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Automatic testing of maritime collision avoidance algorithms

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Master of Science in Cybernetics and Robotics

Submission date: June 2017

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Problem description

The target of this master thesis is to design and implement a simulated environment for automatic testing of maritime collisions avoidance algorithms. This includes developing requirements for collision avoidance algorithms and then implementing several algorithms for collision avoidance. The algorithms should then be assessed by the developed requirements. The following tasks are proposed:

- Perform a study on how navigational regulations (COLREGs) are applied in practice and how ships are manually operated to avoid collisions:
  - Identify and list typical situations and the main reasons for collisions.
  - Identify traditional maneuvers to avoid collisions.
- Develop a set of requirements based on this study that identifies important properties for a collision avoidance system.
- Form a set of scenarios selected to test the developed requirements.
- Develop a framework for the testing and verification of such systems, and implement this framework in the DNV GL system for automatic HIL testing.
- Implement several collision avoidance systems/algorithms and assess their performance in the simulated system based on the developed requirements.

Abstract

For Autonomous Surface Vessels (ASVs) to be put into commercial operation and gain public acceptance, they will have to be as safe, or safer then similar vessels operated by humans. Today, maritime control systems are verified by class societies with established methods, such as hardware-in-the-loop (HIL)-testing. ASVs are equipped with collision avoidance systems and are critical for the safety of ASV operations. Sparse research exist on verification of these systems and their underlying collision avoidance algorithms.

In this thesis a framework for enabling automatic testing of collision avoidance algorithms is developed. Two collision avoidance algorithms are implemented. One is based on the velocity obstacle and the other is based on a type model predictive control, called simulation-based control behavior selection. These systems are tested in automatically generated scenarios and evaluated using a set of metrics. The implemented metrics are developed in the PhD thesis by Kyle Woerner. The implemented metrics are able to detect COLREGS violating behaviors and some characteristics of each system are identified.

Sammendrag

For at autonome båter skal bli en realitet, er de nødt til å være like trygge, eller tryggere enn tilsvarende båter styrt av mennesker. De siste årene er maritime kontrollsystem blitt mer komplekse. Etterhvert som kompleksiteten i disse systemene har økt, er en metode kalt “hardware-in-the-loop” testing tatt i bruk for å verifisere slike systemer. Autonome båter er avhening av antikollisjonsystemer for å trygt kunne utføre oppdrag. Dette er en ny type system det enda ikke finnes etablerte metoder for å verifisere.

I denne masteroppgaven er et rammeverk for automatisk testing av antikollisjon utviklet. To antikollisjonsalgoritmer er implementert og testet i dette rammeverket. Den første antikollisjonsalgoritmen er basert på en metode kalt “Velocity obstacles”. Den andre er basert på en type “model predictive control” kalt “Simulation-based control behavior selection”. Flere sett med kollisjonsituasjoner er automatisk generert. Algoritmenes evne til å håndtere disse situasjonene er analysert med en serie metrikker. Disse er utviklet i PhD avhandlingen til Kyle Woerner og implementert i forbindelse med denne oppgaven.

Preface

This work hopefully concludes my studies in Engineering Cybernetics, specializing in Guidance, Navigation and Control at the Department of Engineering Cybernetics at the Norwegian University of Science and Technology. The master thesis is written with support of DNV GL, Marine Cybernetics Services and builds upon a preliminary project conducted during the autumn of 2016. In this project a guidance and control system with collision avoidance based on velocity obstacles were implemented.

This past year has been fun and extremely challenging. Working on the thesis has taught me a lot about maritime control system, collision avoidance, and software development. I am grateful to be allowed to work on this project and I would like to express my gratitude towards some of the people that made this thesis possible. First of all I would like to thank my supervisor Edmund F. Brekke, and my co-supervisors Øystein Engelhardtsen, Jon Arne Glomsrud, and Bjørn-Olav Holtung Eriksen; for support, feedback and useful insights throughout the year. Most importantly they created an environment that made it very motivating to work on this project. I would also like to thank the team at DNV GL that has helped me with the technical aspects of the CyberSea simulator. Dong Trong Nguyen, Luca Pivano and Halvor Platou. Finally I would like to thank my family, Ragnhild and Hanna. For being helpful, extremely patient, and staying positive.

Paal Kristian Eknes Minne
Trondheim, June 2017

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Abbreviations

ASV Autonomous Surface Vessel.

CAS Collision Avoidance System.

COLREGS International Regulations for Preventing Collisions at Sea 1972.

CPA Closest Point of Approach.

DOF Degrees of Freedom.

GNC Guidance, Navigation, and Control.

HIL hardware-in-the-loop.

ILOS Integral Line-of-sight.

IMO International Maritime Organization.

LOS Line-of-sight.

MPC Model Predictive Control.

NED North-East-Down.

PSV Platform Supply Vessel.

SBMPC Collision avoidance using Simulation-based control behavior selection.

VO Velocity Obstacle.

CHAPTER 1

Introduction

1.1 Motivation

Advancement of technology has sparked an increased interest in ASVs from both private and public sector. Some believe that it is now only a question of time before ASVs will be put into commercial operation (Levander, 2017). The collision avoidance system is an important part of an ASV. For ASVs to be put into operation and gain public acceptance, they will have to be proven as safe, or safer than similar vessels operated by humans. It is therefore of great interest to investigate new methods for evaluating collision avoidance systems and the algorithm they are built upon.

1.2 Review

Substantial research have been conducted in the field of autonomous collision avoidance. Statheros et al. (2008) reviews several collision avoidance methods based on tools from artificial intelligence, such as evolutionary algorithms and neural networks. Tam et al. (2009) aims to extend the review by Statheros et al. (2008), and reviews the historical developments in collision avoidance techniques. Campbell et al. (2012) gives a review of the state of the research conducted on collision avoidance for ASVs. It focus on several aspects of the collision avoidance problem; including motion control, path planning, and collision avoidance architecture with regards to COLREGS incorporation. It is common to distinguish between deliberate and reactive collision avoidance algorithms. The first group of algorithms are suited for static environments where the path can be computed offline before it is executed (Campbell et al., 2012). Reactive algorithms typically use knowledge about their local environment through sensors and finds a new safe path to be followed if an obstacle appears. The reactive algorithms are usually computationally inexpensive, allowing them to quickly take action for obstacles appearing in the vessels way. A weakness of reactive algorithms is that they might find suboptimal paths.

The International Regulations for Preventing Collisions at Sea 1972 (COLREGS) is a set of rules to be followed by vessels at sea to avoid collisions. The COLREGS is a subject in motion planning for ASVs that has received limited attention (Campbell et al., 2012). A reactive collision avoidance system that takes COLREGS into account was developed by Kuwata et al. (2011, 2014). The system use stereo vision to detect vessels to be avoided, and choose a safe velocity for ASV to follow based on method called the velocity obstacles. This method is described Section 2.5. The velocity obstacle makes it possible to determine which side of the obstacle the ASV will pass if a certain velocity is followed; this way the COLREGS can be taken into account. An other recently proposed system by Johansen et al. (2016) is based on a method from model-predictive control, called simulation-based control behavior selection. Here possible trajectories of the ASV is simulated, and based on predicted positions and orientations of the ASV, it is determined if the trajectory violate the COLREGS.

The COLREGS can be difficult to take into account for designers of collision avoidance algorithms due to the nature of the rules. They are written in a way that allows seafarers to apply common sense when interpreting the rules in a collision situations. This can also make it difficult to verify these algorithms and sparse research exist in this area. The first know work on this topic is Woerner (2016). Woerner developed a set of metrics for evaluating collision avoidance algorithms and argued that enough provisions from case law exists to be able to quantify what should be considered as in compliance with the COLREGS. Based on this work Woerner et al. (2016) proposed a road-test that could be used to verify ASVs by. This test would be structured similarly to a driving test for humans today. The ASV would be tested in a large set different types situations to inspect if its performance is sufficient.

1.3 Objective and scope

In addition to the collision avoidance algorithms, an obstacle detection system is critical in the collision avoidance system. This system provides information to the collision avoidance algorithm about obstacles to be avoided. Although obstacle detection is an essential prerequisite for any collision avoidance algorithms, this part of the collision avoidance system is not considered in this thesis.

The aim of this thesis is to develop a framework for testing collision avoidance algorithms.

This includes extending an existing vessel simulator (CyberSea) with functionality to enable automatic testing of collision avoidance algorithms. The metrics developed by Woerner (2016) are implemented to define requirements of collision avoidance algorithms. The requirements are based on the COLREGS which are quantified by provisions from case law. Texts on how to apply the COLREGS (Allen (2005); Cockcroft and Lameijer (2004)) and research on what is considered safe by seafarers are also used.

The developed framework should then be used to test previously proposed reactive collision avoidance algorithms, and inspect to what extent they comply with the requirements defined by the metrics. Two algorithms are implemented. One is based on the Velocity Obstacle by Kuwata et al. (2011, 2014). The other is based on the simulation-based control behavior selection algorithm by Johansen et al. (2016).

1.4 Contributions

The main contributions of this thesis is:

- Implement a framework for automatic testing in the simulator infrastructure CyberSea.
- A detailed description is provided of a set of implemented metrics developed by Woerner (2016).
- Testing of the Velocity obstacle and the Simulation-Based Control Behavior selection algorithms with a set of metrics quantifying COLREGS compliance.
- Testing simulation-based control behavior selection, and the Velocity obstacle algorithms in scenarios with other ASVs equipped with Velocity Obstacles collision avoidance systems.

1.5 Outline

This thesis is divided into six chapters. Following the introduction Chapter 1, the theoretical background for this thesis is given in Chapter 2. Chapter 3 describe metrics developed by Kyle Woerner and how they have been implemented in order to evaluate collision avoidance algorithms. In Chapter 4, the developed system used to test collision avoidance algorithms is described. This includes details on how scenarios are automatically generated, how the collision avoidance algorithms, and obstacles are implemented. Chapter 5 presents and discuss the results from the evaluation of the collision avoidance algorithms, before concluding remarks and suggestions for future work is presented in Chapter 6.

Table 1.1: Conventions used

Example	Comment
$\boldsymbol{p}$	Vectors are denoted with bold lower case letters.
$\boldsymbol{M}$	Matrices are denoted with bold upper case letters.
$\boldsymbol{v}^a_{b/a}$	The velocity of reference frame b with respect to reference frame a, expressed in a.
$\alpha_{cpa}, t_{cpa}, \beta_{cpa}, r_{cpa}$	A variable with the subscript cpa, means this is the value of the variable when two vessels are at the closest point of approach.

1.6 Notation

Some notational conventions are followed throughout this thesis. These are given in Table 1.1. The remaining notation i presented as it is introduced.

CHAPTER 2

Background and theory

This chapter presents the background for this thesis, as well as the theory central to the remaining chapters. An overview of the roles and relationship between Guidance, Navigation, and Control systems is presented in Section 2.1, before modeling of marine crafts in 3 Degrees of Freedom (DOF) will be discussed in Section 2.2. Section 2.3 covers integral line-of-sight guidance, which is the guidance scheme that is used throughout this thesis. Then the rules governing collision situations at sea will be presented in Section 2.4, before two collision avoidance systems and the previous work on verification and testing of ASVs, will be covered in Section 2.5 to 2.7.

2.1 Guidance, Navigation, and Control

Guidance, Navigation, and Control (GNC) systems are central systems to enable autonomous or remote operation of a marine crafts (Fossen, 2011).

The navigation system determines and estimates the states of the craft. This includes the position, attitude, velocity and the acceleration. This is achieved with sensors such as GNSS, gyros, compass, together with observers that estimates the states of the vessel. For ASVs, navigation systems can also include sensors such as radar, LIDAR, sonar, and cameras to give the ASVs situational awareness. It is critical to provide the guidance system with necessary information about the ASVs surroundings to enable safe maneuvering of the craft.

Guidance is the system that computes a path for the marine craft to follow. The path is computed based on the state of the marine craft provided by the navigation system, and other factors, such as information about the environment. It either generates a feasible trajectory based on commands from a human operator, or can find a path to follow autonomously by determining a path based on a final destination, or a set of predefined waypoints. The guidance system can include features to find paths based on the current mission objectives. Collision avoidance is one feature which can be included here.

Based on the trajectory or set-points provided by the guidance system, the control system calculates generalized forces and distributes these to to the actuators of the marine craft, and the marine craft will move towards its objective. How these three systems are connected is illustrated in 2.1.

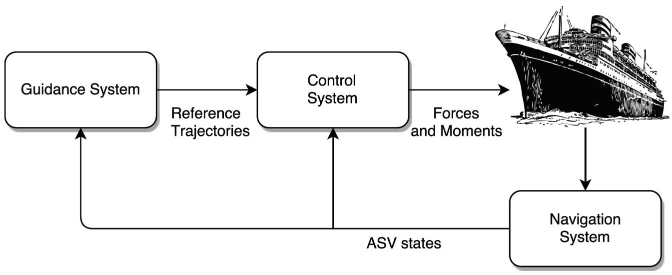

Figure 2.1: Relationship between the Guidance, Navigation and Control systems.

2.2 Modeling of marine crafts

A model of the marine craft is required to design guidance and control systems. This thesis is concerned with motion of the vessel in the horizontal plane. A 3 DOF model from Fossen (2011) has been used in this thesis to model the motion of the vessel. An overview of the notation and the model that has been used is presented here. A more in depth discussion of the model can be found in Fossen (2011).

2.2.1 Notation and coordinate frames

The SNAME notation is used to describe the motion of the vessel and is presented in Table 2.1. Two reference frames are used here; the $North-East-Down(NED)$ and the body reference frames.

The position and orientation is expressed in NED. It has its origo placed on Earths reference

DOF		Forces and moments	Linear and angular velocities	Position and orientation
1	motion in the x direction (surge)	X	u	x
2	motion in the y direction (sway)	Y	v	y
3	rotation about the z axis (yaw)	N	r	ψ

Table 2.1: SNAME notation for marine vessels (Fossen, 2011)

ellipsoid, the x-axis points towards north, the y-axis towards east, and the z-axis completes the reference frame and points towards Earths center. The reference-frame is denoted $\{n\}$.

The linear and angular velocities are expressed in the body frame. The frame is denoted $\{b\}$ and is fixed on the vessel. The origo of body frame, with respect to the $\{n\}$-frame, expressed in $\{n\}$, is given by the vector $\boldsymbol{p}^n_{b/n} = [x, y]^T$. The orientation of the body frame, expressed in $\{n\}$, is given by a rotation ψ around the z-axis. The linear and angular velocity of the vessel in $\{b\}$with respect to $\{n\}$, expressed in $\{b\}$ is given by $\boldsymbol{v}^b_{b/n} = [u, v]^T \in \mathbb{R}^2$ and $\boldsymbol{\omega}^b_{b/n} = r$.

When modeling the motions of a vessel, the $\{n\}$-frame can be assumed to be an inertial reference frame. Additionally, CO denotes the origin of $\{b\}$, and CG is defined as the center of gravity of the vessel. The vector from CO to CG is given by

$$\vec{r}_g = [x_g, y_g, z_g]^T.$$

2.2.2 3 Degree-of-Freedom vessel model

A 3 DOF model for displacement vessels from Fossen (2011) is used in this thesis to model to design controllers and predict trajectories of a vessel. Marine vessels have motion in 6 DOF. The 3 DOF model assumes that motion in other directions than in the horizontal plane are negligible. In addition the model is based on the following two assumptions:

- Symmetry about the xz-plane and homogenous mass symmetry such that

$$I_{xy} = I_{yz} = 0$$

- CO (origin of the $\{b\}$-frame) is set in the center line of the craft.

The model from Fossen (2011) is presented in (2.1).

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu} \tag{2.1a}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C_{RB}}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{C_A}(\boldsymbol{v_r})\boldsymbol{v_r} + \boldsymbol{D}(\boldsymbol{v_r})\boldsymbol{v_r} = \boldsymbol{\tau} + \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{wave} \tag{2.1b}$$

Each term is briefly described below:

- $\boldsymbol{\eta} = \begin{bmatrix} \boldsymbol{p}^n_{b/n} \\ \psi \end{bmatrix}$ is the pose of the vessel. It consists of the position and orientation of the marine craft with respect to $\{n\}$, expressed in $\{n\}$.
- $\boldsymbol{\nu} = \begin{bmatrix} \boldsymbol{v}^b_{b/n} \\ r \end{bmatrix}$ is the linear and angular velocity of the marine craft with respect to $\{n\}$, expressed in $\{b\}$. The velocity is given by $\boldsymbol{v}^b_{b/n} = [u, v]^T$.
- $\boldsymbol{\nu}_r$ is the relative velocity vector given by

$$\boldsymbol{\nu}_r = \boldsymbol{\nu} - \boldsymbol{\nu}_c, \tag{2.2}$$

  where $\boldsymbol{\nu}_c$ is the velocity of the ocean currents.
- $\boldsymbol{R}(\psi) \in SO(3)$, is the transformation matrix from $\{b\}$ to $\{n\}$ as shown in (2.3).

$$\boldsymbol{R}(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.3}$$

- $\boldsymbol{M}$ is the inertia matrix.
- $\boldsymbol{C_{RB}}(\boldsymbol{\nu_r})$ is the rigid body Coriolis and centripetal matrix.
- $\boldsymbol{C_A}(\boldsymbol{\nu_r})$ is the hydrodynamic Coriolis and centripetal matrix.
- $\boldsymbol{D}$ is the damping matrix.
- $\boldsymbol{\tau}$ is the generalized forces and moments acting on the ship from the actuators.
- $\boldsymbol{\tau}_{wind}$ and $\boldsymbol{\tau}_{wave}$ are the environmental forces acting on the ship.

The inertia matrix $\boldsymbol{M}$ is given by $\boldsymbol{M} = \boldsymbol{M}_{RB} + \boldsymbol{M}_A$. Where $\boldsymbol{M}_{RB}$ is the rigid body inertia matrix and $\boldsymbol{M}_A$ the added mass inertia matrix. These matrices are shown in (2.4).

$$\boldsymbol{M}_{RB} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & mx_g \\ 0 & mx_g & I_z \end{bmatrix}, \boldsymbol{M_A} = \begin{bmatrix} -X_{\dot{u}} & 0 & 0 \\ 0 & -Y_{\dot{v}} & -Y_{\dot{r}} \\ 0 & -Y_{\dot{r}} & -N_{\dot{r}} \end{bmatrix} \tag{2.4}$$

In (2.4), m is the mass of the vessel, and the elements of $\boldsymbol{M}_A$ is the hydrodynamic coefficients (Fossen, 2011)). $\boldsymbol{C_{RB}}(\boldsymbol{\nu_r})$ and $\boldsymbol{C_A}(\boldsymbol{\nu_r})$ are shown in (2.5) and (2.6).

$$\boldsymbol{C_{RB}}(\boldsymbol{\nu}) = \begin{bmatrix} 0 & 0 & -m(x_g r + v) \\ 0 & 0 & mu \\ m(x_g r + v) & -mu & 0 \end{bmatrix} \tag{2.5}$$

$$C_A(\nu) = \begin{bmatrix} 0 & 0 & Y_{\dot{v}}v + Y_{\dot{r}}r \\ 0 & 0 & -X_{\dot{u}}u \\ -Y_{\dot{v}}v - Y_{\dot{r}}r & X_{\dot{u}}u & 0 \end{bmatrix} \tag{2.6}$$

The final term of (2.1) is the hydrodynamic damping term $D(\nu)$. It is common to express this term as a sum of linear and non-linear damping.

$$D(\nu) = D + D_n(v_r) \tag{2.7}$$

The linear damping is dominant at lower speeds, and the non-linear damping is dominant at higher speeds (more than $2m/s$). The linear damping is modeled as follows:

$$D = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix} \tag{2.8}$$

For control design, not taking the non-linear damping into consideration is an advantage as it reduces the complexity of the controllers. Due to the passive nature of the non-linear hydrodynamic damping forces, omitting them should enhance the directional stability of the marine craft (Caharija et al., 2016).

For thorough discussion of each term presented above, and their physical interpretation, the reader is referred to Fossen (2011).

2.3 Integral Line-of-sight Guidance

A method that is commonly used to make surface vessels follow a predefined path, is the Line-of-sight (LOS) guidance. How the path is generated is outside the scope of this thesis, but it is typically provided by either an operator or a path planner as a set of waypoints. Fossen (2011) described a LOS guidance law for following straight line paths defined by a sequence of waypoints in $\{n\}$.

$$waypoints := \begin{bmatrix} p_1^n & p_2^n & \dots & p_n^n \end{bmatrix}^T \tag{2.9}$$

Two consecutive waypoints from the list of waypoints defines a straight line path to be followed by ASV. The LOS guidance scheme presented in Fossen (2011) will be briefly presented here. Figure 2.2 gives an overview of the line-of-sight guidance scheme between the two waypoints p_{k-1}^n and p_k^n. The angle from the North axis to the straight line defined by the two waypoints, is the path-tangential angle α_k. The position of the ASV is $p^n(t) = \begin{bmatrix} x(t) & y(t) \end{bmatrix}^T$. The distance the ASV has moved along the track since the previous waypoint, is called the along-track distance denoted s. e is the cross-track error. That is the distance from the path to the ASV. The along-track distance, and cross-track error can be found as shown in (2.10).

$$\varepsilon(t) = \begin{bmatrix} s(t) \\ e(t) \end{bmatrix} = R_p(\alpha_k)^T (p^n(t) - p_k^n) \tag{2.10}$$

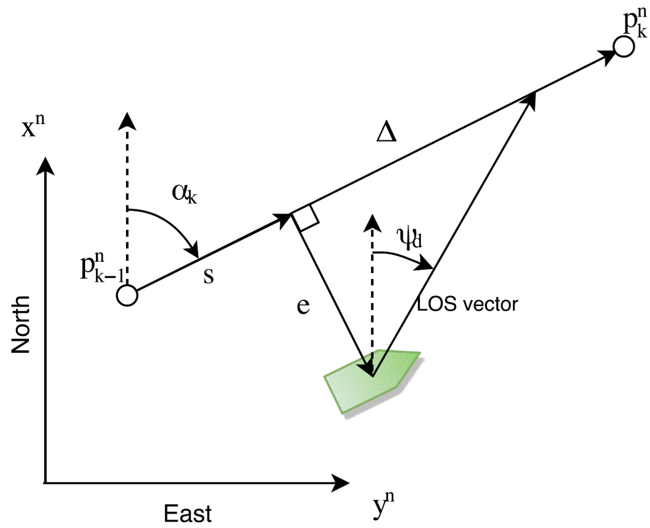

Figure 2.2: Line of sight guidance between waypoint $\boldsymbol{p}^n_{k-1}$ and $\boldsymbol{p}^n_k$

$$\boldsymbol{R}_p(\alpha_k) := \begin{bmatrix} \cos(\alpha_k) & -\sin(\alpha_k) \\ \sin(\alpha_k) & \cos(\alpha_k) \end{bmatrix} \in SO(2)$$

A steering law can now be obtained to find a desired course. This is done by controlling the cross-track error to zero.

$$\chi_d = \alpha_k + \chi_r(r) \tag{2.11}$$

$$\chi_r(e) \triangleq arctan\left(\frac{-e}{\Delta}\right) \tag{2.12}$$

Δ is the lookahead distance and the proportional gain in the control law. A smaller Δ results in a more aggressive controller and yields a heading reducing the cross-track error to zero faster. A larger Δ results in a slower convergence towards the defined path, but allows the ship to move along-track towards the next waypoint as it reduces the cross-track error.

