body-fixed frame of the ASV. Components D_a and D_b are used as baselines for the arena dimensions to ensure the arena is never smaller than the ship domain. The position of the ASV within the arena is shifted to account for the COLREGs and to ensure obstacle vessels approaching from the fore and starboard side are observed earlier. These shifts are defined as

$$\Delta a = A_F - A_A \tag{9}$$

$$\Delta b = A_S - A_P \tag{10}$$

where Δa represents the shift in longitudinal direction and Δb represents the shift in transverse direction. Variables A_F, A_A, A_S, and A_P represent the arena size in fore, abaft, starboard, and port direction. A graphical overview of the arena and its components can be seen in Figure 3.

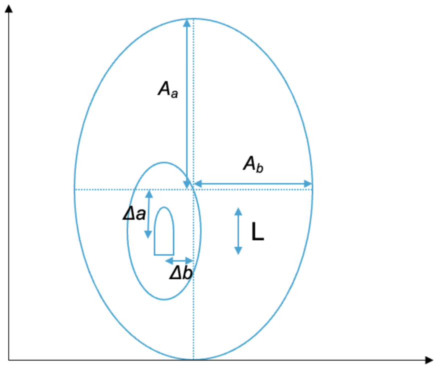

Fig. 3. A graphical overview of the semi-major and minor axes of the ship arena

III. COLREG AWARE VELOCITY OBSTACLE

In this section, the novel VO algorithm is presented. The baseline VO algorithm is presented, the COLREG classification and implementation are provided, the passing side constraint is presented, and the control algorithm's objective function is displayed.

A. Velocity Obstacle algorithm

The Velocity Obstacle algorithm, as presented by Kuwata et al. (2014) has been a staple control algorithm in ASV collision avoidance. Let A be the ASV running the proposed algorithm, whose ship domain is denoted $\mathbf{D^A}$. The dynamic OV is denoted B, and the according ship domain is denoted $\mathbf{D^B}$. Vectors $\mathbf{p} \in \mathbb{R}^2$ and $\mathbf{p_B} \in \mathbb{R}^2$ represent the current positions of the ASV and OV_B and $\mathbf{v_B} \in \mathbb{R}^2$ represents the velocity of OV_B. The velocity obstacle for A computed by B is denoted by $VO_B^A(\mathbf{v_B})$, which represents the set of velocities $\mathbf{v_A} \in \mathbb{R}^2$ that will result in a collision between the ASV and OV_B within a certain time $t \in [0, t_{VO}]$, assuming OV_B maintains a constant velocity. A graphical overview of the VO algorithm as presented by Van den Berg et al. (2008) is shown in Figure 4.

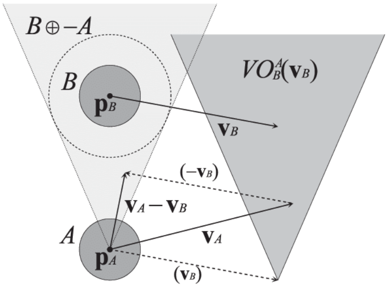

Fig. 4. A graphical interpretation of the VO algorithm (Van den Berg et al. (2008))

Let

$$A \oplus B = (\mathbf{D^A} + \mathbf{D^B} | \mathbf{D^A} \in A, \mathbf{D^B} \in B) \tag{11}$$

be the Minkowski sum of the ship domains of the ASV and OV_B and let

$$-A = (-\mathbf{D^A} | \mathbf{D^A} \in A) \tag{12}$$

be the reflection. A ray going from the position of the ASV into the direction of the velocity of the ASV is denoted by λ and is presented as

$$\lambda(\mathbf{p}, \mathbf{v}) = (\mathbf{p} + t\mathbf{v} | t \geq 0) \tag{13}$$

Then, the velocity obstacle from OV_B in the velocity space of the ASV is denoted by

$$VO_B^A(\mathbf{v_B}) = (\mathbf{v_A} | \lambda(\mathbf{p_A}, \mathbf{v_A} - \mathbf{v_B}) \cap (\mathbf{B} \oplus -\mathbf{A}) \neq \varnothing) \tag{14}$$

where any $\mathbf{v_A} \in VO_B^A(\mathbf{v_B})$ will lead to a collision between the ASV and OV_B at some time $t < t_{VO}$, and if $\mathbf{v_A} \notin VO_B^A(\mathbf{v_B})$, the ASV and OV_B will not collide assuming they both maintain their current velocity.