Integral action can be added to the control law to compensate for slowly varying disturbances, such as ocean currents. A LOS guidance law with integral action is called Integral Line-of-sight (ILOS). An ILOS-control law from (Caharija et al., 2016) is used in this project.

$$\chi_r(e) \triangleq -\arctan\left(\frac{e + \sigma e_{int}}{\Delta}\right), \quad \Delta, \sigma > 0 \tag{2.13a}$$

$$\dot{e}_{int} = \frac{\Delta e}{(y + \sigma y_{int})^2 + \Delta^2} \tag{2.13b}$$

From the desire course angle χ_r, the desired heading ψ_d that is output to the control system can be set to

$$\psi_d = \chi_r \tag{2.14}$$

The ILOS guidance system should also output a desired reference speed. The desired speed is often specified by the operator or the mission planner and is provided to the motion control system without any alteration.

2.4 The Rules of the Road

The International Maritime Organization (IMO) is a specialized agency of the United Nations with responsibility for safety and security of shipping. It is this agency that published the regulations for preventing collisions at sea in 1972. The rules were agreed upon in 1972, but the history of the rules, and work for creating a set of standardized international rules, dates back more than a century. As the industrial revolution caused an upsurge in the amount of marine traffic, the need for rules governing marine vessels became apparent. The London Trinity House drafted the first set of rules in 1840, which in 1846 were adopted by the British Parliament (Allen, 2005). The first set of rules that became widely adopted by many nations was introduced by Great Britain and France in 1863. These rules were rewritten, modified and improved until 1972, when the rules found its current form. Since then there has been no major revision, but the COLREGS have been amended several times. The COLREGS have been ratified by more than 140 countries, which represents more than 97 percent of the world's shipping tonnage (Allen, 2005).

The COLREGS contain 38 different rules that are divided into five parts. In addition the COLREGS contain four annexes.

- Part A - General
- Part B - Steering and Sailing
- Part C - Lights and shapes
- Part D - Sound and light signals
- Part E - Exemption
- Annexes

This thesis is mostly concerned with Part B covering steering and sailing. Part B contains Rule 4 to 19 and is again divided into three Sections.

- Section I. Conduct of Vessel in Any Condition of Visibility (Rule 4 to 10)
- Section II. Conduct of Vessels in sight of One Another (Rule 11 to 18)
- Section III. Conduct of Vessels in Restricted Visibility (Rule 19)

The rules in Part B specify navigational requirements for vessels in collision situations. They also specifies the crew and officers responsibilities while on watch. This is included to ensure that sufficient situational awareness is maintained for detecting and interpreting collision situation in ample time.

The most common rules to take in account for by collision avoidance system designers, will by presented in the following section. This is to support the background theory on collision avoidance systems. A more in depth discussion of the COLREGS will follow in Chapter 3 on evaluation of collision avoidance algorithms.

Rule 8 - Action to avoid collision

Rule 8 sets standards for action taken by vessels in situations with a risk of collision. Specifically, Rule 8 states that action should made in ample time and any alteration of course or speed, should if the case admit, be readily apparent. It also states that any action taken, should result in a passing of the vessel at a safe distance. However, it also specifies that any action taken, should be in accordance with the rules in Part B. That means that violation of any of the rules in Part B to pass the other vessel at a safe distance, is considered a violation of Rule 8.

Rule 13 - Overtaking

Rule 13 covers the overtaking scenario. A vessel is deemed to be overtaking an other vessel when approaching from a direction more than 22.5 degrees abaft the other vessels beam. The overtaking vessel should keep out of the way of the vessel being overtaken. An overtaking scenario is illustrated in Figure 2.3.

Rule 14 - Head-on Situation

Rule 14 covers the head-on scenario. This occurs when two power-driven vessels are meeting on reciprocal or nearly reciprocal courses and there is a risk of collision. Each vessel should alter their course to starboard such that the two vessels pass on the port side of each other.

Rule 15 - Crossing Situation

Rule 15 assigns responsibility between vessels in crossing situations. The vessel which has the other on her starboard side should keep out of the way of the other and avoid passing

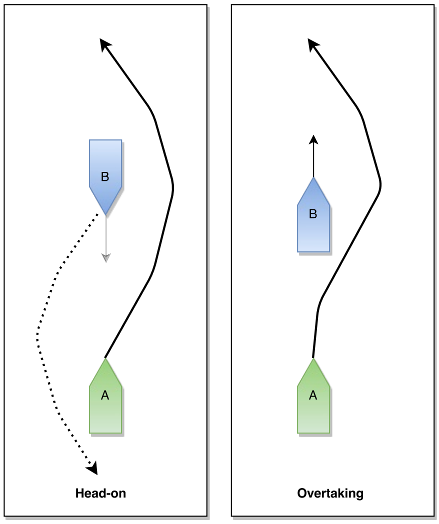

Figure 2.3: The required behavior by the own ship (A) in the head-on and overtaking scenario. The dotted line is required behavior by the other ship (B). The own ship should be able to avoid collision even if the other ship does not follow the dotted path.

ahead of the other vessel. In combination with Rule 17, Rule 15 makes the vessel which has the other on her port side the stand-on vessel.

Rule 16 - Action by Give-Way Vessel

Rule 16 states that every vessel which is directed to keep out of the way of another vessel, shall so far as possible, take early and substantial action to keep well clear.

Rule 17 - Action by Stand on Vessel

The vessel which is classified as the stand-on vessel, should keep her course and speed. However, if it becomes apparent that the other vessel is not taking appropriate action to keep out of the way, the stand-on vessel can take action to avoid collision. The stand-on vessel is required to take action to best avoid collision in scenarios where she finds herself so close to the give-way vessel, that collision cannot be avoided by the actions of the give-way vessel only.

In crossing situations when it has become apparent that the give-way vessel is not taking appropriate action, the stand-on vessel may take action. If action is taken, the vessel should not alter course to port, as this may result in conflicting actions.

The appropriate action for the own-ship in crossing scenarios is illustrated in Figure 2.4.

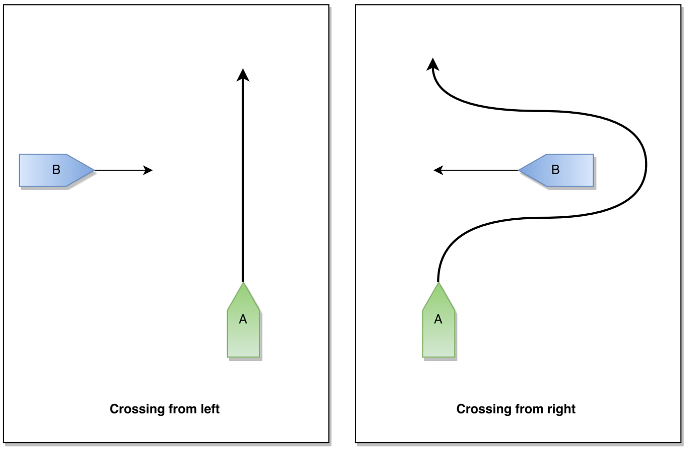

Figure 2.4: COLREG compliant behavior by the ASV in the crossing situation.

2.4.1 COLREGS and Autonomous COLAV literature

The COLREGS are written in a way that allows seafarers to exercise judgment and common sense when applying COLREGS to collision situations. This makes it difficult to design Collision Avoidance Systems (CASs) and claim compliance with the rules, as it is not immediately clear what compliance to the COLREGS would imply. Woerner (2016) pointed out that it is common for researchers of collision avoidance systems to claim COLREGS compliance without defining the scope compliance. Papers often implicitly refers to that the proposed or developed algorithm satisfies the navigational requirements of vessels in sight of each other. Specified by rule 13 to 17.

Even if the rules are inherently vague, Woerner (2016) claimed that there exists enough provisions from case law, and writings on marine practice, that it is possible to design a system and claim COLREGS compliance, but one would have to be clear on which rules of the COLREGS that were taken into account. In order to have a more precise discussion in academia, Woerner et al. (2016) suggested that the COLREGS should be divided into categories and one should specify compliance with respect to these categories. The categories are presented in Table 2.2.

2.5 Collision avoidance using Velocity Obstacles

Velocity Obstacle (VO) is a method used for collision avoidance in robot motion planning and was first introduced in Fiorini and Shiller (1993). The method uses the current position

Table 2.2: Proposed categories for COLREGS verification by Woerner et al. (2016)

Category	COLREGS	
I	Rules 1 - 3	General Rules
II	Rules 4 - 8	General Conduct of Vessels
III	Rules 9 - 10	Special Traffic Schemes
IV	Rule 12	Sailing in Sight of Another Sailing Vessel
V	Rules 13 - 17	Vessel Encounters in Sight of One Another
VI	Rules 11, 18	Responsibilities in Sight of One Another
VII	Rule 19	Restricted Visibility
VIII	Rules 20 - 31	Lights and Shapes
IX	Rules 32 - 37	Sound and Light Signals
X	-	Inter-vehicle Communications
XI	-	Cumulative performance including local customs

and velocities of the obstacles to determine which robot velocities will result in a collision. The set of all velocities that will result in a collision, is defined as the Velocity Obstacle. A safe velocity is chosen from outside the VO.

Several modifications and extensions to the original method have been proposed since it was first introduced, and VO has been used in collision avoidance systems for ASVs. Kuwata et al. (2011, 2014) presented a VO based algorithm that takes the COLREGS into account in crossing, overtaking, and head-on situations. The system was implemented on a 12 meter long vessel and tested on-water with up to four other vessels. Stenersen (2015) developed an 3DOF vessel simulator in the Robotic Operating System and implemented a collision avoidance system using VO. Stenersen described most parts of the implemented system in detail in his thesis.

This section will present the VO-algorithms that have been proposed by Kuwata et al. (2011) and Stenersen (2015). The system presented here has been implemented in CyberSea, and details regarding the implementation are described further in Section 4.4.1.

2.5.1 The Velocity Obstacle

For the own-ship A, Kuwata et al. (2011) expressed the VO of obstacle B as shown in (2.15). For the own-ship denoted A, Kuwata et al. (2011) expressed the VO induced by obstacle B by (2.15).

$$VO_B^A(\boldsymbol{v}_B) = \{\boldsymbol{v}_A \mid \lambda(\boldsymbol{p}_A, \boldsymbol{v}_A - \boldsymbol{v}_B) \cap (\mathcal{B} \oplus -\mathcal{A}) \neq \emptyset\} \tag{2.15}$$

$\boldsymbol{p}_A$ is the position of the own-ship. $\boldsymbol{v_A}$ and $\boldsymbol{v_B}$ are the velocities of the own-ship A, and the obstacle B respectively. Additionally,

$$\lambda(\boldsymbol{p}, \boldsymbol{v}) = \{\boldsymbol{p} + t\boldsymbol{v} | t \geq 0\} \tag{2.16}$$

is a ray starting in the point $\boldsymbol{p}$, pointing in the direction of $\boldsymbol{v}$. In (2.15), $\lambda(\boldsymbol{p}_A, \boldsymbol{v}_A - \boldsymbol{v}_B)$ is a ray starting at the position of the own-ship, pointing in the direction of the relative velocity of the obstacle and the own-ship. $\mathcal{A} \oplus \mathcal{B} = \{\boldsymbol{a} + \boldsymbol{b} \mid \boldsymbol{a} \in \mathcal{A}, \boldsymbol{b} \in \mathcal{B}\}$ is the Minkowski sum, and $-\mathcal{A} = \{-\boldsymbol{a} \mid \boldsymbol{a} \in \mathcal{A}\}$ is the reflection of a set. Taking the Minkowski sum of the set representing the geometry of obstacle B, and the reflection of the set representing the geometry of the own-ship A, will result in a set that represents the combined geometries of both the obstacle and the own-ship. If the own-ship position $\boldsymbol{p}_A \cap (\mathcal{B} \oplus -\mathcal{A}) \neq \emptyset$, a collision between the own-ship A and obstacle B has occurred.

Now (2.15) can more easily be interpreted. If ray from $\boldsymbol{p}_A$ in the direction of $(\boldsymbol{v}_A - \boldsymbol{v}_B)$ intercepts the combined own-ship and obstacle geometry, $\boldsymbol{v}_A$ is in the VO_B^A, and the velocity will result in a collision. The velocity $\boldsymbol{v}_A$, is then an element in the VO induced by obstacle B. All $\boldsymbol{v}_A$ resulting in a collision makes up the VO, which has the shape of a cone. This is illustrated in Figure 2.5.

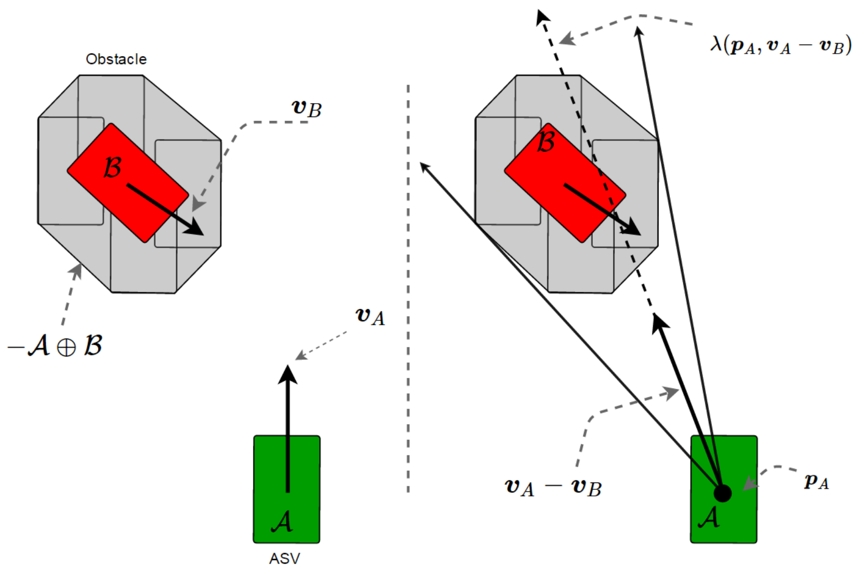

Figure 2.5: The Velocity Obstacles based on the Minkowski sum from Kuwata et al. (2014).

A common assumption in the literature, is to assume that the object and the obstacles are circular (Fiorini and Shiller, 1998; Guy et al., 2009; Stenersen, 2015). This simplifies the computation of the VO. The radius of the circle approximating the own-ship geometry is denoted r_A. Similarly r_B is the radius of the circle approximating the obstacle geometry. The combined geometry of the obstacle and the ASV, is now a circle with radius $r_A + r_B$.

One approach to identify if a velocity $\boldsymbol{v}_A$ is in the VO, relies on finding the left and right edges of the VO cone. Stenersen (2015) determined these by finding the angle α, illustrated in Figure 2.6, then rotating the position vector $\boldsymbol{p}_{AB}$ by $\pm\alpha$ radians. α is determined with (2.17).

$$\alpha = \sin^{-1}\left(\frac{r_A + r_B}{||\boldsymbol{p}_{AB}||}\right) \tag{2.17}$$

If (2.18) holds true, $\boldsymbol{v}_A$ is in $VO_B^A(\boldsymbol{v}_B)$ (Guy et al., 2009; Stenersen, 2015).

$$\boldsymbol{v}_{BA} \cdot \boldsymbol{p}^{\perp}_{AB,left} \geq 0 \wedge \boldsymbol{v}_{BA} \cdot \boldsymbol{p}^{\perp}_{AB,left} < 0 \tag{2.18}$$

$\boldsymbol{p}^{\perp}_{AB,left}$ is a unit vector perpendicular to the left edge of the VO. Similarly $\boldsymbol{p}^{\perp}_{AB,right}$, is a perpendicular unit vector to the right edge. These are calculated as shown in (2.19) (Stenersen, 2015).

$$\boldsymbol{p}^{\perp}_{AB,left} = \boldsymbol{R}(-\alpha + \pi/2)\frac{\boldsymbol{p}_{AB}}{||\boldsymbol{p}_{AB}||} \tag{2.19a}$$

$$\boldsymbol{p}^{\perp}_{AB,right} = \boldsymbol{R}(\alpha - \pi/2)\frac{\boldsymbol{p}_{AB}}{||\boldsymbol{p}_{AB}||} \tag{2.19b}$$

$$\boldsymbol{R}(\theta) = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \tag{2.19c}$$

In encounters where the obstacle get closer than $r_A + r_B$, (2.17) is not defined. This can

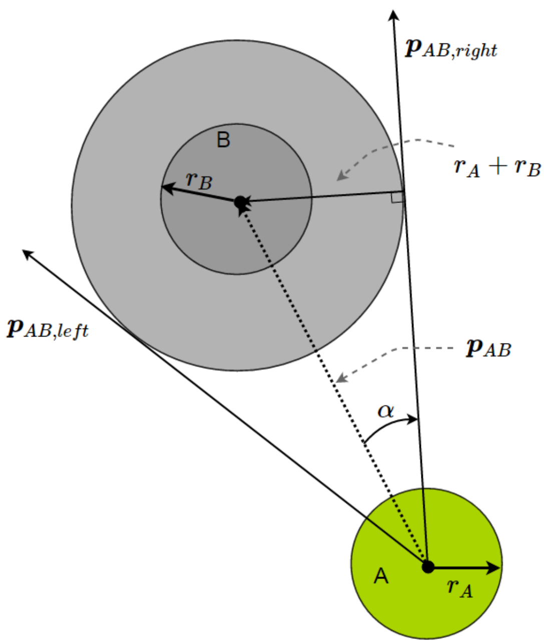

Figure 2.6: The geometric properties used to identify the edges of the VO.

happen in encounters with faster vessels with smaller safety margins than the own-ship, or as a result slow dynamics of the ASV. In this case, α is set to $90°$. This is the solution used in the VO implementation by Stenersen (2015). With $\alpha = 90°$, the edges of the VO will form a straight line, perpendicular to the line-of-sight vector from the own-ship to the obstacle. This will cause the ASV to choose a velocity causing the ship to move away from obstacle.

2.5.2 Taking COLREGS into account

Kuwata et al. (2011) showed that the area around the VO could be divided into three regions. Based on which region $\boldsymbol{v}_A$ was chosen from, the side which the ASV would pass the obstacle on, would be know. This information was then used to make the algorithm comply with the navigational requirements specified by the COLREGS in crossing, head-on, and overtaking situations. The three regions are shown in Figure 2.7. If $\boldsymbol{v}_A$ is chosen from $\mathcal{V}_1$, the ASV will pass ahead of the obstacle, seeing it on its starboard side. If it is chosen from $\mathcal{V}_2$, the ASV will see the obstacle on the port side, and finally, if $\boldsymbol{v}_A$ is chosen from $\mathcal{V}_3$, the ASV will move away and not pass the obstacle. In order to identify the region a

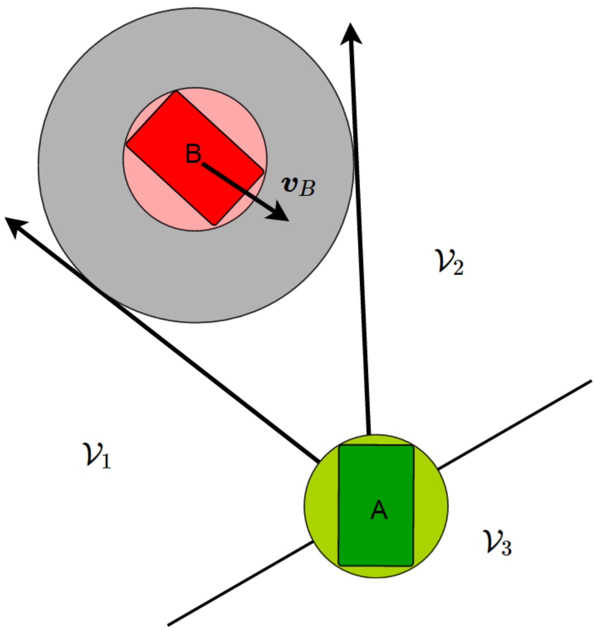

Figure 2.7: Regions determining which side the ASV will pass the obstacle on.

velocity vector belongs to, Kuwata et al. (2011) used the relations in (2.20).

$$\boldsymbol{v}_A \in \mathcal{V}_3 \Rightarrow (\boldsymbol{p}_B - \boldsymbol{p}_A) \cdot (\boldsymbol{v}_A - \boldsymbol{v}_B) < 0 \tag{2.20a}$$

$$\begin{aligned} \boldsymbol{v}_A \in \mathcal{V}_1 \Rightarrow\ & \boldsymbol{v}_A \notin VO_B^A(\boldsymbol{v}_B), \\ & \boldsymbol{v}_A \notin \mathcal{V}_3, \\ & [(\boldsymbol{p}_B - \boldsymbol{p}_A) \times (\boldsymbol{v}_A - \boldsymbol{v}_B)]_z < 0 \end{aligned} \tag{2.20b}$$

$$\boldsymbol{v}_A \in \mathcal{V}_2 \Rightarrow \boldsymbol{v}_A \notin VO_B^A(\boldsymbol{v}_B), \quad \boldsymbol{v}_A \notin \mathcal{V}_1 \tag{2.20c}$$

In equation (2.20b), $[]_z$ denotes the z-component of cross product vector.

If a velocity is determined to be in region $\mathcal{V}_1$ when the ASV has give-way responsibility, it is considered to violate the COLREGS. This property was used by both Kuwata et al. (2014) and Stenersen (2015).

2.5.3 Determining if action is required

Kuwata et al. (2011) used a precollision to check to determine if any action was required of the ASV. This was done by computing the time to the Closest Point of Approach (CPA) by (2.21), and the distance between the vessels at CPA by (2.22) .

$$t_{CPA} = \begin{cases} 0, & \text{if } ||\boldsymbol{v}_A - \boldsymbol{v}_B|| \leq \epsilon \\ \dfrac{(\boldsymbol{p}_A - \boldsymbol{p}_B) \cdot (\boldsymbol{v}_A - \boldsymbol{v}_B)}{||\boldsymbol{v}_A - \boldsymbol{v}_B||^2}, & \text{otherwise} \end{cases} \tag{2.21}$$

$$d_{CPA} = ||\,(\boldsymbol{p}_A + \boldsymbol{v}_A t_{CPA}) - (\boldsymbol{p}_B + \boldsymbol{v}_B t_{CPA})\,|| \tag{2.22}$$

For each vessel, collision is only determined to apply if the distance to the other vessel is less than d_{min}, and the time to CPA is larger than zero and less than t_{max}, as shown in (2.23).

$$0 \leq t_{CPA} \leq t_{max} \quad \text{and} \quad d_{CPA} \leq d_{min} \tag{2.23}$$

2.5.4 Determine situation type

If the ASV is determined to be in a collision situation after the precollision check, Stenersen (2015) used a method based on the normalized relative bearing to determine the type of the situation. The different types of situations are crossing from left, crossing from right, overtaking, and head on.

The relative bearing is the angle from the heading of a vessel, to the line-of-sight vector from the vessel to an object. The relative bearing is given by $\beta \in [0°, 360°)$. The normalized relative heading is given by $\beta^{180} = \beta - 180°$.

The type of situation is based on the normalized relative bearing of the own-ship as seen from the obstacle. The situations are defined as follows:

- Head-on: $\beta^{180} \in [-15^\circ, 15^\circ)$
- Crossing from right: $\beta^{180} \in [15^\circ, 112.5^\circ)$
- Overtaking: $\beta^{180} \in [112.5^\circ, 180^\circ) \cup [-180^\circ, -112.5^\circ)$
- Crossing from left: $\beta^{180} \in [-112.5^\circ, -15^\circ)$

Choosing a safe velocity

When the velocity obstacle has been found and the situation has been determined, a desired speed and heading for the ASV must be found. Both Kuwata et al. (2011) and Stenersen (2015) defined a grid of possible headings and speeds, where each cell represents a velocity. A cost is assigned each cell based on if it is in a VO, violates any active COLREG rules, and how much it deviates from the desired heading and speed provided by the ILOS guidance. Stenersen (2015) formulated this as the following cost function:

$$\mathcal{C}_{ij} := \alpha_c f_{collision}(u_i, \psi_j) + \beta_c f_{COLREGS}(u_i, \psi_j) + \tilde{\boldsymbol{v}}_{ij}^T \boldsymbol{Q} \tilde{\boldsymbol{v}}_{ij} \tag{2.24}$$

$\tilde{\boldsymbol{v}}_{ij}$ is the deviation from the desired speed (u_d) and heading (ψ_d) given by ILOS-guidance. $\boldsymbol{Q}$ is a weighting matrix defining the cost of deviation from the desired velocity.

$$\tilde{\boldsymbol{v}}_{ij} = \begin{bmatrix} u_d \cos(\psi_d) - u_i \cos(\psi_j) \\ u_d \sin(\psi_d) - u_i \sin(\psi_j) \end{bmatrix} \tag{2.25}$$

$f_{collision}$ is a function that returns 1 if the current pair (u_i, ψ_j) will lead to a collision and $f_{COLREGS}$ returns 1 if the pair is violating COLREGS. α_c and β_c are parameters that define the cost of collision and COLREG violation respectively.

The best desired velocity can now be found by iterating through the search grid and pick the velocity that yields the lowest cost.

2.6 Collision avoidance using Simulation-Based Control Behavior Selection

The collision avoidance concept described in Johansen et al. (2016) is based on Model Predictive Control (MPC). The method simulates trajectories of the ASV, given different set-points in desired course and speed in a collision situation. The resulting trajectories are then evaluated and assigned a cost based on collision risk with predicted trajectories of obstacles, COLREGS compliance, and several other metrics. The trajectory yielding the lowest cost is then selected as the best behavior and the associated set-points in speed and course are executed by the autopilot.

This section describes the key aspects of the collision avoidance system described by Johansen et al. (2016). The collision avoidance system using simulation-based control behavior selection will be referred to as SBMPC (Simulation-Based Model Predictive Control).

2.6.1 Overview of the system

Figure 2.8 shows the architecture of a motion control system for an ASV with the Simulation Based Collision avoidance system, as proposed by Johansen et al. (2016). The figure also displays the information flow between each module of the system. The CAS requires estimated states of the ASV, the obstacles and other potential hazards from the sensor system. It also requires waypoints defining the planned path and the nominal speed from the mission planning module. If the nominal trajectory causes a risk of collision, the CAS will attempt to find a safe, collision-free trajectory close to the nominal one. The CAS then outputs modified steering and propulsion commands (offsets in heading and speed) to the autopilot.

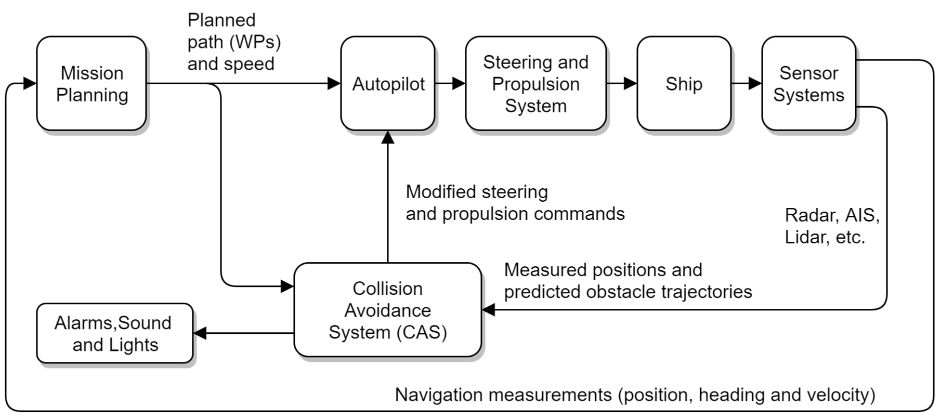

Figure 2.8: Diagram of modules and information flow in the Simulation-based behavior selection CAS (Johansen et al., 2016).

2.6.2 Simulation-Based Collision Avoidance System

The underlying methodology for finding a safe and collision free trajectory for the ASV is based on MPC. MPC is a control design methodology that originated in the late seventies and has since then gained a lot of popularity (Camacho and Alba, 2013). The MPC methodology can be summarized in three steps:

1. Use a model to predict future states on a finite prediction horizon, given a sequence of inputs.
2. Find an optimal and admissible set of control inputs by minimizing an objective function over the prediction horizon.
3. Apply only the first input of the optimal control input sequence and repeat when new measurements are available.

The prediction horizon is the time sequence where the future states of the plant is predicted. Johansen et al. (2016) are using these three steps in the design of the CAS, with some modification in the second step. Numerical optimization is used in most MPC applications to minimize an objective function. This is one of the main challenges when implementing MPC due to problems with computational complexity and convergence of the optimization problem. As the CAS is the last line of defense to avoid collision, it is unacceptable to not to find a solution. Johansen et al. (2016) use concepts from robust MPC to mitigate the challenges normally associated with the MPC methodology. Instead of formulating a numerical optimization problem, a finite set of control behaviors are chosen and the future states are predicted for each control behavior. Each control behavior is evaluated and associated with a cost. The control behavior that yields the lowest cost is then selected and executed by the autopilot. Similar approaches for other applications have previously yielded good results in terms of high performance and low complexity of the software implementation (Johansen et al., 2016). The collision avoidance concept can then be formulated with the following three modified MPC steps:

1. For each control behavior, use a model to predict the future states (the trajectory) of the own-ship. The future states of each detected obstacle are also predicted.
2. Evaluate each trajectory and associate it with a cost. The cost is determined based on several criteria.
    - Risk of collision with other vessels
    - COLREGs compliance
    - Risk of grounding
    - Deviation from nominal propulsion and course
    - etc

    Select the control behavior that yields the trajectory with the lowest cost.
3. Apply the first input of the control behavior. When the control loop is finished, repeat and evaluate based on new measurements

Own-ship trajectory prediction

Simulating the own-ship trajectory is one of the most important aspects of the Collision avoidance using Simulation-based control behavior selection (SBMPC) CAS. In order to simulate the trajectory of the own-ship a 3DOF model as shown in Section 2.2 can be used.

Control behaviors and scenarios

To satisfy time constraints in the system, the amount of different control behaviors that can be simulated is constrained by available computing power. Johansen et al. (2016) proposed the following offsets in course and propulsion as a minimum that should be inspected and evaluated in a collision situation:

- Course offset (in degrees):

  {-90, -75, -60, -45, -30, -15, 0, 15, 30, 45, 60, 75, 90.}

- Propulsion offset:

  {Nominal propulsion, slow forward, stop, full reverse}

The propulsion offset is defined as

$$P \in [-1, 1]. \tag{2.26}$$

$P = 1$ is nominal propulsion, $P = -1$ is full reverse, $P = 0.5$ is slow forward, and $P = 0$ is stop. The offsets that are provided by the CAS to the autopilot. In the autopilot the course offset is added to the nominal desired course, and the propulsion offset is added by multiplying the offset with the nominal propulsion.

In the minimum set of suggested control behaviors, the offsets are constant on the entire prediction horizon. However, a control behavior can be defined by a sequence of inputs on the prediction horizon. It is therefore possible to vary the inputs during the simulation. Johansen et al. (2016) stated that this will rapidly increase the number of scenarios needed to be inspected. When testing all combinations of course and propulsion offsets, there are already 52 control behaviors to test. If one allows one change of course and propulsion offset on the prediction horizon, the number of control behaviors needed to be simulated, will increase to $52^2 = 2704$. Johansen et al. (2016) claimed that an advantage of evaluating more control behaviors, is that higher performance can be expected from the CAS.

For each control behavior, different scenarios can be investigated. For example different environmental disturbances and different obstacle trajectories. In this thesis, no additional scenarios are investigated. The set of control behaviors will therefore be equal to the set of scenarios.

Obstacle Trajectories

Obstacle position, velocity, and heading is estimated in the tracking module of the ASV. Based on these estimates the future trajectories obstacles can be estimated. The simplest solution is to assume that the obstacles follow straight line trajectories (Johansen et al., 2016).

$$\bar{\boldsymbol{p}}_i^N(t) = \hat{\boldsymbol{p}}_i(t_0) + \hat{\boldsymbol{v}}_{\boldsymbol{i}}(t - t_0) \tag{2.27}$$

In equation (2.27), $\bar{\boldsymbol{p}}_i^N(t)$ is the estimated position of obstacle i at time t. t_0 is the current time, $\hat{\boldsymbol{p}}_i$ is the current best position estimate of the obstacle, and $\hat{\boldsymbol{v}}_i$ is the current best velocity estimate.

Identification of situation

When the trajectories of the own-ship and the obstacles have been predicted, it is necessary to determine if there is a developing collision situation taking place. Then the type of collision situation the ASV finds itself in should be determined. The different possibilities are crossing, head-on, overtaking, being overtaken. This will later be used to determine if a trajectory is violating the COLREGS. Figure 2.9 illustrates an ASV in a collision situation and the properties used to determine the type of the situation.

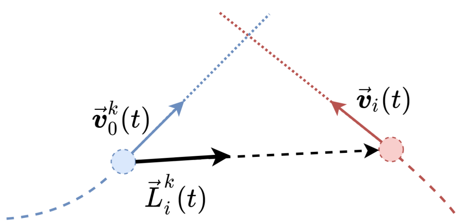

Figure 2.9: Properties used to determine the type of situation in Johansen et al. (2016).

The blue dot is the predicted own-ship position in scenario k, at time t. The red dot is obstacle i at time t. The blue and red vectors illustrate the velocities of the own-ship and the obstacle at time t. The blue and red lines are the predicted trajectories for the own-ship and the obstacle. $\vec{L}_i^k(t)$ is a unit vector along the Line-of-sight vector from the own-ship to the obstacle i, at time t in scenario k. Using the information from Figure 2.9, Johansen et al. (2016) described a method for identifying what kind of situation the ASV found itself in. The remaining paragraphs of this section is devoted to explaining this method.

The first property to be determined, is if the ASV in scenario k finds itself in a situation which might require action to comply with the COLREGS. If

$$d_{0,i}^k(t) \leq d_i^{cl}$$

then the ASV is defined to be $CLOSE$ to an obstacle and action might be required. Here $d^k_{0,i}(t)$ is the distance from the own-ship to obstacle i and d^{cl}_i is a parameter determining the maximum range COLREGS might apply.,

The own-ship is defined to be $OVERTAKEN$ by obstacle i if the obstacle has a higher speed than the ASV and (2.28) is satisfied.

$$\vec{\boldsymbol{v}}^k_0(t) \cdot \vec{\boldsymbol{v}}_i(t) > \cos(68.5°)|\vec{\boldsymbol{v}}^k_0(t)||\vec{\boldsymbol{v}}_i(t)| \tag{2.28}$$

Obstacle i is defined to be $STARBOARD$ of the own-ship at time t if the bearing of angle $\vec{L}^k_i(t)$ is larger than the heading angle of the own-ship.

Obstacle i is defined to be approaching the own-ship *HEAD-ON* if the speed of the obstacle and the own-ship is not close to zero and both (2.29a) and (2.29b) is true.

$$\vec{\boldsymbol{v}}^k_0(t) \cdot \vec{\boldsymbol{v}}_i(t) < -\cos(22.5°)|\vec{\boldsymbol{v}}^k_0(t)||\vec{\boldsymbol{v}}_i(t)| \tag{2.29a}$$

$$\vec{\boldsymbol{v}}^k_0(t) \cdot \vec{L}^k_i(t) > \cos(\phi_{ahead})|\vec{\boldsymbol{v}}^k_0(t)| \tag{2.29b}$$

ϕ_{ahead} is an angle that has to be selected. In Hagen (2017) ϕ_{ahead} was set to $15°$.—

The obstacle i is being *CROSSED* by the ASV if

$$\vec{\boldsymbol{v}}^k_0(t) \cdot \vec{\boldsymbol{v}}_i(t) < \cos(68.5°)|\vec{\boldsymbol{v}}^k_0(t)||\vec{\boldsymbol{v}}_i(t)|. \tag{2.30}$$

Scenario evaluation

At this point all necessary information to evaluate the scenarios have been determined. In this section, the evaluation criterion as presented by Johansen et al. (2016) will be summarized. What is considered when assigning a cost to a scenario is listed below:

- Collision risk factor
- The consequence of collision
- COLREGS compliance
- Deviation from nominal path
- Risk of groundings

In Johansen et al. (2016) the predicted risk-factor for obstacle i, in scenario k, at time t is determined by (2.31).

$$\mathcal{R}^k_i(t) = \begin{cases} \dfrac{1}{|t-t_0|^p}\left(\dfrac{d^{safe}_i}{d^k_{0,i}(t)}\right)^q, & \text{if } d^k_{0,i} \leq d^{safe}_i \\ 0, & \text{otherwise} \end{cases} \tag{2.31}$$

The term $\left(\frac{d_i^{safe}}{d_{0,i}^k(t)}\right)^q$ quantifies the risk of getting closer to an obstacle than d_i^{safe}. The factor $\frac{1}{|t-t_0|^p}$ lowers the risk towards the end of the prediction horizon. Meaning that risks occurring sooner result in a higher risk-factor than risks occurring later. The exponents p and q are tunable parameters that should satisfy $p \geq 1/2$ and $q \geq 1$ according to Johansen et al. (2016). It is important that q is chosen large enough, such that the ASV takes substantial action to keep well clear in accordance to Rule 8 of the COLREGS.

The next term is the cost associated with collision. The suggested method to quantify the cost of a collision by Johansen et al. (2016) is to inspect the relative velocity between the own-ship and the obstacle as shown in (2.32). The coefficient might depend on several properties. The type of obstacle, the size, and the responsibility for the own-ship to stay out of the way.

$$\mathcal{C}_i^k(t) = K_i^{coll}|\vec{\boldsymbol{v}}_0^k(t) - \vec{\boldsymbol{v}}_i^k(t)|^2 \tag{2.32}$$

The next term is a binary term, $\mu_i^k(t)$, and determines if the own-ship is violating any COLREGS at time t. $\mu_i^k(t) \in \{0,1\}$, where 1 means the own-ship is violating COLREGS, and 0, that it's not.

$$\mu_i^k(t) = \text{RULE14 or RULE15} \tag{2.33a}$$
$$\text{RULE14} = \text{CLOSE \& STARBOARD \& HEAD-ON} \tag{2.33b}$$
$$\text{RULE15} = \text{CLOSE \& STARBOARD \& CROSSED \& NOT OVERTAKEN} \tag{2.33c}$$

Combining all the concepts presented in this section, Johansen et al. (2016) defines the hazard or cost associated with scenario j in (2.34).

$$\mathcal{H}^j(t_0) = \max_{k \in S^j} \max_i \max_{t \in D(t_0)} \left(\mathcal{C}_i^k(t)\mathcal{R}_i^k(t) + \kappa_i \mu_i^k(t)\right) + f\left(P^k, \chi_{ca}^k\right) + g\left(P^k, \chi_{ca}^k\right) \tag{2.34}$$

S^j is all the scenarios with one control behavior j. i indicates all obstacles. $D(t_0)$ is the discrete time sequence with time steps of length T_s from time t_0 until the end of the prediction horizon, denoted T.

$$D(t_0) = \{t_0, t_0 + T_s, \ldots, t_0 + T\} \tag{2.35}$$

$g\left(P^k, \chi_{ca}^k\right)$ represents the risk of grounding in scenario k and $f\left(P^k, \chi_{ca}^k\right)$ is a function penalizing alteration of course and propulsion.

$$f(P, \chi_c a) = k_P(1-P) + k_\chi \chi_{ca}^2 + \Delta_P(P - P_{last}) + \Delta_\chi(\chi_{ca} - \chi_{ca,last}) \tag{2.36}$$

- k_P and k_χ should be positive and add cost for altering propulsion and course. This makes the ASV prioritize nominal velocity and ensure that it is moving towards the next waypoint.

- Δ_P and Δ_χ should be positive penalty functions, adding cost for changing cost. This should make the maneuvers readily apparent and make ASV avoiding a series of small turns as advised against in Cockcroft and Lameijer (2004).

The parameters k_χ and Δ_χ should be asymmetric and favor alterations of course to starboard."

When the hazard has been calculated for each scenario, the control behavior associated with the lowest hazard score is selected.

2.7 Maritime Collision Avoidance testing

Sparse amounts of published research exists on verification and testing of ASVs, collision avoidance systems and algorithms. Woerner (2016) developed algorithms for evaluating ASVs in collision situations based on track data. The evaluation algorithms proposed in the thesis were concerned with four areas: spatial efficiency, temporal efficiency, protocol-compliance (COLREGS compliance), and safety. The two first metrics quantify performance, and the last two are important for COLREGS compliance. Based on the developed metrics in Woerner (2016), a road test framework was proposed in Woerner et al. (2016). The road test framework is supposed to work like a driver's test for humans, but for ASVs. It is suggested that the test should include the following attributes in order to ensure that the CAS being tested is sufficiently robust:

- non-canonical and reasonably exhaustive geometries
- multi-vehicle, multi-rule scenarios
- conflicting simultaneous collision avoidance rules
- conflicting mission, rule, and navigational priorities
- various initial own-ship and contact speed
- over-constrained encounters
- robot-robot and robot-human interactions
- exercise of a default safe mode
- statistical significance of testing encounters
- broadcasting appropriate signals.

The list is obtained from Woerner et al. (2016).

2.7.1 Iterative Geometric Testing

Woerner and Benjamin (2015) proposed a scheme for testing collision avoidance systems that they named Iterative Geometric Testing. The testing scheme was also described in detail in Woerner (2016). Iterative Geometric Testing generates scenarios that address many of the attributes of the road test proposed in Woerner et al. (2016). A framework implementing iterative geometric testing, will output a large amount of collision scenarios that expose the tested CAS to multi-vehicle, multi-rule, and conflicting rules scenarios.

Iterative Geometric Testing is conducted by choosing a set of initial configuration (speed and heading) of obstacles in a collision scenario. A configuration of obstacles is called a contact geometry. The selected initial contact geometry forms the basis for the generated scenarios and is called the baseline geometry. Initial heading and speed for the own- ship are chosen next. Next a position $P \triangleq (P_x, P_y)$ and a duration t_{col} is chosen. P is a common point where all obstacles should meet after t_{col} seconds. If no action to avoid collision is taken, all vessels will collide at this point. The initial position of the own-ship and all obstacles can now be calculated. To generate non-canonical scenarios, noise is drawn from a uniform or normal distribution are added to the initial heading and speed of the obstacles, before the initial positions are calculated.

A large number of scenarios are generated by keeping the baseline geometry constant, and choosing many different initial own-ship speeds and headings. This is illustrated in Figure 2.10.

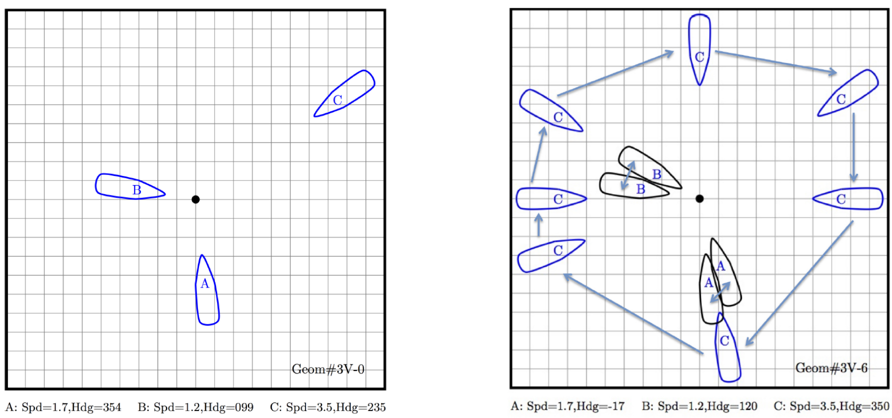

Figure 2.10: An example of scenarios generated by Iterative Geometric Testing. Vessel A and B are obstacles to be avoided. The baseline geometry is shown in the left frame. The right frame show how the initial velocity of the own-ship C is varied to test how it handles the situation from different approaching angles and speeds, while still meeting the obstacles in point P. The image is Figure 5-4 from Woerner (2016)

Because all vessels in the scenario will arrive at the same point, at the same time, the testing method can ensure that several COLREGS rules are active for the own-ship in each scenario. A common scheme used to prioritize COLREGS obligations, is the time until CPA or collision risk. Iterative geometric testing force the algorithms to reason about the collision situation in a more elegant way (Woerner and Benjamin, 2015).

By choosing different baseline geometries for the obstacles, it will be possible to investigate how collision avoidance systems also reason about scenarios where conflicting COLREGS rules apply.

CHAPTER 3

Maritime Collision Avoidance Evaluation

This chapter presents a collection metrics developed by Woerner (2016) and how they have been implemented for use in this thesis. The metrics specify the required behaviors and properties of collision avoidance systems. They will be used for automatic evaluation of collision avoidance algorithms and determine how well these algorithms handle close range encounters with other vessels and obstacles. Woerners metrics and evaluation procedures is the first known work on this topic.

The metrics quantify COLREGS compliance. To give background for the metrics and why they take their current form, the COLREGS is therefore discussed in greater detail here than in Section 2.4. Several parameters are required in the metrics to determine what is safe and in compliance with the COLREGS. Allen (2005) and Cockcroft and Lameijer (2004) have written extensively on how the COLREGS should be interpreted. The discussions in these texts on which behaviors at sea should be considered compliant with the COLREGS, is to a large extent based on case law from admiralty courts. Several of the parameters used in the implemented metrics are equal to the ones used in the metrics developed by Woerner (2016). These coincides to a large extent with the advice given in Allen (2005) and Cockcroft and Lameijer (2004). Where no suggestions on parameters are given in Woerner (2016), research on seafarer's perception of what is safe is used in addition to advice from Cockcroft and Lameijer (2004) and Allen (2005).

Section 3.2 to 3.9 presents Woerners metrics, as they have been implemented in this thesis. Some of the metrics deviates slightly from his work. This is specified where it applies and the reader is referred to Woerner (2016) for the metrics in their original form. Woerner (2016) presents the metrics as evaluation algorithms. In this work, the essential parts from each algorithm is attempted extracted and presented as mathematical formulas with the aim of improved readability. How the metrics have been implemented and visualization of each metric is also presented here.

The metrics have been used to develop an analysis tool for automatically evaluating a large number of simulated collision avoidance scenarios. The tool should identify weaknesses of the CAS being tested and identify scenarios where its actions are unsafe, or violating the COLREGS. These scenarios could later be inspected manually by the designers of the collision avoidance system or a class society conducting tests for verification.