Collision cone $\mathbf{C^i}$ belongs to OV_i and represents the set of velocities leading to a collision with OV_i. To construct the edges of the collision cone, lines are drawn from the position of the ASV that pass through the tangent points with circle $\mathbf{T^i}$ that encircles the irregular shape that consists of the Minkowski sum $\mathbf{D} \oplus \mathbf{D^i}$ of the ship domain of the ASV and the ship domain of OV_i centered at the position of OV_i. One edge starts at the position of the ASV, $\mathbf{Q_1}$, and goes through $\mathbf{Q_2}$, one of the tangent points. The other edge also starts at $\mathbf{Q_1}$ but passes through the other tangent point, $\mathbf{Q_3}$. The cone is then shifted based on the velocity of OV_i, corresponding to the traditional VO algorithm. A visual representation of how these collision cones are created can be seen in Figure 5.

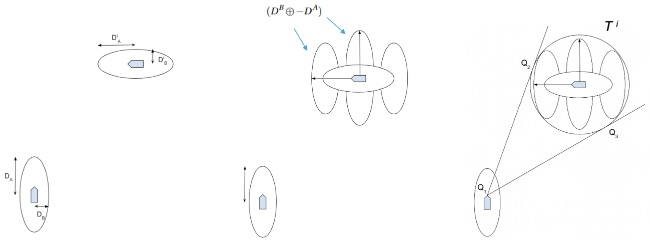

Fig. 5. The generation of the VO collision cone

B. COLREG classification

After filtering out the irrelevant COLREGs and the COLREGs unrelated to the motion control of the ASV, COLREG 6-8 and 13-17 remain. COLREGs 13-17 mainly consider vessel-to-vessel encounter situations and a schematic overview of the different kinds of encounter situations can be seen in Figure 6, as presented by Thyri and Breivik (2022).

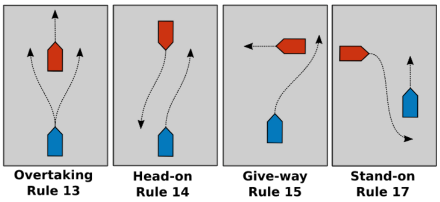

Fig. 6. The different kind of encounter situations

The classification of the COLREGs in this work is performed through the relative bearing β_r and the relative heading ψ_r. The relative bearing β_r^i is calculated by deducting the heading of the ASV from the true bearing of OV_i. The true bearing θ^i of OV_i is calculated as follows, where x and y embody the x- and y-position of the ASV and OV_i:

$$\theta^i = tan^{-1}\left(\frac{x^i - x}{y^i - y}\right) \tag{15}$$

The relative bearing β_r^i of OV_i from the ASV is given by deducting the heading of the ASV from this true bearing θ^i. If the resulting relative bearing is below zero, 2π is added:

$$\beta_r^i = \theta^i - \psi_{ASV} \tag{16}$$

$$if\ \beta_r^i < 0, \beta_r^i = \beta_r^i + 2\pi \tag{17}$$

The relative heading ψ_r^i is calculated by deducting the heading of OV_i from the heading of the ASV. If the relative heading ψ_r^i is below zero, 2π is added:

$$\psi_r^i = \psi_{ASV} - \psi_i \tag{18}$$

$$if\ \psi_r^i < 0, \psi_r^i = \psi_r^i + 2\pi \tag{19}$$

A graphical overview of how the relative bearing β_r and the relative heading ψ_r are computed is shown in Figure 7.

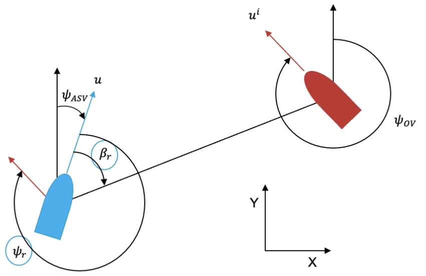

Fig. 7. A graphical representation of the relative bearing β_r and relative heading ψ_r

These values are compared to the entry criteria of the implemented finite state machine, which is done to guarantee the controller maintains the responsibility to give way until an encounter situation is fully resolved. In this research, a classification method by Cho et al. (2020) is extended to avoid any uncertainty in the classification of the encounters. Figure 8 shows what encounter situation is classified for every possible combination of β_r and ψ_r. The reason why there is an encounter situation for every combination of β_r and ψ_r is that the encounter only needs to be classified once OV_i has violated the corresponding ship arena $\mathbf{A^i}$, meaning risk of collision is always deemed to exist.