Scope

The focus of the evaluation tool developed is COLREGS category V as specified in Woerner et al. (2016). This includes Rule 13 - 17 of the COLREGS. Additionally, Rule 8 from category II is subject to testing.

Notation

All metrics presented in this chapter give scores from 0 to 1, based on behavior or a several behaviors. The defined metrics are denoted with either $\mathcal{P}$ or $\mathcal{S}$.

- $\mathcal{S}$, denotes a score where 0 is the lowest, and 1 is the best possible score.
- $\mathcal{P}$, denotes a penalty score, where 1 is the largest penalty (or worst behavior) and 0 is the smallest penalty (best behavior).

The metrics that quantify compliance with the COLREGS Rules, are all of type $\mathcal{S}$, and are combining several other metrics.

Assumptions

How currents and other environmental disturbances are impacting the COLREGS and the encounters are not considered in this work. In the implementation the heading of the own-ship is assumed equal to the course, and the speed is assumed equal to the surge of the ship. These assumptions are valid for a larger ships.

Definitions

To ensure clarity throughout this chapter, some definitions are presented below:

- A **scenario** is defined by one simulation; where the ASV is approaching one or more obstacles and has to take action to avoid collision. A scenario is also referred to as a **situation**.
- An **encounter** is defined as the interaction between the ASV and one vessel or obstacle. A scenario can include several obstacles and therefore, several encounters.

3.1 Overview of the evaluation process

The evaluation process of a scenario consists of three steps.

1. Determine which rules apply for each encounter in a scenario.
2. Evaluate the encounters with appropriate metrics.
3. Find the lowest encounter score. This is defined as the total scenario score.

In step one, the encounter is categorized as one of the following types:

- Rule 13-16: Overtaking encounter where the own-ship is the give-way vessel.
- Rule 13-17: Overtaking encounter where the own-ship is the stand-on vessel.
- Rule 14: The own-ship is in a head-on encounter.
- Rule 15-16: Crossing encounter where the own-ship is the give-way vessel.
- Rule 15-17: Crossing encounter where the own-ship is the stand-on vessel.

Each encounter type is associated with a set of metrics that will be presented in this chapter. Each encounter type is given an initial score of 1. Then the metrics associated with each encounter type can deduct score from this initial encounter score. This means that a perfectly handled encounter will receive a score of 1.

A similar approach for scoring the encounters is used in Woerner (2016). Instead of giving scores on the appropriate behavior in an increasing manner, an encounter can receive a score of zero even if it complies with some parts of the COLREGS. In a head-on encounter, a vessel can take early and substantial action in accordance with the COLREGS. However, if the action taken is an alteration for course to port, this should give a significant deduction in score, as this is a clear violation. The total score for the scenario should therefore be close to zero, even if the action was in compliance with some parts of the rules.

3.2 Safety

The first metric quantifies safety and is used in the evaluation of all encounters. The safety of an encounter is quantified based on the range to the other vessel at CPA. This range is denoted by r_{cpa} and by inspecting this quantity, encounters and situations that resulted in a collisions or dangerously close passing, can easily be identified when inspecting a large set of simulations. These are situations that need to be addressed by the designer of the collision avoidance system, before it is put into operation. Situations with low safety should be inspected regardless of how well the vessel handled its other duties in accordance with the COLREGS.

When using the range at CPA to evaluate the behavior of an ASV or a collision avoidance system, a nuanced approach can be useful. Woerner (2016) suggested a metric for quantifying safety of an encounter. He used four range values to determine different levels of safety.

- R_{pref}, preferred passing distance.
- R_{min}, minimum acceptable passing distance at CPA.
- R_{nm}, near miss passing distance.
- R_{col}, distance at CPA where a collision most likely would have occurred.

The safety function proposed by Woerner (2016) is used in this thesis. The metric is expressed as a piecewise linear function of r_{cpa} and is shown in (3.1). A difference in this implementation compared to what is proposed in Woerner (2016), is that three levels of ranges are used instead of four. These are R_{min}, R_{nm}, and R_{col}. R_{min} is “merged” with R_{pref} due to difficulties with separating the two when defining appropriate values from the literature. Ranges greater than R_{min} is considered safe. If r_{CPA} gets smaller than R_{min}, the metric should start deducting score.

γ_{nm} and γ_{col} in (3.1) are penalty parameters that define the slopes of the function between each range level, and quantify the severity of a passing at R_{nm} and R_{col}.

$$S_{safety}(r_{cpa}) = \begin{cases} 1, & \text{if } R_{min} \leq r_{cpa} \\ 1 - \gamma_{nm}\left(\dfrac{R_{min} - r_{cpa}}{R_{min} - R_{nm}}\right), & \text{if } R_{nm} \leq r_{cpa} < R_{min} \\ 1 - \gamma_{nm} - \gamma_{col}\left(\dfrac{R_{nm} - r_{cpa}}{R_{nm} - R_{col}}\right), & \text{if } R_{col} \leq r_{cpa} < R_{nm} \\ 0, & \text{else.} \end{cases} \tag{3.1}$$

To avoid a negative $S_{safety}(r_{cpa})$ the parameters γ_{nm} and γ_{col} should be constrained by

$$\gamma_{nm} + \gamma_{col} \leq 1.$$

$\mathcal{S}_{safety}(r_{cpa})$ is implemented in the metric library with the values in Table 3.1 resulting in a safety function as shown i Figure 3.1. What is considered as a safe distance at

Table 3.1: Parameters used in (3.1).

Parameter	Value
R_{min}	1000 [m]
R_{nm}	800 [m]
R_{col}	200 [m]
γ_{nm}	0.4
γ_{col}	0.6

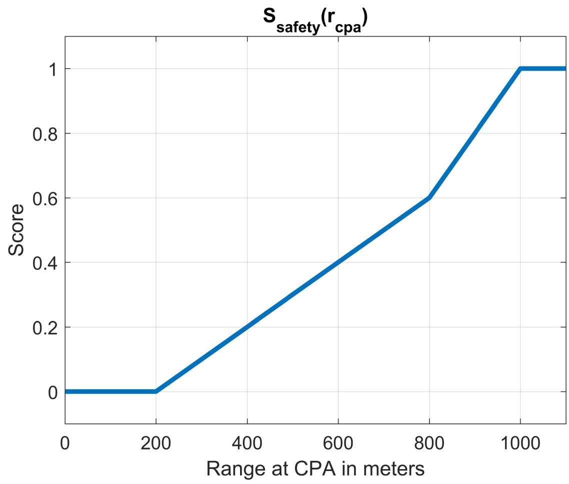

Figure 3.1: The safety score as a function of r_{cpa}.

CPA varies with circumstances of the situation (the ship size, weather, location etc.) The parameters in Table 3.1 is specified based on observations from case law and research on what CPA ranges seafarers considered safe (Allen, 2005; Rudan et al., 2012).

Rule 8d of the COLREGS is closely related to this metric and has been a subject of discussion in admiralty courts. Rule 8d states that action to avoid collision should be taken such that the vessels are passing at a safe distance. Allen (2005) referred to two cases in court where specific distances at CPA are mentioned. One case from the English Admiralty Court held that a CPA of 860 yards (786 meters) was a distance where it was not acceptable to conclude with that there is no risk of collision. A distance of 600 yards (548 meters), would be considered a violation of Rule 8d, as this distance would leave no room for the unexpected. An other court case from the U.S. Fifth Circuit, stated that a 600 yard CPA in a fairway would be a clear and sufficient distance.

Rudan et al. (2012) conducted a survey of officers and masters on their subjective definition of a near miss in terms of distance to other vessels in a collision situation. The survey discovered that there was a relation between what vessels the subjects had operated last and what they considered as a near miss situation. Subjects operating larger ships (length greater than 250 meters) considered longer distances as near misses, than subjects operating smaller vessels (length less than 169 meters). The average distance considered as a near miss was 0.43 nautical miles (approximately 800 meters).

Based on the vessel being evaluated and the characteristics of the scenario being evaluated, the ranges in Table 3.1 might be too small or too large. Officers on larger vessels would consider distances greater than 800 meters a near miss (Rudan et al., 2012). This means R_{nm} and R_{min} is probably set too small for evaluating these vessels.

3.3 Rule 8 - Action to avoid collision

When it is apparent that action is required to avoid collision or reduce the risk of collision, rule 8 determine how action should be taken. This rule therefore applies to all encounter types where action is taken or required. The metrics presented in this section are penalty metrics that deduct score from encounters if violated.

The parts of Rule 8 relevant to the design of metrics are presented here. The rules are obtained from from Cockcroft and Lameijer (2004).

Rule 8 - Action to avoid collision

- **(a)** Any action to avoid collision shall be taken in accordance with the rules of this Part and, if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship.
- **(b)** Any alteration of course and/or speed to avoid collision shall, if the circumstances of the case admit, be large enough to be readily apparent to another vessel observing visually or by radar; a succession of small alterations of course and/or speed should be avoided.
- **(d)** Action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance. The effectiveness of the action shall be carefully checked until the other vessel is finally past and clear.

3.3.1 Rule 8a - Action in ample time

Rule 8a states that action should be made in ample time. When action is required of a ship, it should as soon as possible take appropriate action. Rule 8a therefore applies to give-way vessels in overtaking and crossing encounters, and both vessels in head-on encounters.

What is considered as early action or in ample time depends on the situation. Allen (2005) referred to a rule of thumb stated by U.K. Marine Accident Investigation Branch (2000): "a large vessel at sea, should take avoiding action at a range of at least four to six miles". Allen (2005) also referred to court rulings that suggested the rule thumb of what is considered as early action, should be increased to five, or even six miles.

However, each situation should be carefully assessed before action is taken. Rule 7c states that assumptions should not be made, and especially not based on scanty information. Action should therefore be made as soon as it is possible for an operator to determine that a collision situation is developing and determine what action is required. For an ASV rule 8a could be interpreted as: action should be taken once an obstacle is detected and its course and speed can be estimated with a certain probability. In the implemented rule 8a metric, it is assumed that the ASV will log the time when obstacles are detected, such that this information is available when evaluating the encounters. When class societies are verifying ASVs' compliance with rule 8a in the future, a distance can be specified as the minimum acceptable distance or time until CPA, before action should be taken to avoid collision in a COLREGS compliant manner in ample time.

Woerner (2016) developed a metric to investigate if actions were made in ample time. The metric is based on the distance traveled from when the ship detects the obstacle to when the own-ship has determined itself to be the give-way vessel and a maneuver is initiated. The suggested algorithm uses the range between the own-ship and the obstacle when it first was detected, the range when a maneuver was initiated and the range at CPA. Then it gives a score from 0 to 1, where 0 indicate instant action, and 1 that no action was taken.

The metric requires three properties:

- r_{detect}, range to contact at time of detection
- $r_{maneuver}$, range to contact at time of own-ship's maneuver
- r_{cpa}, range to contact at CPA

The metric developed by Woerner is given by (3.2).

$$\mathcal{P}'_{delay} \triangleq \left(\frac{r_{detect} - r_{maneuver}}{r_{detect} - r_{cpa}} \right) \tag{3.2}$$

In some encounters, the ASV might already be taking action to avoid collision with an other vessel. Which means $r_{maneuver}$ can get larger than r_{detect}. To avoid a negative score, $\mathcal{P}$ is implemented as

$$\mathcal{P}_{delay} \triangleq min \left(1, \left(\frac{r_{detect} - r_{maneuver}}{r_{detect} - r_{cpa}} \right) \right) \tag{3.3}$$

An example of the score the metric would yield is shown in Figure 3.2.

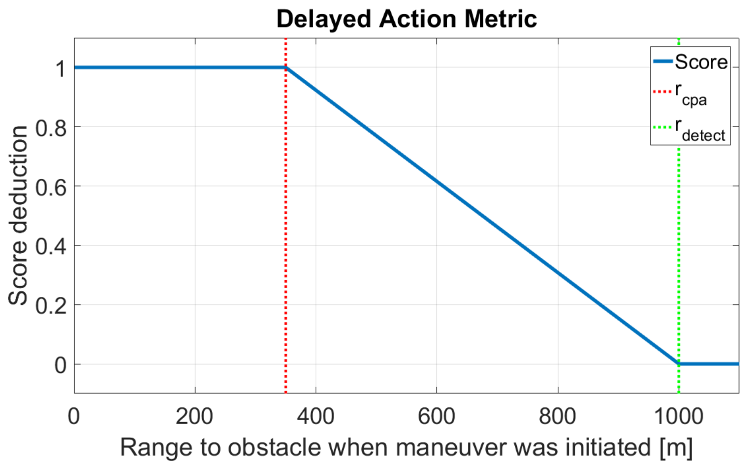

Figure 3.2: The metric developed by Woerner (2016) to determine if action is taken in ample time. Here $\mathcal{P}_{delay}$ is given as a function of $r_{maneuver}$ in a scenario where $r_{cpa} = 350$ meters, $r_{detect} = 1000$ m.

Implementation of the Rule8a metric

In order to implement the $\mathcal{P}_{delay}$ three values have to be found: r_{detect}, $r_{maneuver}$, and r_{cpa}. r_{cpa} is identified by inspecting the vessels tracks and find the shortest range between the ASV and the obstacle. r_{detect} and $r_{maneuver}$ are more difficult to obtain.

In the implemented system, the time of detection for all obstacles are saved to logs. This allows the evaluator to determine r_{detect}. In Woerner (2016) r_{detect} was set to a constant distance $(1.8 \cdot R_{pref})$. This is a viable option when verifying collision avoidance algorithms. A class society might determine a minimum acceptable detection and identification distance of other vessels. By specifying this distance for a certain scenario, r_{detect} would be known in advance. The sensor and tracking system would then have to be verified to satisfy this specified requirement. This requirement could be set based on the rule of thumb for early action presented previously.

$r_{maneuver}$ should be available to the evaluator if the system is compliant with Part D of the COLREGS. This property can be determined when the vessel signals a course or speed change with either the whistle or light signals. However, this is not implemented in the tested systems in this thesis. A method for detecting when a maneuver is initiated was developed.

A simple solution to determine when a maneuver is initiated based on track data, is to look at the course and speed of the ASV. The course and speed at t_{detect} is given by $\chi(t_{detect})$ and $U(t_{detect})$. At the first time instance t subsequent to t_{detect}, where course has changed more than some ϵ_χ or the speed has changed more than ϵ_U, it is assumed that a maneuver has been initiated. This is shown in (3.4). Now $r_{maneuver}$ can be found.

$$|\chi(t_{detect}) - \chi(t)| \geq \epsilon_{\chi} \tag{3.4a}$$
$$|U(t_{detect}) - U(t)| \geq \epsilon_{U} \tag{3.4b}$$

Allen (2005) stated that any alteration of course less than three degrees could not be considered visible on the radar. In the metric library ϵ_{χ} is set to four degrees. At this time a maneuver is considered to be initiated and detectable to other vessels. No suggestion to how much the speed must change in order to be visible on radar was given in Allen (2005). A speed change of $0.5m/s$ is used in metric library and is able to determine with sufficient accuracy when a maneuver was initiated. Examples illustrating detections of maneuvers can be found in Appendix A.

A weakness of the current implementation becomes apparent in a multi encounter scenario. If the vessel is already taking action for an other obstacle, the metric will assume immediate action for the recently detected obstacle, even if the ASV has yet to take any action.

3.3.2 Rule 8b - Readily apparent action

The need for substantial action has always been stressed in court (Allen, 2005). Both for vessels in sight of one another, and vessels in restricted visibility. The courts stresses that the give-way vessels should make a significant alteration of course or speed to indicate her intentions for the stand-on vessel. Based on provisions from case law, Cockcroft and Lameijer (2004) argued that at any alteration of course should be at least 30 degrees to make the intentions of give-way vessel obvious to the stand on vessel. In restricted visibility any alterations should be in the order of 60 to 90 degrees. Case law provides clear guidance on how alterations of course should be conducted in order to be considered as compliant with the COLREGS.

Cockcroft and Lameijer (2004) did not refer to case law or quantify what could be determined as a readily apparent speed change . Cockcroft and Lameijer (2004) did however state that alterations of speed takes longer to put into effect and are therefore less likely to be readily observed.

Woerner (2016) suggested three metrics for determining if an action to avoid collision is readily apparent based on case law. The first determines if the course change is readily apparent. The second determines if the speed change is readily apparent. The third combines the two metrics in order to decide if the entire maneuver is readily apparent.

Rule 8b - Detect Non-Readily Apparent Course Change

The metric developed by Woerner (2016) uses three parameters.

- $|\Delta\chi|$, the absolute course alteration in a maneuver.
- $\Delta\chi_{app}$, the course alteration threshold which is considered readily apparent. The default is 30° for vessels in sight of each other.
- $\Delta\chi_{md}$, minimum detectable course alteration. The default used in Woerner (2016) is 0°.

The metric for penalizing non-apparent course changes suggested by Woerner is given by (3.5). It gives a score from 0 to 1, where 0 represents an apparent alteration of course, and 1 a non-readily apparent alteration of course.

$$\mathcal{P}'_{\Delta\chi_{app}}(\Delta\chi) \triangleq \min\left(0, \left(\frac{\Delta\chi_{app} - |\Delta\chi|}{\Delta\chi_{app} - \Delta\chi_{md}}\right)\right) \tag{3.5}$$

A stricter function is developed for this thesis to penalize non-apparent course changes.

$$\mathcal{P}_{\Delta\chi_{app}}(\Delta\chi) \triangleq \min\left(0, 1 - \left(\frac{|\Delta\chi|^2}{\Delta\chi_{app}^2}\right)\right) \tag{3.6}$$

By using (3.6) instead of (3.5), small alterations of course will result in a larger penalty, and should be detected more easily when inspecting the evaluation results.

Implementation of the course alteration metric

To implement (3.6) the parameter $|\Delta\chi|$ has to be determined. The value can be identified by finding maximum deviation in course in the track data from t_{detect} to t_{cpa} as shown in (3.7). The initial course is given by $\chi_0 = \chi(t_{detect})$.

$$|\Delta\chi| = max\left\{|\chi(t_{detect}) - \chi_0|, |\chi(t_{detect} + 1) - \chi_0|, \ldots, |\chi(t_{cpa}) - \chi_0|\right\} \tag{3.7}$$

There is a drawback of using the maximum deviation of course to identify an apparent course change. The maximum deviation does not consider that vessel might have reached that course deviation by a sequence of small turns. This is not considered as an apparent course alteration as this can be difficult to detect with radar (Cockcroft and Lameijer, 2004).

Rule 8b - Detect Non-Readily Apparent Speed change

Woerner (2016) proposed a metric to detect non-readily apparent speed changes. The metric uses a speed reduction threshold δ_U to determine what is considered a sufficient change in speed. δ_U is given in percentage change. The parameters used in the metric are listed blow.

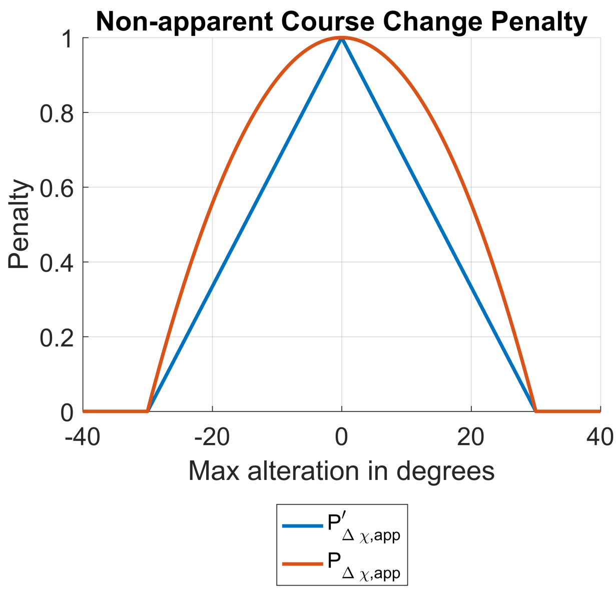

Figure 3.3: Comparison of $\mathcal{P}'_{\Delta\chi_{app}}$ and $\mathcal{P}_{\Delta\chi_{app}}$. The plot show the penalty score as a function of the maximum alteration of course in maneuver.

- δ_{app}, apparent speed reduction threshold. $\delta_{app} \in [0, 1]$. Default 50 % ($\delta_{app} = 0.5$).
- U_0, initial speed at time of detection.
- U_{min}, speed after slowing.

Woerner determined the speed change in percentage, ΔU, based on the properties above as shown in (3.8).

$$\delta'_U = \frac{U_0 - U_{min}}{U_0} \tag{3.8}$$

The metric defined by Woerner (2016) is then given by (3.9). A score of 1 represents a non-readily apparent alteration of speed, and 0 represents an apparent alteration of speed.

$$\mathcal{P}'_{\Delta U_{app}} = \frac{\delta_{app} - \delta_U}{\delta_{app}} \tag{3.9}$$

The metric is a function of U_{min}. Woerner (2016) did not specify how U_{min} is identified.

Implementation of the Speed alteration metric

Instead of using U_{min} to determine if a speed change is apparent or not, the implementation in this work uses the maximum absolute deviation from the initial speed, denoted $|\Delta U|$; from the initial speed at t_{detect} to t_{cpa}. The same approach that was used to find $|\Delta \chi|$ in (3.7), is used to find $|\Delta U|$. This penalizes both positive and negative non-apparent speed alterations. The metric is then expressed as

$$\delta_U \triangleq \frac{U_0 - |\Delta U|}{U_0} \tag{3.10}$$

$$\mathcal{P}_{\Delta U_{app}} \triangleq \frac{\delta_{app} - \delta_U}{\delta_{app}} \tag{3.11}$$

Rule 8b - Detect non-readily apparent maneuver

Woerner (2016) combined the metrics for detecting non-readily apparent alteration of course and speed into one metric for detecting non-readily apparent maneuvers. A similar approach is used in this thesis and is shown in (3.12). For the original metric developed by Woerner, the reader is referred to Algorithm 13 in Woerner (2016)

$$\mathcal{P}_{\Delta} \triangleq \mathcal{P}_{\Delta U_{app}} \mathcal{P}_{\Delta \chi_{app}} \tag{3.12}$$

A heat map illustrating the penalty score $\mathcal{P}_{\Delta}$ is given in Figure 3.5. As both $\mathcal{P}_{\Delta U_{app}}$ and $\mathcal{P}_{\Delta \chi_{app}}$ give penalty scores from 0 to 1, the metric yields a score of 0 if either the course alteration or the speed alteration is considered apparent. The worst case score is one, if no alteration of course or speed is present.

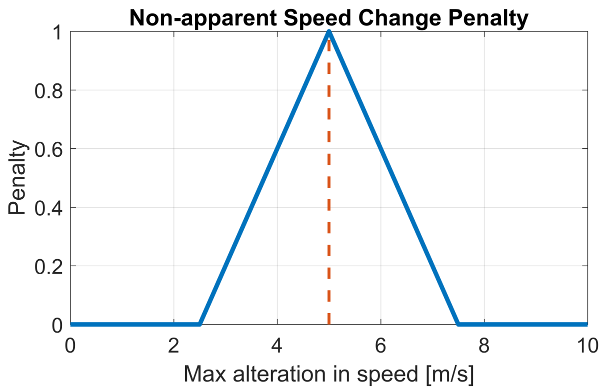

Figure 3.4: Penalty of speed change in a scenario where the ASV has an initial speed of 5 m/s.

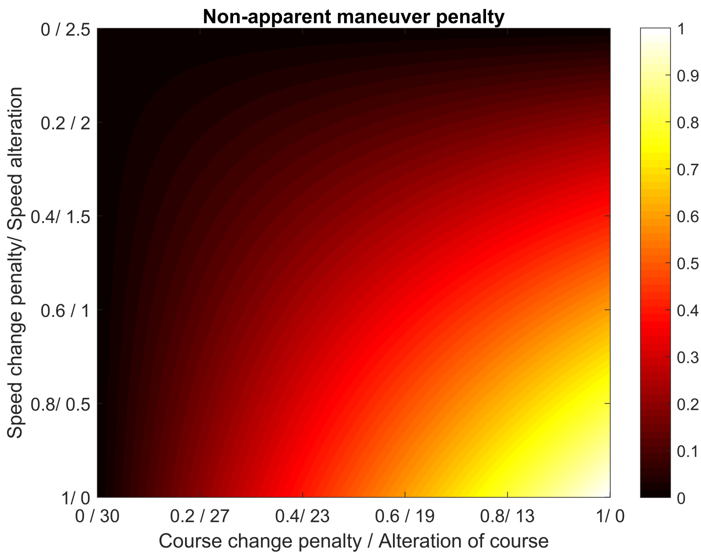

Figure 3.5: The score $\mathcal{P}_{\Delta}$ as a function of $\mathcal{P}_{\Delta U_{app}}$ and $\mathcal{P}_{\Delta \chi_{app}}$. Along the x-axis, the course change penalty and the absolute alteration of course in degrees are shown. Along the y-axis, the speed change penalty and the absolute speed alteration is shown.

3.4 Determining applicable rules

In order to determine if an ASV is acting in accordance to the rules in a collision situation, an algorithm for defining the rules associated with an encounter is needed. As seen in Chapter 2, designers of collision avoidance algorithms are using different techniques for determining how the vessel should maneuver to abide to the COLREGS. Both the VO and the SBMPC determine what kind of situation is present, and then determine if an action is violating the CORLEGS or not. None of these approaches describe the full picture. Woerner (2016) developed an algorithm that can specify which COLREGS rule that applies for the own-ship for all encounter in a situation. The algorithm is presented in Algorithm 1. This algorithm does not take the precedence rules from COLREGS rule 18 into account. Rule 18 states that a power-driven vessel underway shall keep out of the way for vessels not under command, restricted in her ability to maneuver, engaged in fishing or sailing vessels.

When two vessels are in sight of one another and the risk of collision exist, the encounter type can be determined and it will not change as the situation develops. This is expressed explicitly in Rule 13d, where it is stated that a vessel overtaking another, will remain the give-way vessel, although the bearings might change. According to Allen (2005) courts have applied Rule13d to crossing situations as well. Once encounter types have been determined, it should remain the same type throughout the entire scenario.

Algorithm 1 determines the rules associated with each encounter by using the initial poses of the own-ship and the obstacles. From the poses, the relative bearing β and the initial contact angle α determines which rules that is applicable.

The relative bearing is the angle in the clockwise direction from the heading of the own-ship, to the line-of-sight vector from the own-ship to the target-ship. The relative bearing is defined in the interval

$$\beta \in [0, 360).$$

The initial contact angle is the relative bearing of the own-ship as seen from the obstacles. The contact angle α is defined in the interval $[-180, 180)$, and is equal to the normalized relative bearing as described in Section 2.5.4.

The constants β^{180° and α^{360° are used in Algorithm 1, and defined as follows:

$$\beta^{180^\circ} \triangleq \beta - 180 \tag{3.13}$$

$$\alpha^{360^\circ} \triangleq \alpha + 180 \tag{3.14}$$

Algorithm 1 use three parameters to define the define the different encounter types; $\alpha^{13}_{crit}, \alpha^{14}_{crit}, \alpha^{15}_{crit}$. Woerner (2016) named these critical contact angles.

- α^{13}_{crit}, is the overtaking tolerance to define when a vessel is approaching another from abaft the beam.

- α_{crit}^{14}, is the tolerance for when vessels are approaching on reciprocal, or nearly reciprocal courses.
- α_{crit}^{15}, is the tolerance for specifying when a vessel is crossing.

All critical contact angles are relative to the bearing of the own-ship and the other vessel in the encounter. They are tunable by the evaluator, but the default values specified in Woerner (2016) are used and given below.

$$\alpha_{crit}^{13} = 45°, \quad \alpha_{crit}^{14} = 13°, \quad \alpha_{crit}^{15} = 10°$$

Algorithm 1 Determining COLREGS rules for encounters (Woerner, 2016)

function DETERMINE RULE SET(ASV, obstacle ship)
    $\alpha_{crit}^{13} \leftarrow$ overtaking tolerance
    $\alpha_{crit}^{14} \leftarrow$ head-on tolerance
    $\alpha_{crit}^{15} \leftarrow$ crossing aspect limit
    $\alpha_0 \leftarrow$ initial contact angle
    $\beta_0 \leftarrow$ initial bearing angle
    if $(\beta_0 > 112.5) \quad \&\& \quad (\beta_0 < 247.5) \quad \&\& \quad (|\alpha_0| < \alpha_{crit}^{13})$ **then**
        The own-ship is being overtaken (is stand on vessel)
    else if $(\alpha_0^{360°} > 112.5) \quad \&\& \quad (\alpha_0^{360°} < 247.5) \quad \&\& \quad (|\beta_0|^{180°} < \alpha_{crit}^{13})$ **then**
        The own-ship is overtaking the target ship (is give-way vessel)
    else if $|\beta_0|^{180°} < \alpha_{crit}^{14} \,\&\&\, |\alpha_0| < \alpha_{crit}^{14}$ **then**
        Vessel is head on
    else if $(\beta_0 > 0) \,\&\&\, (\beta_0 < 112.5) \,\&\&\, (\alpha_0 > -112.5) \,\&\&\, \alpha_0 < \alpha_{crit}^{15}$ **then**
        The vessel is crossing and is the give way vessel
    else if $(\alpha_0^{360°} > 0) \,\&\&\, (\alpha_0^{360°} < 112.5) \,\&\&\, (\beta_0^{180°} > 112.5) \,\&\&\, (\beta_0^{180°} < \alpha_{crit}^{15})$ **then**
        Vessel stand-on in crossing.
    else
        No risk of collision. Keep monitoring contact for developing COLREGS scenario
    end if
end function

3.5 Rule 13 - Overtaking scenario

Rule 13 of the COLREGS applies to overtaking scenarios and it is provided in its entirety below.

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 with reference to the vessel she is overtaking, that at night she would be able to see only the sternlight of that vessel but neither of her sidelights.*

(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 distinguish itself from the other rules in a way that its entry criteria is very specific. A vessel approaching another vessel from more than 22.5° abaft the beam, is defined as the overtaking vessel and should keep out of the way of the other. The vessel being overtaken should then keep her course and speed as the stand-on vessel. This is specified by Rule 17.

In the evaluation library developed by Woerner (2016), Rule 13 was evaluated by determining whether or not the own-ship is the give-way or the stand-on vessel with Algorithm 1. It is then evaluated with metrics developed for Rule 16 if it is determined to be the give-way vessel, and the metrics developed for Rule 17 if it is determined to be the stand-on vessel.

Woerner (2016) specified that the give-way vessel should avoid crossing ahead of the stand-on vessel in the overtaking encounter. This is an important aspect when the overtaking vessel is approaching an other on a course that is close to crossing. In these encounters, the metrics should favor give-way maneuvers that results in a passing astern of the stand-on vessel. Woerner (2016) argued that passing in front of the overtaken vessel would create a situation associated with higher risk and might degrade the overtaken vessels ability to maintain course and speed.

However, Allen (2005) stated that an ahead passing in itself is not violation of the COLREGS if the give-way vessel pass at a safe distance. But the vessel passing ahead should keep in mind the constant risk of mechanical breakdown when considering what is a safe distance to pass ahead. Allen (2005) also stated that the prudent action for a conventional vessel would to alter course or slow down to pass astern of the stand-on vessel. As what is considered safe distance is difficult to quantify, detected ahead passings should probably be investigated by the evaluator manually when detected.

In Woerner (2016) a metric to evaluate if a vessel passed ahead of the stand on vessels in crossing encounters was presented for crossing situations. This metric is described in Section 3.7. The same metric is used, but with different constraints on the contact angle at CPA.

$$\mathcal{P}^{13}_{ahead} \triangleq \begin{cases} 1, & \text{if } \alpha_{cpa} > -45^\circ \wedge \alpha_{cpa} < 45^\circ \\ 0, & \text{else.} \end{cases} \tag{3.15}$$

Following Woerner (2016), the total metric quantifying Rule 13 compliance is given by

$$S^{13} \triangleq \begin{cases} S^{16} - \gamma^{13}_{ahead}\mathcal{P}^{13}_{ahead}, & \text{if own-ship is the give-way vessel.} \\ S^{17}, & \text{if own-ship has stand-on responsibility.} \end{cases} \tag{3.16}$$

S^{16} and S^{17} are metrics covering give-way and stand-on encounters. These are described in Section 3.8 and 3.9 respectively. γ^{13}_{ahead} is a penalty parameter defining the severity of an ahead passing. This is tunable by the evaluator. In the implemented metric library, the parameter is set to

$$\gamma^{13}_{ahead} = 0.3.$$

3.6 Rule 14 - Head-on scenario

Rule 14 covers head-on scenarios, where two vessels are approaching each other on reciprocal or nearly-reciprocal courses. Rule 14 is provided below.

> **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.*

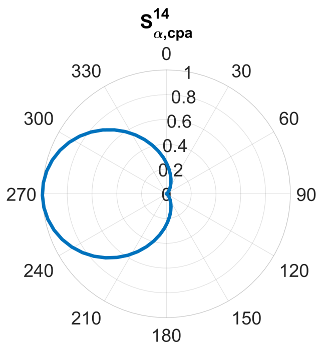

Figure 3.6: Polar plot of $\left(\frac{\sin(\alpha_{cpa})-1}{2}\right)^2$. Source: Woerner (2016)

Based on Rule 14a, a metric for rule 14 should evaluate if the vessels alter course to starboard and if they pass each other port to port. In addition to these navigational requirements, the vessels have to comply with rule 8.

Woerner (2016) developed an algorithm to evaluate the head-on scenario. It consist of four parts listed below:

1. Penalize delayed action (Rule 8a)
2. Penalize non-readily apparent course changes (Rule 8b)
3. Penalize non port-to-port passings (Rule 14a).
4. Penalize non-starboard turns (Rule 14a).

The metrics developed for Rule 8 are used to assess compliance by Rule 14. Additionally, two new metrics must be defined; one for detecting non-starboard turns and one for detecting port-to-port passing.

Woerner (2016) suggested a metric for detecting port-to-port passing based on the relative bearing and contact angles at t_{cpa}. A perfect port-to-port passing at t_{cpa} would give $\alpha_{cpa} = -90°$ and $\beta_{cpa} = 270°$. The metric proposed in Woerner (2016) is shown in (3.17).

$$S^{14}_{\Theta_{cpa}} \triangleq S^{14}_{\alpha_{cpa}} \cdot S^{14}_{\beta_{cpa}} = \left(\frac{\sin(\alpha_{cpa})-1}{2}\right)^2 \left(\frac{\sin(\beta_{cpa})-1}{2}\right)^2 \tag{3.17}$$

$S^{14}_{\alpha_{cpa}}$ and $S^{14}_{\beta_{cpa}}$ are functions that give scores closer to 1 when a vessel sees the other on the port side. By multiplying $S^{14}_{\alpha_{cpa}}$ and $S^{14}_{\beta_{cpa}}$, port-to-port passes are quantified with a port-to-port pass resulting in a score of 1, and a starboard-starboard pass resulting in a score of 0. To visualize the function, $S^{14}_{\alpha_{cpa}}$ is shown in Figure 3.6.

The penalty for a starboard-starboard passing can be expressed as the complement of (3.17) and is denoted $\mathcal{P}^{14}_{\Theta_{cpa}}$.

$$\mathcal{P}^{14}_{\Theta_{cpa}} \triangleq 1 - S^{14}_{\Theta_{cpa}} \tag{3.18}$$

Woerner (2016) did not specify how non-starboard maneuvers were detected. A penalty metric based on the maximum course deviation to starboard from the initial course at t_{detect}, to t_{cpa} is used. The maximum alteration of course to starboard is found in (3.19).

$$\Delta\chi^{+} = max\left\{\chi(t_{detect}) - \chi_0,\ \chi(t_{detect}+1) - \chi_0,\ \ldots,\ \chi(t_{cpa}) - \chi_0\right\} \tag{3.19}$$

Where $\chi_0 = \chi(t_{detect})$. The penalty metric is then given by

$$\mathcal{P}^{14}_{nsb} \triangleq \begin{cases} 0, & \text{if } \Delta\chi^{+} > 20^{\circ} \\ \left(\frac{\Delta\chi^{+}}{20}\right)^4, & \text{otherwise.} \end{cases} \tag{3.20}$$

Figure 3.7 illustrates the penalty given by the metric. If the starboard course change is larger than 20°, a starboard maneuver is considered present.

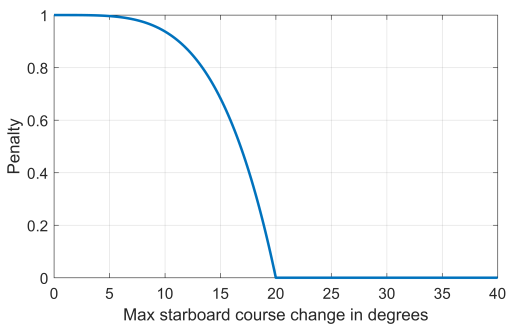

Figure 3.7: The penalty given by non-starboard turn penalty metric. The x-axis show the largest detected course to starboard from the initial course to the course at t_{cpa}

$\mathcal{P}_{\Delta\chi_{app}}$ might seem redundant to $\mathcal{P}^{14}_{nsb}$. However, if a maneuver is made to port and it is readily apparent, this might be useful information when conducting analysis of collision avoidance algorithms. Both metrics are therefore included in the developed evaluation library.

The four parts considered important for evaluating Rule 14, can now all be combined to one metric as shown in (3.21). S^{14} is defined here in a slightly different manner than in Woerner (2016). Woerner multiplied the total score with the complement of the delay penalty. Here the delay penalty is subtracted from the total score instead. However, the characteristics of the metric should remain the same.

$$S^{14} \triangleq (1 - \gamma_{nsb}\mathcal{P}^{14}_{nsb} - \gamma^{14}_{delay}\mathcal{P}_{delay} - \gamma^{14}_{\Theta_{cpa}}\mathcal{P}^{14}_{\Theta_{cpa}})(1 - \mathcal{P}_{\Delta\chi_{app}}) \tag{3.21}$$

Table 3.2: Penalty parameters in the metric for rule 14.

Parameter	Value
$\gamma^{14}_{\Theta_{cpa}}$	1
γ^{14}_{delay}	0.2
γ_{nsb}	0.6

The parameters defining the severity of each penalty is given in Table 3.2. These are tunable by the evaluator.

In some head-on encounters, altering course to starboard will cause the vessel to cross the track of the other vessel. In these encounters it might seem intuitive to alter course to port in order to increase the passing distance in accordance with Rule 8d. However, Allen (2005) and Cockcroft and Lameijer (2004) advised against this. If the officer on watch alters course to port to increase the passing distance, a risk of collision is implicitly present. Altering course to port can then be dangerous. The other vessel might alter course to starboard in accordance with Rule 14 at the same time, resulting in conflicting actions.

3.7 Rule 15 - Power-Driven Crossing

Rule 15 assigns responsibilities to vessels meeting in a crossing situation.

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.*

If the vessel is assigned the role as the give-way vessel, it should keep out of the way in accordance with Rule 16 and not pass ahead of the stand on vessel. Woerner (2016) evaluated the give-way vessel with a metric developed for Rule 16, and deducted a penalty if the give-way vessel passed ahead of the stand-on vessel. The same approach is used here. Woerner (2016) used (3.22) to determine a passing ahead. That is, if the critical contact angle at the closest point of apporach, is between $-25°$ and $165°$, an ahead passing is determined to be present.

$$\mathcal{P}^{15}_{ahead} \triangleq \begin{cases} 1, & \text{if } \alpha_{cpa} > -25° \wedge \alpha_{cpa} < 165° \\ 0, & \text{else.} \end{cases} \tag{3.22}$$

The stand-on vessel is simply evaluated against a developed metric for Rule 17. This is again the same approach as used by Woerner (2016).

The rule 15 metric, can then be combined as shown in (3.23).

$$\mathcal{S}^{15} \triangleq \begin{cases} \mathcal{S}^{16} - \gamma^{15}_{ahead}\mathcal{P}^{15}_{ahead}, & \text{if own-ship is give-way vessel.} \\ \mathcal{S}^{17}, & \text{if own-ship is stand-on vessel.} \end{cases} \tag{3.23}$$

In the developed metric library, the tunable parameter γ^{15}_{ahead} is set to 0.5.

The implementation of the analysis tool does not take into account power-driven vessels not under command, or restricted in their abilities to maneuver, or engaged in fishing. This means that, in the evaluated scenarios, all crossing situations are covered by Rule 15.

3.8 Rule 16 - Action by give-way vessel

Rule 16 - Action by Give-way vessel

Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear.

Rule 16 defines the responsibility of vessels giving-way. It does not define the required maneuvers, but it specifies that early action has to be taken to keep the vessel well well clear of the stand on vessel. Rule 16 should be applied in conjunction with Rule 8.

Following directly from Rule 16 as stated in the COLREGS, give-way vessels should be tested against the following properties:

- Take early action. Any alteration in course or speed should be made in ample time.
- Take substantial action. Any alteration in course or speed should be large enough to be readily apparent.
- Keep well clear. The vessels should be passing at a safe distance.

Woerner (2016) also pointed out these properties. The first two properties can be tested with the metrics defined for Rule 8. A score for early action can be obtained by taking the complement of $\mathcal{P}_{delay}$, defined in (3.3). A non-apparent maneuver is quantified by $\mathcal{P}_{\Delta}$ in (3.12). A score defining if a maneuver is apparent can be obtained by taking the complement of $\mathcal{P}_{\Delta}$. If the give-way vessel keeps well clear as a result of the actions taken, a good safety score, S_{safety}, should be observed.

In addition to these three properties, Woerner (2016) checked if the give-way vessel was a hindrance for the stand-on vessels. From the text it is not clear how this was implemented.

The metric developed by Woerner, based on the properties presented in the top of this section is combined to one metric as shown in (3.24).

$$\mathcal{S}^{16} = \mathcal{S}_{safety}(1 - \mathcal{P}_{delay})(1 - \mathcal{P}_{\Delta}) \tag{3.24}$$

3.9 Rule 17 - Action by stand-on vessel

Rule 17 covers the required actions of stand-on vessels.

Rule 17: Action by 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.*

Rule 17 is probably the hardest rule to quantify. The reason is difficulties in quantifying when the different parts of the rule apply. Cockcroft and Lameijer (2004) divided a collision situation for a vessel with stand-on responsibilities into four stages. These are

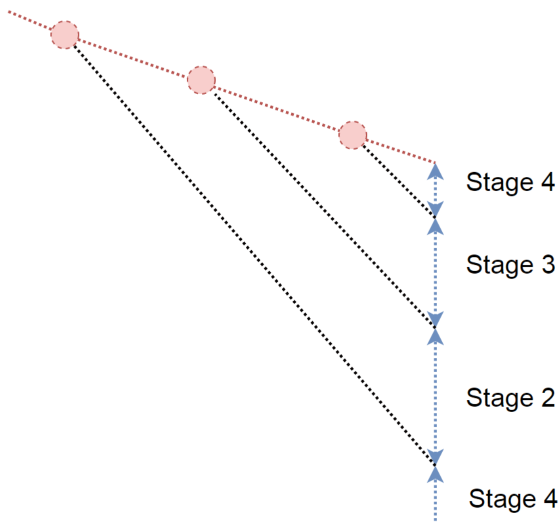

Figure 3.8: The four different stages of a collision situation for a stand on vessel. The red lines and circles, illustrates a give-way vessel which is not taking action. The blue lines, illustrates the track of a stand-on vessel, not taking action either.

shown in Figure 3.8. Cockcroft and Lameijer (2004) stated that the outer range of each stage will vary considerably. But approximate ranges were suggested for power driven vessels in crossing situations in the open sea. The outer range of stage two can be considered to be in the order of 5 to 8 miles (8 to 12 kilometers). The outer limit of stage three was suggested to be about 2 to 3 miles (3 to 5 kilometers). Stage four could be considered to apply when the distance between the vessels is about four ship lengths.

Stage 1: The first stage is when the distance between the vessels in a situation is large and no risk of collision exists. In this stage Section II, Part B the COLREGS does not apply.

Stage 2: When the vessels get closer and a risk of collision is deemed to exist, one vessel is assigned the give-way and the other the stand-on responsibility. This is the second stage of the collision situation. At this point, Rule 17a applies to the stand-on vessel, and it should keep her course and speed. In encounters with more than two vessels, where a vessel has both give-way responsibility and stand-on responsibility, the vessel cannot be expected to both comply with her give-way and stand-on responsibility. According to Cockcroft and Lameijer (2004), giving-way in an encounter like this, is considered to keeping course and speed as the maneuver should be expected by the give-way vessel.

Stage 3: When the vessels are getting closer and it becomes apparent to the stand-on vessel that the give-way vessel is not taking appropriate action, the stand-on vessel enters stage three of the collision situation. This stage is covered by Rule 17a, ii, and Rule 17c. In this stage, the stand-on vessel is allowed to take action to avoid collision, such that collision is avoided by her maneuvers alone. Action is not required by the stand-on vessel at this point. Cockcroft and Lameijer (2004) referred to cases in admiralty courts where the stand-on vessel had been found partly to blame in a collision after action was taken in stage two. The reason was that the action taken was not readily apparent. When a vessel decides to take action at this stage, it is important that action is taken in compliance with Rule 8b.

If the stand-on vessel finds herself in stage three of a crossing situation, she should not alter course to port if the circumstances of the case admit, in accordance with Rule 17c. The stand-on vessel should still expect the give-way vessel to alter course to starboard to comply with Rule 15. A turn to port would result in conflicting actions and increase the probability of a collision (Cockcroft and Lameijer, 2004).

Stage 4: If the stand-on vessel finds herself in a situation where collision cannot be avoided by the give-way vessel alone, then action to avoid collision is required by the stand-on vessel.

Based on these four stages a procedure for evaluating compliance with Rule 17 can be developed. Woerner (2016) proposed a procedure to evaluate Rule 17 compliance. An overview of this procedure and the including the elements are presented as pseudo code in Algorithm 2.

Algorithm 2 Rule 17: Stand-on vessels (Woerner, 2016)

```
function EVALUATE STAND-ON VESSEL BEHAVIOR
    AnalyzeSafety    ▷ "She shall take such action as will best aid to avoid collision"
    Penalize course change
    Penalize speed change
    Compensate for maneuvers required of normal navigation
    if in extremis then
        Compensate for maneuvers required in extremis
        if Power-driven crossing then
            Penalize port maneuvers for port contacts
        end if
    end if
end function
```

Woerner (2016) did not differentiate between vessels in stand-on that finds herself in Stage 3 and 4 of a collision situation. Stage three and four is often referred to as *in extremis*. It was argued that when the stand on vessel got sufficiently close to the give-way vessel, the safety metric would be the best method to evaluate if the stand-on vessel takes sufficient action.