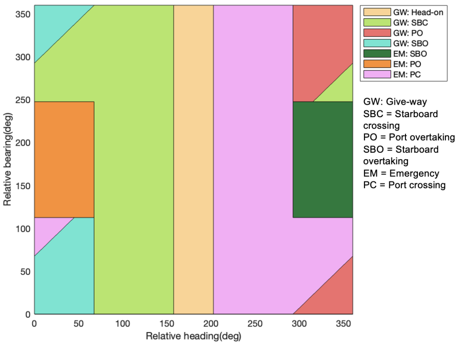

Fig. 8. An overview of the classification for the different values of β_r and ψ_r

C. Preferred passing side

The preferred side for the ASV to pass OV_i in give-way situations is an important distinction within the COLREGs. For head-on scenarios, starboard crossing scenarios, and emergency crossing scenarios, the COLREGs state that the give-way vessel is forced to pass the obstacle vessel while seeing it on its own port side. For overtaking situations, the COLREGs do not explicitly state at what side the ASV should pass the obstacle vessel. In existing research, more often than not, ASVs are forced to alter to starboard side in overtaking scenarios, even if this leads to complicated situations in the near future. For this research, a distinction is made between port and starboard overtaking, based on the relative heading ψ_r. This ensures the ASV takes an optimal route towards its target position while avoiding a future crossing situation with the overtaken obstacle vessel beyond the overtaking maneuver. An approach presented by Kuwata et al. (2014) is used to determine which of the velocity candidates need to be blocked. The cross product between the relative position and the candidate velocity of the ASV and OV_i is calculated as

$$(\mathbf{p_i} - \mathbf{p_{ASV}}) \times (\mathbf{v_c} - \mathbf{v_i}) < 0 \tag{20}$$

and if equation (20) is indeed smaller than 0 for the relative $\mathbf{v_c} \in \mathbb{R}^2$, the ASV passes OV_i while seeing it on its starboard side. For encounter situations where this is undesired, the incompliant $\mathbf{v_c}$ are blocked out.

D. Objective function

To generate the set of velocity candidates $\mathbf{v_c}$, a set of surge velocities and a set of heading angles are combined. 20 surge velocities, evenly distributed from $[0, 3]m/s$ and 32 heading angles, evenly distributed from $[0, 2n]rad$ are combined to generate 640 candidate velocities $\mathbf{v_c}$. The optimal velocity is added as the 641st value, to ensure the algorithm selects this if it is safe and COLREG compliant. After the COLREG incompliant $\mathbf{v_{inc}} \in \mathbf{v_c}$ velocity candidates and the candidates in any collision cone $\mathbf{v_{cone}} \in \mathbf{v_c}$ are blocked out, the optimal course and speed of the ASV can be selected. The remaining safe, COLREG-compliant velocity candidates are translated to a set of surge velocities $\mathbf{u}$ and heading angles $\boldsymbol{\psi}$. Afterwards, cost function J is minimized:

$$\underset{u,\psi}{\text{minimize}} \quad \mathbf{J}(u,\psi) = w_1||u_d - u|| + w_2||\psi_d - \psi|| \tag{21a}$$

$$\text{subject to} \quad \boldsymbol{\eta} \in \mathbf{H} \in \mathbf{H^R}(\boldsymbol{\eta_0}), \tag{21b}$$

$$\boldsymbol{\tau} \in \mathbf{T} \tag{21c}$$

The solution to the presented discrete optimization problem is $\boldsymbol{\tau}_{opt}$ that minimizes cost function (21a) under state constraints (21b) and input constraints (21c). The cost function (21a) is designed such that the ASV prioritizes minimizing deviation to the optimal surge velocity over minimizing deviation to the optimal heading angle, which is desired according to COLREG 8. Variables u_d and ψ_d are the desired surge velocity and heading, and by assigning a significantly higher value to w_1 than w_2, the algorithm applies this prioritization. As the surge velocity ranges from [0,3] m/s and the heading angle ranges from [0,2n] degrees, an initial scaling is needed to equalize their importance in the cost function. On top of this, $w_1 = 5 \cdot w_2$, to ensure the algorithm prioritizes the desired velocity over the desired heading. This concludes the process of finding the optimum control output, guaranteeing collision avoidance and COLREG-compliant maneuvers.

IV. SIMULATIONS

In this section, the setup of the simulations is displayed and the results of the performed simulations are presented. A set of vessel-to-vessel encounters are simulated to display COLREG compliance and provide a comparative study to the state-of-the-art. Complex simulations are then run to show the adaptability and robustness of the algorithm.

A. *Vessel model*

The ASV is assumed to move in a planar workspace $\mathbf{W} = \mathbb{R}^2$, where the x- and y-position combine to represent the position of the ASV. The state of the ASV is denoted with $\boldsymbol{\eta} \in \mathbf{H} \subseteq \mathbb{R}^{3x1}$ and the control input is denoted by $\boldsymbol{\tau} \in \mathbf{T} \subseteq \mathbb{R}^{3x1}$. A 3-degree-of-freedom kinematic model is adapted for the ASV, that contains the position in x- and y-direction as well as the orientation in the North-East-Down (NED) coordinate system: $\boldsymbol{\eta} = (x, y, \psi)^T$. The state of OV_i is assumed to be known to sufficient precision and is represented by: $\boldsymbol{\eta^i} = (x^i, y^i, \psi^i)^T$, where i represents the number of obstacle vessels. The control input $\boldsymbol{\tau}$ is denoted as $\boldsymbol{\tau} = (u, 0, r)^T$, where u represents the surge velocity and r represents the yaw velocity. The sway velocity is assumed to be 0, which is a commonly applied simplification for ASVs. The kinematic equation that displays the evolution of $\boldsymbol{\eta}$ is denoted by

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\tau} \tag{22}$$

where $\mathbf{R}(\psi)$ represents the rotation matrix to convert a position or velocity vector from the body fixed frame to the inertial frame:

$$\mathbf{R}(\psi) = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{23}$$

The states of the ASV and all obstacle vessels are put into the VO algorithm, which computes the optimal surge velocity u_{opt} and optimal heading angle ψ_{opt} that guarantees COLREG compliance and safe navigation. Matlab is used to solve the presented optimization problem.

B. *Vessel-to-vessel simulations*

In this section, we present the results of several vessel-to-vessel batch simulations to display the algorithm's ability to perform maneuvers compliant with the different COLREGs. The simulations consider encounters between an ASV running the proposed algorithm and an obstacle vessel keeping a constant velocity and heading throughout the simulation. The results of these simulations are presented in Figures 9, 10 and 11, where the ASV's starting and target position is shifted by 10 meters for every simulation. The obstacle vessel maintains the same trajectory to display how the ASV performs when bigger maneuvers are required to avoid collision.

Figure 9 shows crossing encounters where the ASV has a give-way obligation to the obstacle vessel crossing from the ASV's starboard side. These results demonstrate that when the ASV has the give-way obligation in a crossing encounter, it avoids collision by adjusting course towards its own starboard side to cross behind the obstacle vessel, which complies with COLREG 15. For the simulations where the ASV starts and ends at x = -90 and x = -80, the ASV does not alter to starboard as it passes sufficiently far ahead of OV_i and OV_i never violates the corresponding arena $\mathbf{A^i}$.

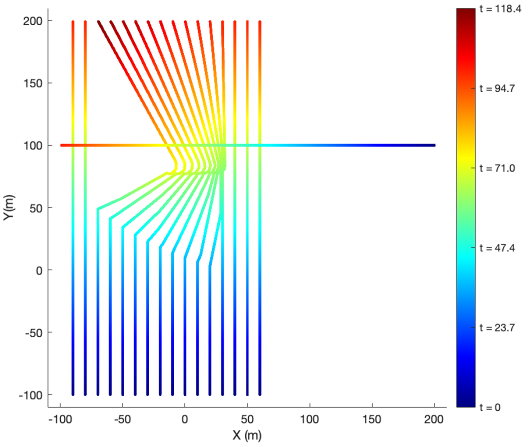

Fig. 9. The batch of crossing simulations

Figure 10 shows a set of head-on encounters where the ASV gives way to the obstacle vessel approaching a head-on encounter. According to COLREG 14, both vessels are forced to give way in a head-on scenario, but only the ASV moving from right to left is running the algorithm for these simulations. These simulations display that the ASV alters to its own starboard side once OV_i has violated ship arena $\mathbf{A^i}$. If the ship arena is never violated, the ASV continues its path without any alterations.