Following Woerner (2016), we do not differentiate between stage 3 and 4 when evaluating stand-on encounters in this work. Four new metrics are needed to implement the stand-on evaluation procedure. These are the stand-on course change penalty, the stand-on speed change penalty, stand-on maneuver penalty, and the detect port turn penalty. These will be described below.

3.9.1 Stand-on course change penalty

The metric used to determine stand-on course change, is obtained from Woerner (2016). The metric is given by

$$\mathcal{P}^{17}_{\Delta\chi} \triangleq \frac{|\Delta\chi| - \chi_{md}}{\Delta\chi_{app} - \chi_{md}} \tag{3.25}$$

where

- $|\Delta\chi|$, the maximum course change
- $\Delta\chi_{app}$, the apparent course change
- χ_{md}, the minimum detectable course change

The metric is saturated at 0 and 1. The maximum course change, is found using the method presented in (3.7). The minimum detectable course change is set to four degrees for the same reason as in the procedure for detecting when a maneuver is initiated in (3.4). Allen (2005) stated that any alterations of course less than three degrees, could not be considered visible on radar.

3.9.2 Stand-on speed change penalty

The stand on speed change penalty metric is given by (3.26). The metric is based on the speed change penalty metric developed by Woerner (2016), but deviates in the case of speed increases. This was done to simplify the implementation of the metric. The original metric can be found in Algorithm 17 in Woerner (2016).

$$\mathcal{P}^{17}_{\Delta U} \triangleq \begin{cases} 0, & \text{if } |\Delta U| < \Delta U_{md} \\ 1 - \left(\dfrac{U_0}{|\Delta U|}\right)^2, & \text{if } \Delta U > 0 \\ \dfrac{|\Delta U|}{U_0}, & \text{if } \Delta U < 0 \end{cases} \tag{3.26}$$

In (3.26), ΔU is the maximum deviation in speed from t_{detect} to t_{cpa}. U_{md} is the minimum detectable speed change and is set to 0.2 m/s. This is the same threshold as used in Woerner (2016). (3.25) is saturated at 0, and 1 in the implementation.

3.9.3 Detect port turn penalty

If the own-ship is determined to be the stand-on vessel in a crossing encounter, it should not alter course to port. A metric used to determine whether a port turn has taken place has been developed and will be described here.

When a stand on situation was determined to take place, the current own-ship body reference frame is saved. This is the body reference-frame at t_{detect}. From time t_{detect} to t_{cpa}, all positions are transformed into this reference frame. If the the own-ship moves more than two ship widths into the left half plane, a port turn is determined to take place.

$$\mathcal{P}_{PortTurn} \triangleq \begin{cases} 1, & \text{if port turn detected} \\ 0, & \text{otherwise.} \end{cases} \tag{3.27}$$

3.9.4 Stage 3 - Stand-on maneuver penalty

As described in the four stages of a stand-on encounter, an alteration of course or speed is allowed in Stage 3. This should be reflected in the metric covering Rule 17. Additionally, in Algorithm 2 a method for compensating for maneuvers *in extremis* is required. This is achieved in this thesis with a developed stand-on maneuver penalty. This penalty metric is based on the ranges specified in Cockcroft and Lameijer (2004) for the outer limits of stage 3 in open waters for power-driven vessels. These are given below.

- $R_{stage3,max} = 5000$ meters
- $R_{stage3,min} = 3000$ meters

In addition, the range to the obstacle when a maneuver is initiated is used. This range is given by $r_{maneuver}$ which is described in Section 3.3.1. The stand-on maneuver penalty is given by (3.28).

$$\mathcal{P}_{\Delta}^{17} \triangleq 1 - \left(\frac{r_{maneuver} - R_{stage3,max}}{R_{stage3,max} - R_{stage3,min}} \right)^2 \tag{3.28}$$

Figure 3.9 visualize (3.28). When penalties are given to a maneuver in stand-on with either the speed change or course change penalty metrics, the penalties are multiplied with $\mathcal{P}_{\Delta}^{17}$. The result is that when a maneuver is initiated in stage 2, the full penalty for initiating a maneuver is deducted from the total score. When a maneuver is initiated when the vessel closer than the inner limit of stage 3, no penalty is deducted from the total score if a maneuver is initiated.

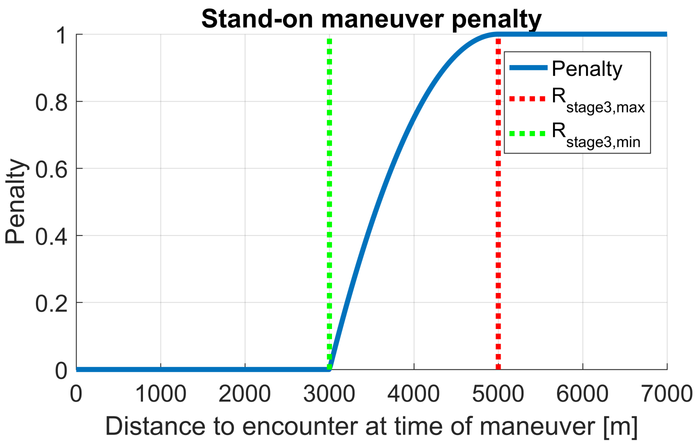

Figure 3.9: Stand-on maneuver penalty shown as a function of the range to the obstacle when a maneuver is initiated.

3.9.5 Implementation of the Rule 17 metric

The implementation of the Rule 17 metric, is best shown with pseudo code similar to Algorithm 2.

Algorithm 3 Implementation of metric for Rule 17

function EVALUATE STAND-ON VESSEL BEHAVIOR
 $\mathcal{S}^{17} := 1 - \gamma^{17}_{safety}(1 - \mathcal{S}^{safety})$
 if vessel is **not** required to give-way or alter course for other encounters **then**
  $\mathcal{S}^{17} := \mathcal{S}^{17} - \mathcal{P}^{17}_{\Delta}(\mathcal{P}^{17}_{\Delta U} + \mathcal{P}^{17}_{\Delta \chi})$
 end if
 if Power-driven crossing **then**
  $\mathcal{S}^{17} := \mathcal{S}^{17} - \gamma^{17}_{PortTurn}\mathcal{P}_{PortTurn}$
 end if
end function

The penalty parameters $\gamma^{17}_{PortTurn}$ and γ^{17}_{safety}, are tunable parameters. These are set to 0.6 and 0.7 respectively.

In the metrics previously described in this chapter, the safety metric is able to reduce the COLREGS compliance score to zero alone. γ^{17}_{safety} reduce the required safety distance for Rule 17. As smaller passing distances should be considered as appropriate behavior, if the stand-on vessel is waiting for the give-way vessel to take action (Allen, 2005).

A drawback of the implemented $\mathcal{S}^{17}$ metric, is that when a maneuver is initiated in stage 3, the metric does not evaluate if the maneuver taken is readily apparent. Cockcroft and

Lameijer (2004) referred to a collision where the stand-on vessel was held partly to blame after action was taken in stage 3 of a collision situation. When the vessels were two miles apart, the stand-vessel altered course $20°$ to starboard. A collision occurred, and court determined that insufficient action was taken by the stand-on vessel. A course alteration of $40°$ to starboard, and reduction of speed was suggested as the appropriate action in this scenario.

CHAPTER 4

Simulator development and testing strategies

This chapter will describe the developed simulator and the systems that have been developed to enable automatic testing of collision avoidance algorithms. Figure 4.1 gives a general overview of the three top level modules in the developed system. This chapter is concerned with the two first systems. The first module is the scenario generator. This defines all

Figure 4.1: High level illustration of the relationship between the developed systems.

scenarios that will be simulated by the collision avoidance simulator. The simulator then runs the generated scenarios automatically and saves all relevant data to log files. The logs are then post processed by the Evaluation and analysis module. Each scenario is evaluated, and aggregated results are generated and allow the evaluator to inspect and analyze the results.

This chapter is divided into six sections. First the collision avoidance simulator will be described. Then the systems that makes up the ASV subject to testing will be described. This includes the vessel model, the implemented guidance and control system, and the implemented collision avoidance systems. Next the obstacles that are implemented in the simulator will be described. Finally the developed scenario generation scheme will be presented in Section 4.6.

The vessel model in Section 4.2, and the Guidance and Control system in Section 4.3 were developed in the preliminary project, and are reused in this thesis.

4.1 The simulator infrastructure

The simulator infrastructure used in this project is developed by DNV GL and is called CyberSea. It is used for HIL testing of maritime control systems. This is a testing methodology where the control system is connected and tested on a simulator, before being deployed on the plant it is designed to control (Skjetne and Egeland, 2006). This allows a class society, or a control system engineer to detect software errors and verify correct functioning in a safe virtual environment. The models in the HIL-simulator will have to be accurate enough to fool the control system.

The CyberSea simulator infrastructure allows engineers to develop models of the systems subject to testing. The models are implemented in their own modules. The modules can be connected with signals, and simulations are run by simulating all modules and the signals between each module.

In this thesis a Platform Supply Vessel (PSV) modeled and implemented in CyberSea is used as the test subject. The full vessel model consists of several modules connected together. These include models of the power-systems, the thruster dynamics, and the hull of the vessel. The vessel systems can be controlled with an external control system. This would be the case when conducting HIL-tests. It can also be controlled by a control system module developed and implemented internally in CyberSea. The latter has been done in this thesis.

An overview of the modules used in CyberSea and the implemented modules are presented in Figure 4.2. The green boxes are models provided by the DNV GL CyberSea simulator. This includes the Hull module which models the dynamics of the hull of a PSV; the thrusters which models the thruster dynamics; and the thruster allocation module, which distributes the generalized control forces to the thrusters in terms of control inputs. Also the environmental forces, such as wind and waves included, all though not used for tests in this thesis. The blue boxes are modules developed to enable testing of CAS. This includes a GNC-system with collision avoidance; a module representing the tracking system; and the Obstacle module which models obstacles to be avoided.

All modules inside the yellow box make up the systems that simulate the ASV. Notice that Figure 4.2 is not an exhaustive diagram of all modules and signals used in the simulator. It is an overview to show the most important modules being used.

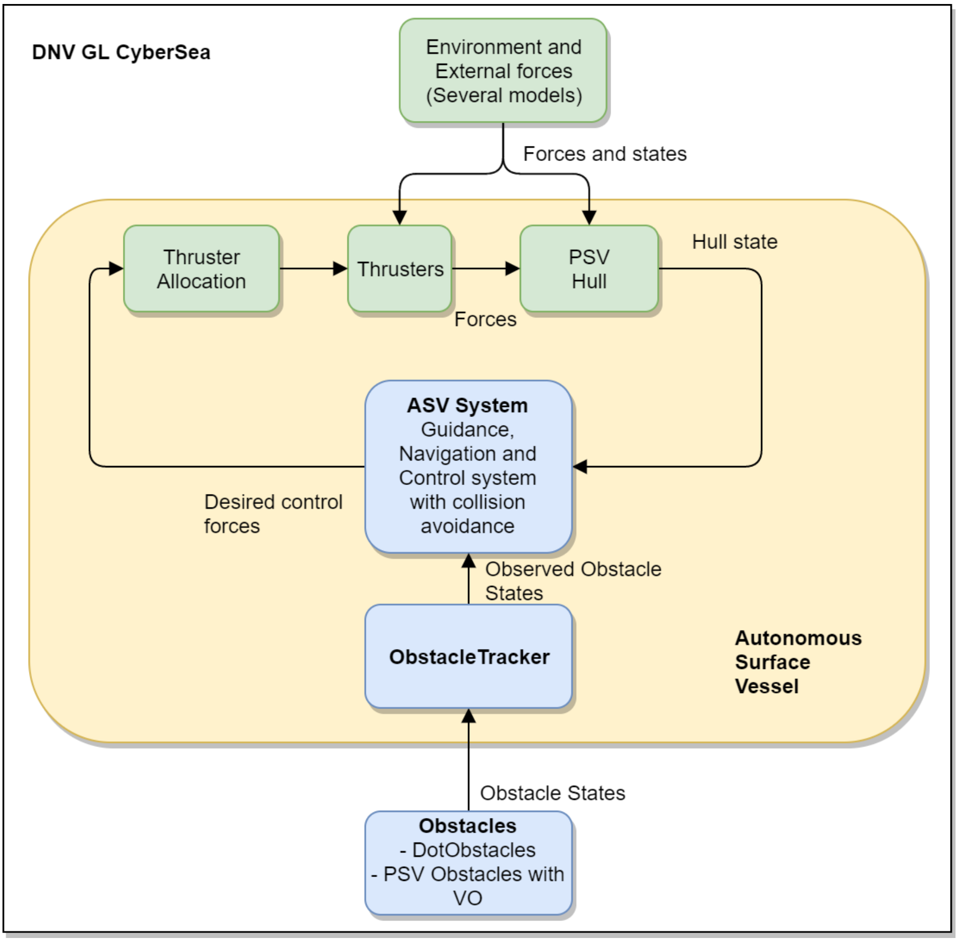

Figure 4.2: Overview of modules in the CyberSea collision avoidance simulator.

4.1.1 Signature

A tool named Signature is part of the CyberSea simulator infrastructure. This is a tool that can run Groovy[1]-scripts to control simulator. A sequence of events can be defined in the scripts. This functionality is used to enable automatic-testing of collision avoidance systems.

[1] http://groovy-lang.org/

4.2 Vessel model

A PSV is modeled in CyberSea and used as a test platform for the collision avoidance systems. A similar vessel to the one modeled is shown in Figure 4.3. The modules

Figure 4.3: Platform Supply Vessel similar to the vessel that is modeled in the CyberSea simulator. Source: https://www.flickr.com/photos/zeesenboot/10317626005/ [2]

that include the model of the PSV is provided by DNV GL. The vessel has a length of 116 meters, width of 25 meters, and a weight of about 15500 tons. A 3DOF model as described in Section 2.1 has been used to design a motion control system for the ship. The same model is used to simulate the dynamics in implementation of the SBMPC CAS. The parameters required in the 3DOF-model is presented in Table 4.1. The PSV is equipped

Table 4.1: Parameters for a 3DOF PSV-model.

Parameter	Value	Unit
m	15524000	kg
I_z	$1.0437 \cdot 10^{10}$	$kg \cdot m^2$
x_g	-3.7	m
$X_{\dot{u}}$	-979290	kg
$Y_{\dot{v}}$	-10727527	kg
$Y_{\dot{r}}$	-11357800	$kg \cdot m$
$N_{\dot{r}}$	$-6.2422 \cdot 10^9$	kg/m^2
X_u	-1650	kg/s^2
Y_v	-10501	kg/m^2
Y_r	0	$kg \cdot m/s$
N_v	0	$kg \cdot m/s$
N_r	-19622349	$kg \cdot m^2/s$

with six thrusters; four azimuth thrusters that can rotate 360° and two tunnel thrusters. The layout of the thrusters are shown in Figure 4.4.

Figure 4.4: Thruster configuration of the PSV. A denotes 360° azimuth thruster, and T denotes a tunnel thruster.

4.3 Guidance, Navigation, and Control system

The guidance and control system presented here was developed in a preliminary project during autumn 2016. The developed controllers will be presented here. A block diagram with the structure of the developed system is given in Figure 4.5. It is assumed that the state of the ASV is known, and therefore no navigation system is implemented.

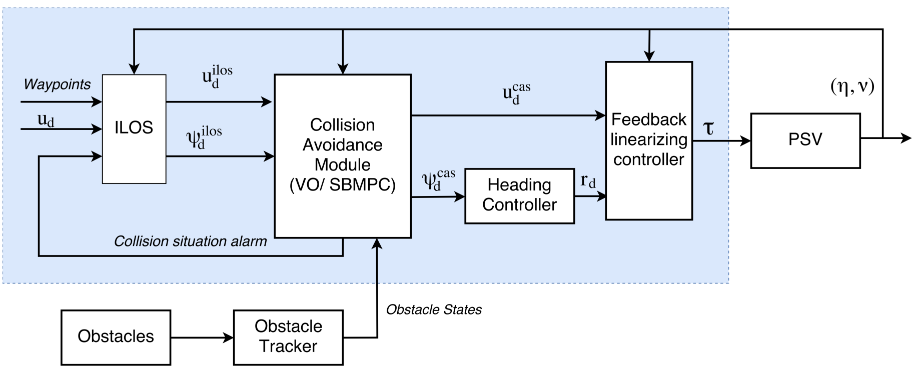

Figure 4.5: Block diagram of the implemented GNC-system on the PSV. The CAS in the diagram will either be a Velocity Obstacles Algorithm or the SBMPC. The SBMPC requires information about the waypoints as well from the ILOS-guidance module.

4.3.1 Controllers for heading, surge, sway, and yaw

A feedback linearizing MIMO P-controller is chosen to control the surge, sway and yaw-rate. It is based on a controller from Fossen (2011).

$$\boldsymbol{\tau} = \begin{bmatrix} F_x \\ F_y \\ F_n \end{bmatrix} = \boldsymbol{M}\left(-\boldsymbol{K}_p\tilde{\boldsymbol{\nu}}\right) + n(\boldsymbol{\nu}, \boldsymbol{\nu}_r) \tag{4.1a}$$

$$\boldsymbol{K}_p = \begin{bmatrix} K_{p,1} & 0 & 0 \\ 0 & K_{p,2} & 0 \\ 0 & 0 & K_{p,3} \end{bmatrix}, \quad K_{p,1}, K_{p,2}, K_{p,3} > 0 \tag{4.1b}$$

$$\tilde{\boldsymbol{\nu}} = \boldsymbol{\nu} - \boldsymbol{\nu}_d = \begin{bmatrix} u \\ v \\ r \end{bmatrix} - \begin{bmatrix} u_d \\ v_d \\ r_d \end{bmatrix} \tag{4.1c}$$

$$n(\boldsymbol{\nu}, \boldsymbol{\nu}_r) = \boldsymbol{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{C}_A(\boldsymbol{\nu_r})\boldsymbol{\nu_r} + \boldsymbol{D}(\boldsymbol{\nu_r})\boldsymbol{\nu_r} \tag{4.1d}$$

$n(\boldsymbol{\nu}, \boldsymbol{\nu}_r)$ is the non-linear component of the 3DOF vessel model. $\boldsymbol{\nu}_d$ is the reference values to the controller. u_d is the speed given from the guidance system. For a large vessel like the PSV considered, surge and speed will be approximately equal. r_d is given from the heading controller (4.2). v_d is set to 0 as the controller is implemented for path following. Velocity in the sway direction is not desired in this when following a path.

The heading controller is implemented as a simple P-controller.

$$r_d = K_{p,\psi}(\psi_d - \psi), \quad K_{p,\psi} > 0 \tag{4.2}$$

The chosen controller gains are shown in (4.3).

$$\boldsymbol{K}_p = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix}, \quad K_{p,\psi} = 0.08 \tag{4.3}$$

4.3.2 Integral Line-of-Sight guidance

The ILOS module has been implemented as described in Section 2.3. Path-following is not the primary concern of this thesis, therefore all waypoints provided to the ILOS module is on the x-axis of the n-frame to keep the simulations simple. The parameters chosen for the ILOS are given in (4.4).

$$\Delta = 2000m, \quad \sigma = 2m \tag{4.4}$$

Δ is chosen rather large as it is not likely that a very aggressive ILOS controller would be used for a PSV on the open sea.

The implemented CASs also provide information to the ILOS module on whether action is taken to avoid collision or not. If action is taken to avoid collision, the integral action is disabled in the ILOS control law.

4.4 Implementation of the collision avoidance systems

4.4.1 Velocity obstacles

The VO collision avoidance algorithm was developed during the preliminary project autumn 2016. It has been implemented in the PSV in the same manner as described in Section 2.5. The chosen values for the parameters are given in (4.5).

$$r_A = r_B = 500m \tag{4.5a}$$
$$t_{CPA} = 1200s \tag{4.5b}$$
$$d_{CPA} = 2000m \tag{4.5c}$$
$$\alpha_c = 200 \tag{4.5d}$$
$$\beta_c = 100 \tag{4.5e}$$
$$\boldsymbol{Q} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{4.5f}$$
$$\tag{4.5g}$$

The parameters r_A and r_B specify the radius of the own-ship and the obstacles. t_{CPA} and d_{CPA} are the parameters defining when the ASV finds herself in a collision situation. α_c, β_c, and $\boldsymbol{Q}$ is parameters in the cost function used for choosing a safe velocity.

The parameters are set to satisfy the safety constraints defined in Section 3.2. Here the radius of the obstacles and the ASV are set to ensure passings at a distance of 1000 meters. t_{CPA} is chosen to ensure action in ample time, in compliance with Rule 8a. d_{CPA} has to be chosen significantly larger than the radius of the combined obstacle geometries. This is to avoid making the algorithm assume the collision situation is over when it is still taking action to avoid collision.

α_c and β_c, are parameters in the cost function (2.24), chosen to define the priorities of the algorithm. First, collision should be avoided. Second, the solution should comply with the COLREGS. Third, the velocity with the least deviation from the nominal heading and speed should be chosen.

The search grid is chosen with a resolution of 128 possible heading alterations, and 8 possible speed alterations. The possible heading alterations are in the range $[-120°, 120°]$. The possible speed alterations is in the range $[-3\text{m/s}, 5\text{m/s}]$. The candidate velocities are evenly spread on the ranges of speed and heading alterations.

4.4.2 Simulation-based control-behavior selection

The implementation of the SBMPC will be described in this section. It attempts to replicate the system described in Johansen et al. (2016), but some design choices are still required and these are presented here.

Information flow

In Figure 4.5 the ILOS module provides u_d^{ilos} and u_d^{ilos} to the CAS. To simulate the trajectories, the SBMPC requires the list of waypoints $waypoints$ and information about the next waypoint from the ILOS module. This way, the waypoints can be taken into account when simulating trajectories in the SBMPC module.

Update frequency

Johansen et al. (2016) suggested that the SBMPC could run in parallel and provide updated control offset every five seconds. In the implemented algorithm the frequency of updates is reduced to provide updated offsets every 10 seconds. This was done to achieve faster simulations. However, due to the slow dynamics and long distances, this should not have a significant impact of the performance of the algorithm. Although the CAS is not implemented in parallel with the rest of the system, the algorithm is only updating the offsets every ten seconds.

Own-ship trajectory prediction

One of the advantages of the SBMPC approach, is that the method takes the dynamics of the vessel into account by simulating the vessels trajectory. This also allows the designers to take into account environmental disturbances such as wind, waves, and current. In the implemented SBMPC, environmental disturbances have not been included when predicting the own-ships trajectory.

When predicting the trajectory of ASV, the 3DOF model from Section 4.2 and the developed controllers from Section 4.3 are used. A drawback with this method is that the model and controllers does not take into account the thruster saturation. If saturation is not taken into account, the predicted trajectories will deviate a lot from the actual trajectories. This is a problem as the saturation of forces is not easy to find. The saturation limit is a function of the rotations of the azimuth thrusters at any given time, and the rotation of the azimuth thrusters are not known. They can not be calculated either, as the control allocation will have to be included in the prediction model, and this is outside the scope of this thesis.