Figure 11 displays a set of overtaking simulations where the ASV runs the proposed algorithm, and Figure 12 displays a set of overtaking simulations where the ASV runs the algorithm proposed by Thyri and Breivik (2022). COLREG 13 considers overtaking situations, and this rule states that the overtaking vessel always has to give way to the vessel being overtaken and maintains the give-way role until the encounter situation is completely resolved. In this work, a distinction is made between overtaking maneuvers toward port side and toward starboard side. In Figure 12 it can be seen that this distinction is not made and the ASV always overtakes towards starboard side. However, this leads to the ASV crossing ahead of OV_i if the target position is to the left of the target position of OV_i. Usually in such a crossing scenario where the ASV encounters OV_i while seeing it on its port side, OV_i would be the give-way vessel. However, as it has just been overtaken by the ASV, the ASV still has the give-way responsibilities in this situation, which is explained in part (d) of COLREG 13. The ASV fails

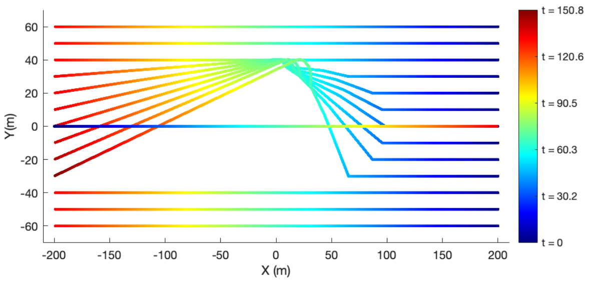

Fig. 10. The batch of head-on simulations

to fulfill this role in these overtaking situations and creates an unnecessary and unsafe encounter situation with OV_i.

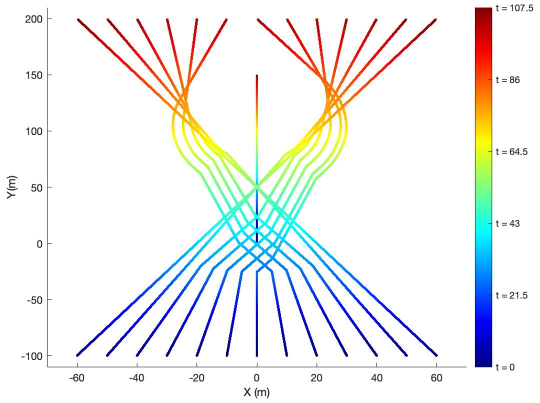

Fig. 11. The batch of overtaking simulations running the proposed algorithm

To display the improvement compared to the state-of-the-art, the time to target of the ASV and the total deviation in the heading angle throughout the simulations are compared. The differences in the time the ASV needs to reach the target position running both the newly developed VO algorithm and the algorithm of Thyri and Breivik in the different encounter situations are presented in Figures 13, 14 and 15. The time to reach the target provides promising insight into the efficiency of the developed algorithm, which was cut down a fair bit for the crossing simulations, cut down significantly for overtaking simulations, and only slightly increased for head-on scenarios. On average, the developed VO algorithm has a 6.8 % shorter time of elapse for overtaking scenarios, a 2.3 % shorter time of elapse for crossing situations, and a 0.36 % longer time of elapse for overtaking situations. The boxplots also show that the developed algorithm shows less deviation in the time to reach the target position than the algorithm of Thyri et al., hinting at a more consistent approach.

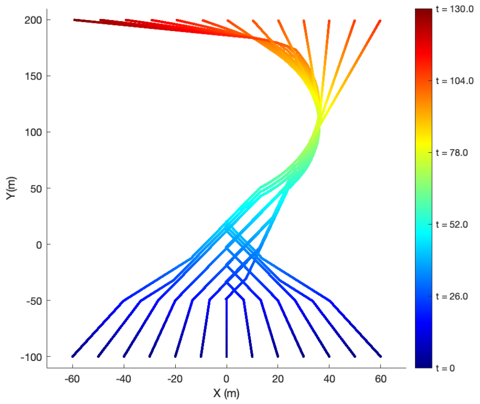

Fig. 12. The batch of overtaking simulations running the algorithm of Thyri and Breivik (2022)

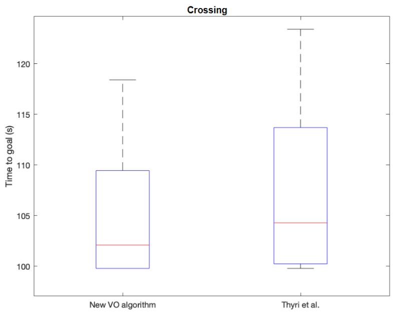

Fig. 13. The time to target of the crossing simulations

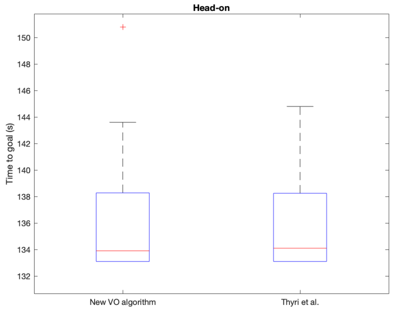

Fig. 14. The time to target of the head-on simulations

To further back up the claims on improving the VO algorithm's reactive nature, the ASV's heading angle deviation throughout the different batch simulations was measured and compared to the algorithm of Thyri and Breivik (2022). The overall changes in heading angle of the ASV throughout 3 of each of the simulations are presented in Table I, showing a clear decrease in the heading deviation of the ASV throughout the performed simulations.

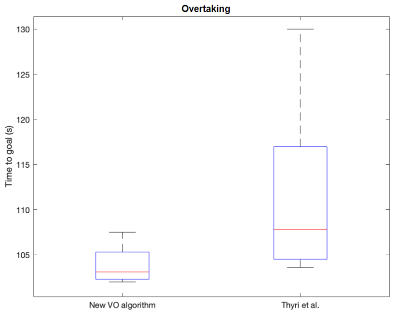

Fig. 15. The time to target of the overtaking simulations

TABLE I
TOTAL HEADING DEVIATIONS RUNNING THE PROPOSED ALGORITHM

Developed algorithm			
Encounter situation	Head-on	Crossing	Overtaking
x/y = -10	58.57 °	66.58 °	36.53 °
x/y = 0	45.74 °	53.04 °	49.04 °
x/y = 10	32.81 °	39.09 °	36.53 °
Algorithm of Thryi and Breivik			
Encounter situation	Head-on	Crossing	Overtaking
x/y = -10	52.51 °	67.65 °	59.28 °
x/y = 0	49.82 °	64.41 °	71.85 °
x/y = 10	23.83 °	61.09 °	62.05 °

C. *Complex scenarios*

In the first complex scenario, the ASV running the algorithm sequentially encounters an obstacle vessel head-on and then crossing from starboard. The ASV running the algorithm starts at the bottom left and moves to the north, where the second ASV is approaching from. After altering to starboard to avoid this head-on encounter, the ASV runs into the third ASV in a starboard crossing encounter, having to alter even further to starboard to cross behind this ASV. The trajectories of the ASVs can be seen in figure 16, showing how the ASV running the algorithm solves this complex scenario, complying with COLREG 14 and 15.

In the second complex scenario, 3 ASVs move across from different corners of a grid. The bottom left and top right ASVs run the proposed algorithm, but the bottom right ASV does not. The top right and the bottom left ASV alter due to the head-on encounter, but the top right ASV then finds itself in an emergency port crossing encounter with the bottom right ASV after it has failed to take action to avoid collision. The top right ASV makes a drastic turn backward to ensure collision is avoided. The trajectories of the ASVs are displayed in Figure 17, displaying that collision is successfully avoided. COLREG 17 states that the ASV was initially forced to stand on but having to take action to avoid collision with a vessel approaching from port is not allowed to maneuver to its own port side, which the top right ASV complies with.

The final situation displays a complex scenario where 4 ASVs running the algorithm move across a grid while starting at 4 different corner points, starting at [-/+ 100; -/+ 100]. Every ASV finds itself in a head-on encounter situation and a starboard crossing encounter simultaneously. The algorithm again manages to solve this situation. Each ASV makes its way to its target position while complying with COLREGs and adequately avoiding collision with the other vessels. The trajectories of the ASVs throughout this simulation can be seen in Figure 18. Figure 19 shows the inter-distance between the ASVs throughout the simulation, where it can be seen that the minimum inter-distance, represented by the blue line, is always bigger than the minimum allowed inter-distance, showing safe navigation.