To get around the problem of unknown saturation limits, approximate values for the saturations were found. This was done by simulating the trajectories of the vessel in CyberSea, and find values for the saturation limits which caused the 3DOF simulated trajectories to get close the CyberSea trajectories. The vessel was accelerated until it reached a steady state at 5 m/s. After 200 seconds, the step in the desired heading was applied, and the trajectory was simulated another 200 seconds, until a new steady state was reached.

The approximate saturation limits that were found with this method are listed in (4.6). The saturation in X (surge), is a function of the absolute surge speed of the vessel. This is because thruster losses are modeled on the vessel. Thurster losses causes the thrusters to saturate at lower levels at higher speeds, because the propellers relative speed to water decreases. This effect is significant and had to be taken into account in order to get better results. The thruster losses are set to reach maximum level at 5 m/s.

$$|X_{max}| = 1665000 - 1300000 \cdot \frac{|u|}{5} \quad [N] \tag{4.6a}$$

$$|Y_{max}| = 1200000 \quad [N] \tag{4.6b}$$

$$|N_{max}| = 35000000 \quad [Nm] \tag{4.6c}$$

A comparison of the resulting trajectories is shown in Figure 4.6. The blue tracks are the simulated trajectories in CyberSea. The red tracks are the 3DOF simulated trajectories. The green tracks are the trajectories for a vessel if the course had changed immediately. These are included to show the trajectory "predicted" by the velocity obstacle algorithm, as it assumes instantaneous course change. The absolute position errors are shown in Figure 4.7. The figures show that the predicted trajectories are quite accurate for small course changes smaller than 50 degrees, (less than 20 meters error, which is less than one ship width) and getting more inaccurate for larger alterations in course. The error in the predicted trajectory might degrade the performance of algorithm. However, the model captures the main characteristics of the vessel dynamics, and the fact that new predictions are made every five seconds should compensate for some of the prediction error. A suggestion for future work is to put more effort into modeling the vessel dynamics to investigate if even better performance can be obtained.

Cost function

A similar cost function to the one presented in Johansen et al. (2016), which is given in (2.34), is used to find the best course and propulsion offset. However, some simplifications have been done. The hazard from grounding is not taken into account, and also the term associated with collision is ignored in the implementation. The cost of collision is assumed to be equal for all obstacles. The resulting cost function is then given in (4.7).

$$\mathcal{H}^j(t_0) = \max_{k \in S^j} \max_i \max_{t \in D(t_0)} \left(\mathcal{R}_i^k(t) + \kappa_i \mu_i^k(t) \right) + f\left(P^k, \chi_{ca}^k\right) \tag{4.7}$$

The size of the set S containing all scenarios, is equal to the amount of different control behaviors tested. This is because environmental disturbances is not taken into account and only one set of obstacle trajectories is considered.

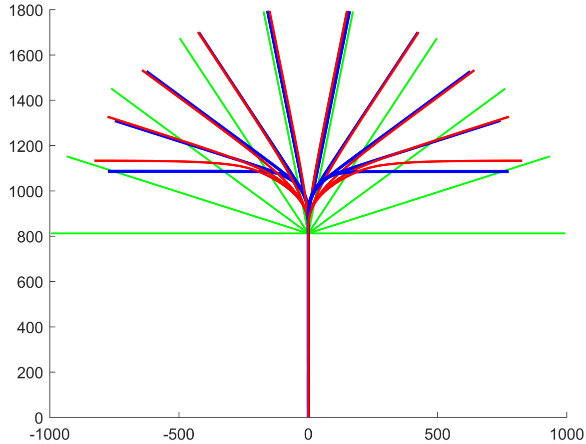

Figure 4.6: Predicted trajectories for the ASV for a case where the ASV is initiated with zero velocity at the point (0,0) and accelerated to a speed of 5 m/s. After 200 seconds, a step in desired heading is applied and maintained for the remaining 200 seconds of the simulated track. The blue track is the simulated trajectory in CyberSea, the red track is the simulated trajectory by the model used to predict future own-ship states in SBMPC, and the green tracks is the "predicted" track if the alteration of course was instantaneous.

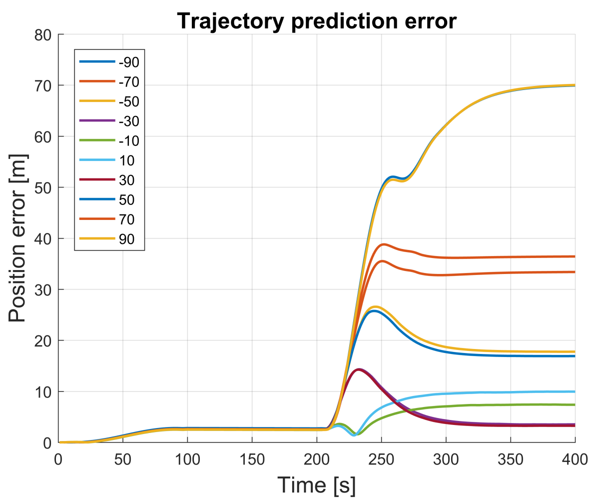

Figure 4.7: The absolute position error of the simulated vessel in 3DOF for different changes in heading. The plot indicates that smaller steps yield smaller errors in the predicted future position, which is used to determine the risk in the SBMPC algorithm.

The risk factor function used is given by

$$\mathcal{R}_i^k(t) = \begin{cases} \dfrac{r}{|t-t_0|^p}\left(\dfrac{d^{safe}}{d_{0,i}^k(t)}\right)^q, & \text{if } d_{0,i}^k(t) < d_i^{safe} \\ 0, & \text{, otherwise.} \end{cases} \tag{4.8}$$

Here an additional parameter r is used compared to the risk factor in Johansen et al. (2016). The risk factor proposed by Johansen et al. (2016) was initially tested. When tuning the SBMPC, the system sometimes provided offsets that resulted in the vessel moving closer to the obstacles than d_i^{safe}. r was added to ease tuning and was set to ensure that choosing a behavior resulting in a trajectory where the ASV got closer to the obstacle than d_i^{safe}, is more expensive than choosing any of the avoidance behaviors. The parameter r ensured that only one parameter had to be changed in order to achieve the desired behavior.

The function $f(P^k, \chi_{ca}^k)$, given in (2.36) is adding an increasing cost as the behaviors deviate from the nominal one. The function is implemented as suggested in Johansen et al. (2016). It includes two asymmetric functions that need to be specified by designer of the CAS. These are k_χ and Δ_χ. Both present to penalize alteration of course to port, more than alteration to starboard. These function are chosen similar to what has been done in Hagen (2017). They are given in (4.9) and (4.10).

$$k_\chi = \begin{cases} K_{\chi,port}, & \text{, if turn to port} \\ K_{\chi,starboard}, & \text{, if turn to starboard} \end{cases} \tag{4.9}$$

$$\Delta_\chi = \begin{cases} K_{\Delta\chi,port}(\chi_{ca} - \chi_{ca,last})^2, & \text{, if turn to port} \\ K_{\Delta\chi,starboard}(\chi_{ca} - \chi_{ca,last})^2, & \text{, if turn to starboard} \end{cases} \tag{4.10}$$

Tuning of algorithm

The tunable parameters in the algorithm are collected in Table 4.2. The d^{safe} parameter is set to satisfy the safety requirements defined by the metrics in Chapter 3. The remaining parameters were identified with tuning in scenarios with one obstacle until satisfactory behavior was obtained.

The prediction horizon T was set to 600 seconds (10 minutes). For the scenarios

4.4.3 COLREGS Agnostic and no collision avoidance

In order to demonstrate that the evaluation library is able to distinguish between vessels that intend to comply with the COLREGS, and vessels that do not intend comply with the rules, a COLREGS agnostic systems have been tested. The tested COLREGS agnostic system is the Velocity obstacle system, but modified to not take COLREGS into account.

Table 4.2: Parameters used to evaluate control behaviors in the SBMPC CAS.

Parameter	Value	Unit
T	600	sec
p	4	
q	0.5	
r	600	
d^{close}	3000	meters
d^{safe}	1000	meters
κ	5	
$K_{\chi,port}$	0.6	
$K_{\chi,starboard}$	2.5	
$K_{\Delta\chi,port}$	1.3	
$K_{\Delta\chi,starboard}$	0.5	
k_p	0.5	
Δ_P	1.3	

This is achieved by changing the cost function to not add cost to COLREGS violating velocities. By setting β_c to zero COLREGS is no longer taken into account. The system is still partly compliant with the metrics from Chapter 3 as it will attempt to pass the obstacles at a safe distance, in compliance with Rule 8. The radius of the obstacles are unchanged and still set to 500 meters.

In addition to the COLREGS Agnostic modifications, a set of tests are also conducted without any collision avoidance. These tests were conducted by removing the CAS block from the control loop.

4.5 Obstacles

Two modules have been developed to model obstacles. This is the obstacle tracker module and the obstacle module. The obstacle tracker is the system in the ASV that is responsible for detecting, tracking, and providing estimated positions of obstacles to the collision avoidance system. In a complete collision avoidance system, this module would contain tracking and sensor fusion algorithms, and be connected to modules containing models of radar measurement, LIDAR measurements, and other sensor data. This is outside the scope of this thesis, and the obstacle tracker have been implemented as tool to handle which obstacles is visible to the ASV. Failure modes, such late detection, and tracks disappearing, can be injected into the collision avoidance system through this module.

The Obstacle module contains models of obstacles. Two types of obstacles are implemented. The first type is moving points, named DotObstacles. These obstacles move in straight line trajectories and does not take any action to avoid collision with either the ASV, or other obstacles. These are described in Section 4.5.1. The second type of obstacles are PSVs that follows a straight line trajectory with a LOS guidance system, and velocity obstacles for collision avoidance. These obstacles are described in Section 4.5.2, and are named PsvObstacles. By implementing this obstacle type, the collision avoidance algorithm can be tested in robot-robot encounters, which is one of the attributes of the road-test described in Woerner et al. (2016). Additionally, it is interesting to investigate how the collision avoidance algorithms behaves in situations where the other vessel intends to comply with the COLREGS.

4.5.1 DotObstacles - Moving points

The DotObstacles have three properties. The speed denoted U_{dot}, the heading denoted ψ_{dot}, and the initial position. The speed and heading is held constant resulting in the constant velocity

$$\boldsymbol{v}_{dot} = \begin{bmatrix} U_{dot}\cos(\psi_{dot}) \\ U_{dot}\sin(\psi_{dot}) \end{bmatrix}. \tag{4.11}$$

The model of the position of the obstacles are given by

$$\boldsymbol{p}_{dot}(k+1) = \boldsymbol{p}_{dot}(k) + t_s\boldsymbol{v}_{dot} \tag{4.12}$$

where $\boldsymbol{p}_{dot}$ is the obstacles position and t_s is the sample time of the model.

4.5.2 PsvObstacles - Obstacles with collision avoidance

The obstacles with Velocity Obstacles as collision avoidance, are implemented to test the algorithms against agents agents complying with the COLREGS. The obstacles that are implemented with dynamics described by the 3DOF model used to simulate the trajectories of the PSV in the SBMPC algorithm.

The vessel is implemented with the controllers and the guidance system presented in Section 4.3. Each obstacle are initiated with the same values as the DotObstacles. This is the initial starting position, the desired speed and the desired heading. The ILOS module is initiated with two waypoints. The first at initial position, and the second, 10 000 meters in the direction of the desired heading, from the initial position.

The VO for the PsvObstacles is implemented with the same parameters as given in Section 4.4.1. To increase the speed of the simulations, a slightly smaller resolution is used in the velocity search grid. Instead of using a search grid of $128 courses \times 8 speeds$, the search grid is reduced to $32 courses \times 5 speeds$.

4.6 Scenario generator

The scheme for generating collision situations used in this thesis is described in section. The scheme resembles the Iterative Geometric Testing presented in Section 2.7.1. However, instead of choosing a base-line geometry and altering the initial position of the ASV, the initial heading, speed, and initial position of the obstacles are altered in each generated scenario. By letting all obstacles meet in a common point, the generation scheme attains many of the attributes of the Iterative Geometric Testing scheme developed by Woerner and Benjamin (2015). These attributes is among those that are suggested in the road-test proposed in Woerner et al. (2016). The procedure used to generate scenarios is described below.

1. Pick the number of obstacles desired in the generated scenarios. The number of obstacles is denoted n_O.
2. The set of possible initial courses is $[-180°, 180°)$. Divide the set of possible initial courses into subsets of equal size. The number of subsets is denoted m_χ.
3. Create m_χ scenarios with one obstacle. Each obstacle is assigned an initial course, χ_{init} randomly from one of the subset of possible initial courses. No obstacles are assigned initial courses from the same subsets. If m_χ was chosen equal to 4, there would now have four scenarios. The first scenario would have one obstacle with an initial course in the set $[-180°, -90°)$, the second an obstacle with initial course $[-90°, 0°)$ etc.
4. Make copies such that there are m_χ instances of each of the generated scenario. Then add new obstacles with initial courses from different subsets of initial courses. Repeat this process until there is n_O obstacles in each scenario. This should generate a total of $m_\chi^{n_O}$ scenarios.
5. For all obstacles in all scenarios, pick a random initial speed, v_{init} from a set of possible obstacle speeds.
$$v_{init} \in [v_{min}, v_{max}]$$
6. For all obstacles, choose an obstacle type. In the current implementation, the following options are available:
   - 1, indicates DotObstacles from Section
   - 2, indicates PSVObstacles with collision avoidance from Section
7. Choose a point, $P_{col} = (x_{col}, y_{col})$, where all obstacles will meet.
8. Choose a time until all obstacles should meet in P_{col}. This time is denoted t_{ttc} (time to collision).
9. Calculate initial starting positions of all obstacles as follows:
$$x_{init}^n = x_{col} - t_{ttc} v_{init} \cos(\chi_{init}) \tag{4.13}$$
$$y_{init}^n = y_{col} - t_{ttc} v_{init} \sin(\chi_{init}) \tag{4.14}$$

In actual collision situations, having several vessels meeting at the exact same location is an improbable scenario. However, by generating scenarios in this manner the ASV will be tested in scenarios with conflicting COLREGS rules. The scheme outlined here can easily be altered to generate encounters occurring after each other. This is done by assigning separate t_{ttc} and P_{col} values to the obstacles generated in the scenario. This type of scenarios is not tested in this thesis.

Figure 4.8 shows an example of nine generated scenarios with the described procedure, with $m_\chi = 3$ and $n_O = 2$. The red circle is the point $P_{col} = (4000, 0)$ where all obstacles will meet. The arrows illustrate the initial velocity of the obstacles as a result of the initial chosen course and speed. The blue vessel in the plots is an example of a possible initial position of an ASV in this scenario.

In the top row, the initial course of the first vessel, painted yellow, is picked randomly from $[-180°, -60°)$, in the second row from $[-60°, 60°)$, and from $[60°, 180°)$ in the last row. In each row, the second vessel, painted green, is initiated once with a heading from each sub set of possible initial courses.

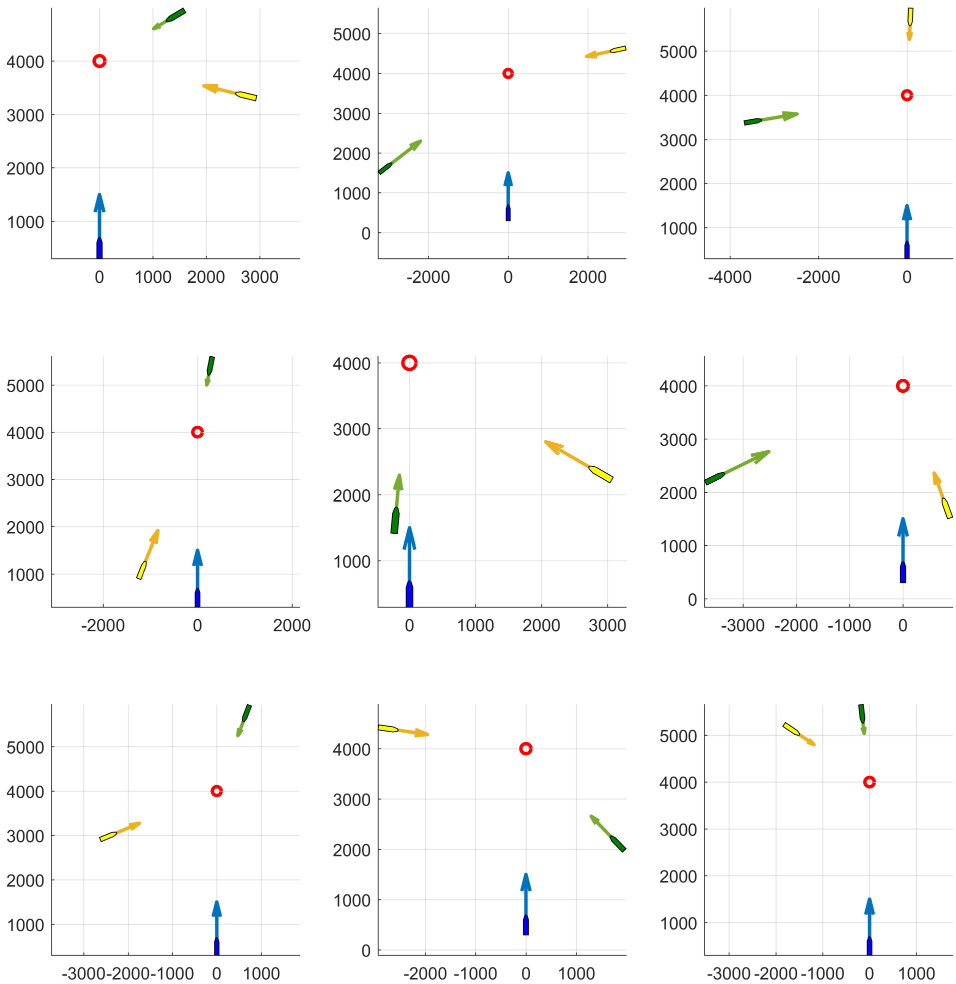

Figure 4.8: Nine scenarios created with the situation generation procedure.

CHAPTER 5

Results and Discussion

The implemented collision avoidance algorithms are tested in scenarios generated by the procedures described in Chapter 4. All scenarios are then evaluated with the metrics described in Chapter 3.

Several aspects of developed system will be inspected.

1. The metrics' ability to detect COLREGS violating maneuvers.
2. Analysis of the SBMPC Algorithm with the metrics.
3. Analysis of the Velocity Obstacles algorithm with the metrics.
4. Comparison of the two algorithms.

This will be done through inspecting results of three simulated test cases. Test Case A demonstrates the metrics' ability to detect behavior violating the COLREGS. The scenarios in this test case is generated with one, two, and three obstacles. Test Case B compares the VO and the SBMPC algorithms in scenarios with one and two obstacles, where the own-ship has relatively good time to take action. Test Case C compares the VO and the SBMPC in set of generated scenarios designed to be tougher than than Test Case B. Here the scenarios are generated with one, two, and three obstacles and the ASV has less time to take action.

Table 5.1: List of CAS abbreviations in figures, in Chapter 5.

CAS	**Label in plots**
SBMPC	Sbmpc
VO	Vo
COLREGS Agnostic VO	AgnVO
No CAS	None

5.1 Description of plots and figures

This chapter includes several figures that show the results of the simulations. To save space, some abbreviations and notation is used.

Several bar-graphs are used to show the scores of metrics associated with set of simulations. The collision avoidance algorithm and the obstacles present in a set of simulations are presented in the following way:

$$C : Algorithm|O : ObstacleType$$

$Algorithm$ is replaced with the abbreviation of the collision avoidance system. The abbreviations are given in Table 5.1. $ObstacleType$ is replaced with the type of obstacles present in the scenarios. This is either DotObstacles, or PsvObstacles and are denoted Dot and VO respectively. Additionally several histograms will be presented to show the mean score of the metrics associated with an encounter type. An example is shown in Figure 5.1. The colors indicates which set of simulations the data is associated with. The labels on the x-axis indicates metrics which are presented. The letter prefixed in the metric name, indicates whether it is a penalty metric or score metric. All metrics are scored in the range 0 to 1. Table 5.2 give an overview of the different metrics and what they are named in the figures in this section.

Figure 5.2 show an example situation. The figure show a snapshot of the situation until the ASV is at its closest range to any obstacle. After this point in the simulation, the range to all obstacles will increase. Each obstacle is labeled with a number at the beginning of their track. The obstacles are initiated when the ASV has reached 500 meters north on the x-axis. The color of the ASV track indicates the speed of the vessel at different points on the track. The color map at the right hand side of the plot, maps the colors to the speed (m/s) of the vessel. Below the plot of the tracks is the encounter type, the score metrics, and penalty metrics listed.

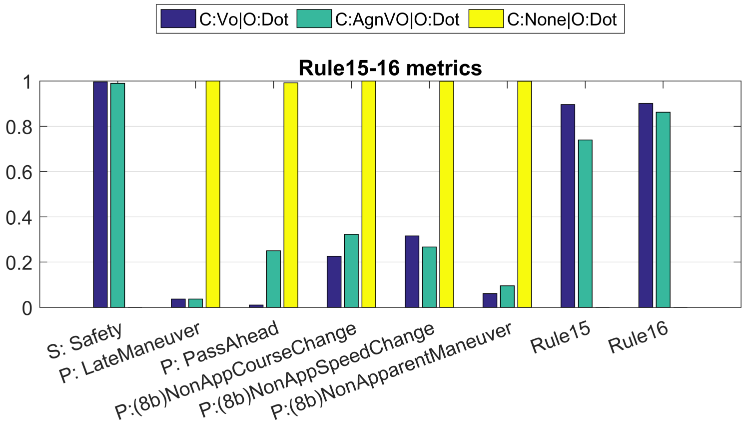

Figure 5.1: Example plot of mean metric scores associated with Rule 15-16.

Table 5.2: Overview of all metrics used to analyze the results.