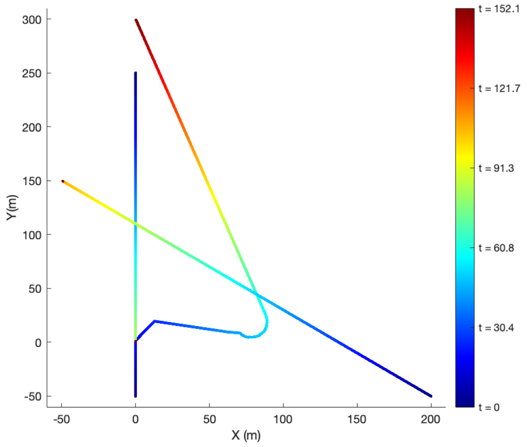

Fig. 16. The trajectories of the ASVs in a head-on + crossing encounter

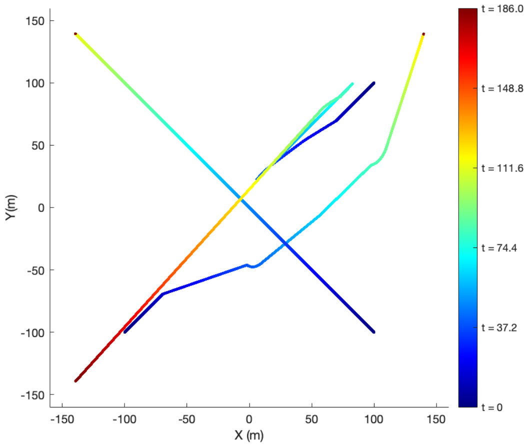

Fig. 17. The trajectories of the ASVs in a head-on + emergency port crossing encounter

V. CONCLUSIONS AND FUTURE WORK

A COLREG-compliant collision avoidance and detection algorithm is proposed, where the Velocity Obstacle (VO) algorithm has been extended by implementing the concept of the ship domain and ship arena into the framework. The VO is formulated by generating the Minkowski sum of the

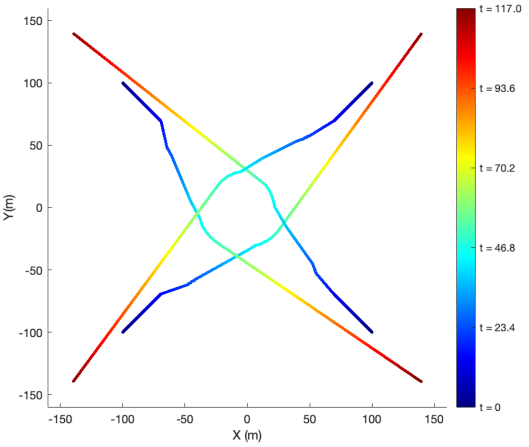

Fig. 18. The trajectories of 4 ASVs starting in opposite corners of a grid

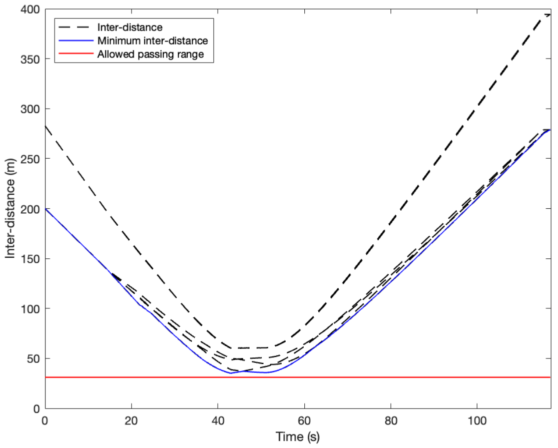

Fig. 19. The inter-distance between the 4 ASVs throughout the simulation compared to the minimum allowed inter-distance

ASV's and the OV's ship domain centered at the position of the obstacle vessel. The ship arena is incorporated to achieve adequate collision risk assessment and to precisely obtain the required collision avoidance maneuver for different encounter situations. The impact of the developed VO algorithm is demonstrated through a set of batch simulations, where compliance with the COLREGs is displayed and where a comparison to the state-of-the-art is made based on the proactive nature of the developed algorithm. Furthermore, the simulations of the complex scenarios show the robustness and wide adaptability of the developed algorithm. Future work includes further verification based on real experiments and the consideration of disturbances and limitations of the dynamic vessel model.

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