Label	**Metric**	**Section**	**Equation**
S: Rule 13	$\mathcal{S}^{13}$	3.5	(3.16)
S: Rule 14	$\mathcal{S}^{14}$	3.6	(3.21)
S: Rule 15	$\mathcal{S}^{15}$	3.7	(3.23)
S: Rule 16	$\mathcal{S}^{16}$	3.8	(3.24)
S: Rule 17	$\mathcal{S}^{17}$	3.9	Algorithm 3
S: Safety	$\mathcal{S}_{safety}$	3.2	(3.1)
S: PortToPortPassing	$\mathcal{S}^{14}_{\Theta}$	3.6	(3.17)
P: LateManeuver	$\mathcal{P}_{delay}$	3.3	(3.3)
P: (8b)NonAppCoursChange	$\mathcal{P}_{\Delta\chi_{app}}$	3.3	(3.5)
P: (8b)NonAppSpeedChange	$\mathcal{P}_{\Delta U_{app}}$	3.3	(3.11)
P: (8b)NonApparentManeuver	$\mathcal{P}_{\Delta}$	3.3	(3.12)
P: (13)PassAhead	$\mathcal{P}^{13}_{ahead}$	3.5	(3.15)
P: NonStarboardManeuver	$\mathcal{P}^{14}_{nsb}$	3.6	(3.20)
P: PassAhead	$\mathcal{P}^{15}_{ahead}$	3.7	(3.22)
P: StandOnCourseChange	$\mathcal{P}^{17}_{\Delta\chi}$	3.9	(3.25)
P: StandOnSpeedChange	$\mathcal{P}^{17}_{\Delta U}$	3.9	(3.26)
P: Stand-On Maneuver	$\mathcal{P}^{17}_{\Delta}$	3.9	(3.28)
P: DetectPortTurn	$\mathcal{P}^{17}_{PortTurn}$	3.9	(3.27)

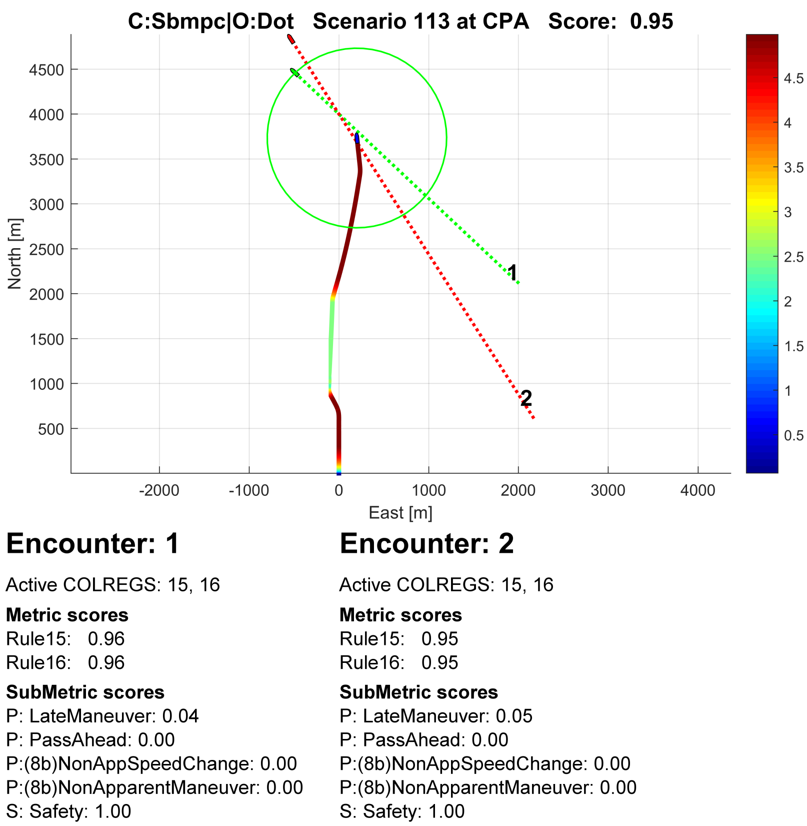

Figure 5.2: Example plot of a simulated scenario.

5.2 Test Case A - Demonstration of metrics

The first Test Case intends to demonstrate that the metrics are able to detect non-compliant behavior. Three different CAS configurations are tested in this test case. The Velocity Obstacles, the Velocity Obstacles not taking COLREGS into account, and a GNC system where the CAS have been removed and does not take action to avoid collision. Similar tests were conducted in Woerner (2016) to show that the metrics were able to detect COLREGS violating maneuvers.

5.2.1 The generated scenarios

The initial position of the ASV is $(500, 0)$ in the NED reference frame, and it is moving in steady state at a speed of 5 m/s. The situation generation scheme presented in Section 4.6 is used to generate a large number of scenarios with one, two, and three obstacles. P_{col} is set to $(4000, 0)$ in $\{n\}$ and t_{col} is set to 700 seconds. From the initial time of detection, the ASV has 700 seconds (almost 12 minutes), and 3.5 kilometers until the point where collision will occur if no action is taken. These numbers, and the time until collision is larger than what is seen in most literature on COLREGS. However, these number are reasonable when testing the collision avoidance systems for a large vessel such as a PSV.

Table 5.3 shows the parameters used to generate the scenarios. A total of 60 scenarios with one obstacle are generated ($m_\chi = 60, n_O = 1$), 144 with two obstacles ($m_\chi = 12, n_O = 2$), and 216 with three obstacles ($m_\chi = 6, n_O = 3$). This gives a total of 420 scenarios.

Only situations with up to three vessels are included. Cockcroft and Lameijer (2004) referred to situations where a vessel finds herself on a collision course with two other vessels as an unlikely event. Three vessels can therefore be considered as even more unlikely. That is why scenarios have been generated with three or fewer obstacles.

The scenarios are defined to last 1800 seconds before the next is initiated. This leaves enough time for the ASV to pass well clear of the obstacles in most of the encounters.

After the scenarios in test case A were generated, those with an initial range between the ASV and the obstacles, smaller than 1000 meters were removed. The final number of scenarios in Test Case A was then 407. The number of encounters with different rules are given in Table 5.4.

This illustrates a weakness of the scenario generation scheme. The scheme generates obstacles approaching the point with courses uniformly distributed from $0°$ to $360°$. As the sectors where obstacles are defined as a crossing obstacle, is larger than the sectors where the vessels are head-on or overtaking, the current scheme generates crossing encounters more frequently than head-on and overtaking encounters. Additionally, the encounters generated in Test Case A have an initial speed distributed uniformly between 2 m/s and 7 m/s. The initial speed of the own-ship is 5 m/s. For the vessel to be overtaken by the

Table 5.3: Parameters for generating encounters in test case A

Parameter	Value	Unit
P_{col}	$(4000, 0)$	
t_{ttc}	700	s
v_{min}	2	m/s
v_{max}	7	m/s
Obstacle types	DotObstacle	
Scenarios with one encounter	60	
Scenarios with two encounters	144	
Scenarios with three encounters	216	

Table 5.4: The number of encounter types generated in Test Case A.

Encounter type	Number of scenarios	Comment
Rule 13 - 16	83	Overtaking, with ASV as give-way
Rule 13 - 17	16	Overtaking, with ASV as stand-on
Rule 14	121	Head-on
Rule 15 - 16	380	Crossing with ASV as give-way
Rule 15 - 17	377	Crossing with ASV as stand-on

own-ship, the obstacle will have to be generated with a higher speed than the ASV. As the obstacles speeds are likely to be slower than the ASV speed, the sample size of encounters with overtaking is small.

5.2.2 Aggregated results for Test Case A

As reminder from Chapter 3, the scenario score is equal to the lowest encounter score in a scenario. Figure 5.3 indicates that the metrics are able to distinguish between systems that intend to comply with the COLREGS and the systems which do not. It is also clear that a system not taking any action to avoid collision is distinguishable from systems that does.

Figure 5.4 shows the spread in scenario scores for the different systems. The COLREGS agnostic CAS is able to get a score larger than 0.75 in almost 20 percent of the scenarios. By intending to avoid collision the algorithm is inherently complying with the COREGS to some degree. If it gets lucky and decides to pass the obstacle on the COLREGS compliant side, this could possibly result in a good compliance score.

Figure 5.5 show the mean rule score of all encounters. The metrics for Rule 14 and Rule 15+17 results in the greatest reduction in score for the COLREGS agnostic vessels. These results are similar to what is seen in Figure 4-17 and 4-19 in Woerner (2016). This is as expected, as the metrics to a large extent are based on his work.

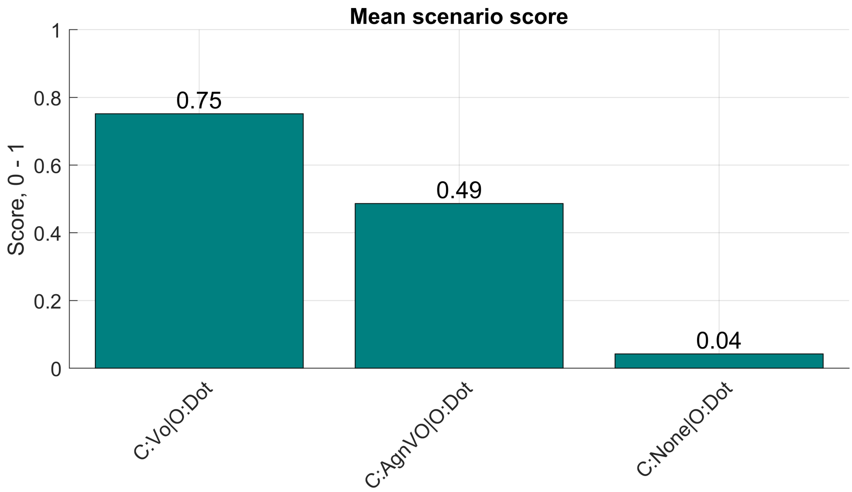

Figure 5.3: Test Case A: The mean scenario scores for the systems tested. The scores indicates that the metrics are able to distinguish between systems intending to take COLREGS into account, systems which do not, and systems not attempting avoid collision at all.

As discussed previously, the sample size for Rule 13 + 17 is small. Additionally, all scenarios that included an encounter of type Rule 13 + 17 also included another encounter that ASV had to give way for. As a result, only the safety score determined the total rule score in these scenarios, as no penalty for maneuvers is given when the ASV is in stand-on with other navigational requirements. Not much can therefore be concluded about the algorithms performance or the metrics ability to detect violating maneuvers in these scenarios.

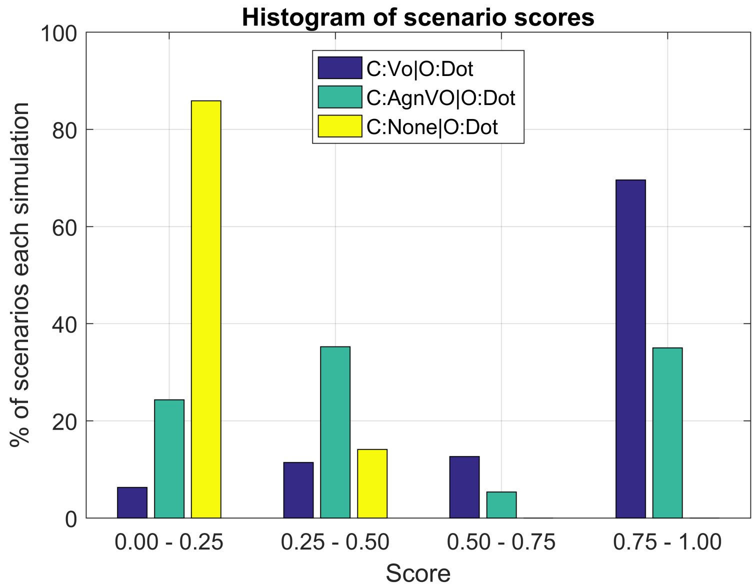

Figure 5.4: Test Case A. Histogram to visualize the spread of the scenario scores.

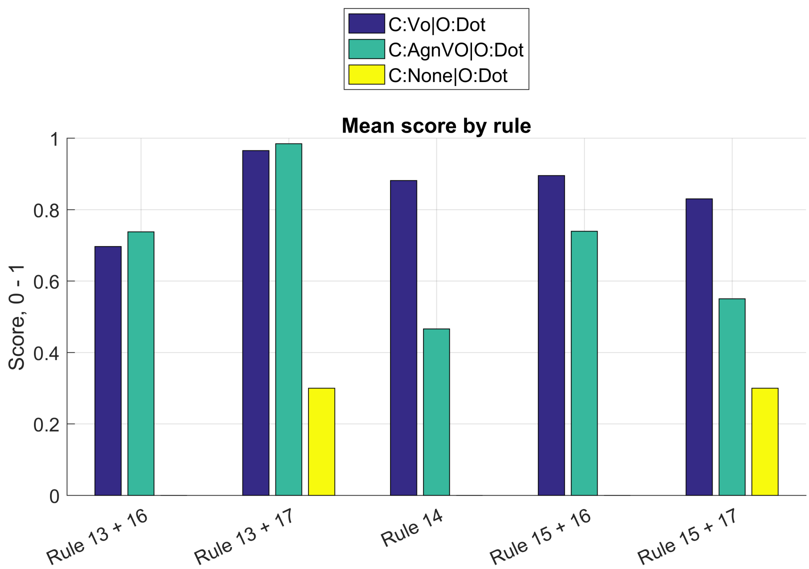

Figure 5.5: Mean encounter score grouped by the applicable COLREGS rule, in Test Case A.

5.3 Test Case B - VO compared with SBMPC

The aim of Test Case B is to investigate the SBMPC and the VO algorithm and compare them. The scenarios in Test Case B are generated with the same parameters as Test Case A, except that scenarios are generated with only one and two obstacles. Additionally, a set of scenarios was generated with PsvObstacles. Again the scenarios with initial ranges less than 1000 meters were removed. The number of scenarios and encounter types in Test Case B are shown in Table 5.5.

Table 5.5: Scenarios and encounter types in Test Case B

	DotObstacles	*PsvObstacles*
Scenarios	198	198
Rule 13 + 16	32	39
Rule 13 + 17	6	0
Rule 14	42	47
Rule 15 + 16	126	120
Rule 15 + 17	131	131

5.3.1 Aggregated results for Test Case B

The mean scenario score for each set of tests are shown in Figure 5.6. The SBMPC algorithm achieve a slightly higher score than the VO algorithm in the simulations with DotObstacles. In the simulations with PsvObstacles, the VO algorithm obtained a 0.14 lower score than th SBMPC algorithm. Figure 5.7 show a histogram of the spread of scenario score. It indicates that most of the scenarios are handled well by both algorithms in all scenarios. However, the histogram also indicates that there are scenarios in the tests that are not handled in accordance with the defined metrics. In Test Case B, most of these are related to scenarios where ASV has a stand-on responsibility. These scenarios are discussed in Section 5.3.5.

Figure 5.8 show the mean scores for each encounter type. The ASV equipped with the SBMPC algorithm generally score slightly higher than the ASV equipped with Velocity Obstacle algorithm. Figure 5.9 to 5.17 show the metrics associated with each encounter. Its important to notice, that the reason Rule 13 + 17 have zero score in the scenarios with PsvObstacles, is that this set of simulations, does not contain any such scenarios.

By inspecting the metrics resulting in the encounter scores, trends in behavior violating COLREGS can be identified. In the following subsection, interesting observations regarding the scores and penalties for each encounter type will be presented and discussed.

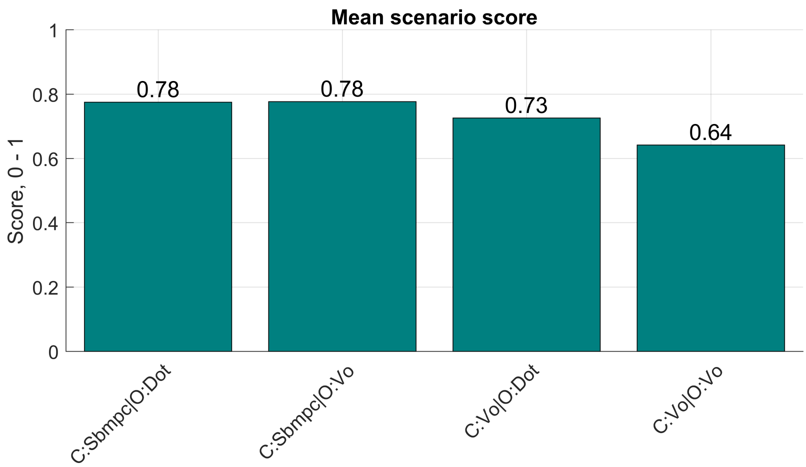

Figure 5.6: The mean scenario scores for CAS tested in Test Case B.

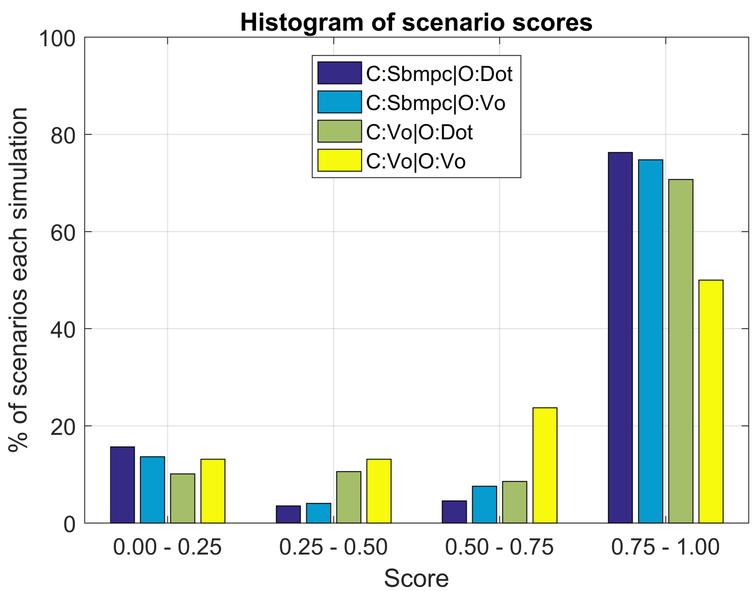

Figure 5.7: Histogram of scenario scores to the CAS in Test Case B.

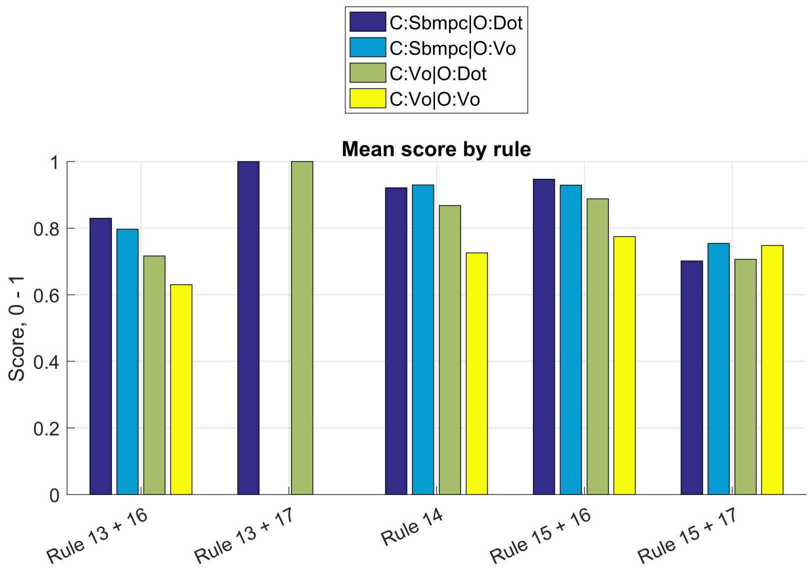

Figure 5.8: Mean encounter score grouped by the applicable COLREGS rules, in Test Case B.

5.3.2 Test Case B: Rule 13 + 16, overtaking

Figure 5.9 show that the largest penalties in the score of the SBMPC are penalties for late maneuvers and deduction from passing ahead of the stand-on vessel. Similar penalties are also seen in the set of tests with the Velocity Obstacles algorithm.

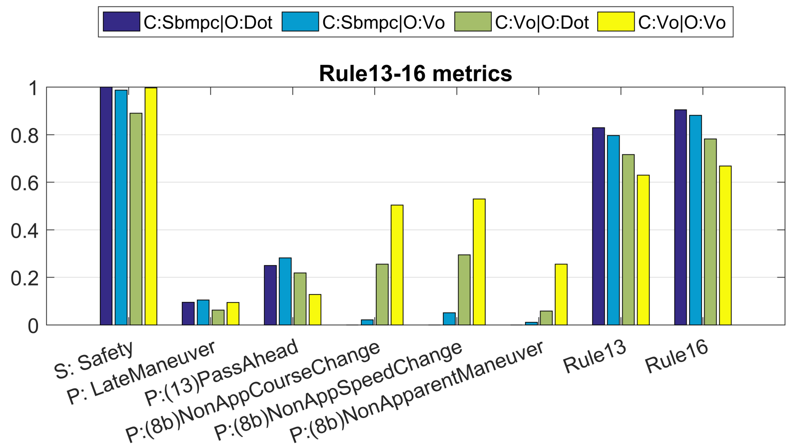

Figure 5.9: Score and penalties for Rule 13 where the ASV is the give-way vessel, in Test Case B

Late-maneuver penalty

The deductions from late-maneuvers are likely due to how $\mathcal{P}_{delay}$, the metric quantifying Rule 8a, is implemented. A maneuver is not considered detected until a change in course of four degrees is seen, or a change of speed of 0.5 m/s is detected. This contributes to a delay from when a maneuver is initiated to when the maneuver is detected, resulting in some late maneuver score. Additionally, The PSV is a large vessel and initiating a maneuver is not done in an instant. Although the decision to alter course or speed is taken instantly, it will take some time before this is seen on tracks. This too contributes to the late maneuver penalty seen in Rule 13 + 16. Both algorithms are implemented in a way such that action should be taken once a collision situation is detected and developing. The two problems considered here are likely the root cause of the late maneuver penalties. This is probably also true for the late maneuver penalties seen in Test Case A and C.

The SBMPC algorithm receives a slightly higher late-maneuver penalty than the velocity obstacles algorithm. This could be caused by the slower update frequency of the SBMPC algorithm. The velocity obstacle algorithm does not require much computation, and can therefore provide updated velocities at each time step in the simulations. As presented in Section 4.4.2, the SBMPC provides new updates every ten seconds. A worst case scenario for an ASV moving at a speed of 5 m/s, the ASV will travel 50 meters before new safe offsets are provided from the CAS. This delay causes higher penalties the closer the obstacle is when it appears.

To illustrate, consider the following two examples. The own-ship is traveling north at a speed of 5 m/s. An obstacle is traveling on a reciprocal course towards south with with a speed of 5 m/s. If the worst case scenario occurs, the distance between the obstacle and the own-ship will have been reduced with 100 meters in the 10 seconds before the SBMPC provides new offsets. If the obstacles appears when the distance between the two vessels are 5000 meters, this results in an additional 0.02 late maneuver penalty ($\mathcal{P}_{delay}$). If the distance is 1000 meters, this results in an additional 0.1 penalty.

Pass ahead penalty

The pass ahead penalty $\mathcal{P}^{13}_{ahead}$ is binary. The penalty seen in Figure 5.9 therefore indicates the fraction of the encounters where an ahead passing was considered present. Although the algorithms guide the ASV to non-ahead passings, most of the time, the scenarios where it did take place should be inspected as these are associated with a high risk.

Figure 5.10 is provided below to illustrate an overtaking situation considered successful and in compliance with the COLREGS by the metrics. This is a scenario from Test Case B where the ASV is equipped with a SBMPC CAS and one obstacle. The ASV overtakes the obstacle in a way that is not considered to pass ahead, resulting in an an almost perfect score. Figure 5.11 and 5.12 illustrates situations where the SBMPC and the VO received penalties for passing ahead. From the discussions in Chapter 3, these scenarios should probably be inspected manually. In Figure 5.11 where the ASV is using SBMPC, the overtaking maneuver seems predictable and clear to the vessel being overtaken. In Figure 5.12, where the ASV is using the Velocity Obstacle algorithm, a sudden turn is initiated by the ASV to cross ahead of the obstacle. Both encounters receive some deduction in the safety score as obstacle get closer than 1000 meters. However, neither of the encounters resulted in a near-miss scenario, defined to take place when a safety score of 0.60 is received. Allen (2005, p.415) discussed this type of scenarios, and the following advice were given:

> "Perhaps the best solution for the vessel to starboard, if she is relatively close to the other, to turn to a parallel course and pass ahead or slow and wait for enough room to pass safely under the other vessel's stern, keeping a sharp lookout for any maneuver by the other."

Based on this advice, the encounters could be determined as safe. But the alternative solution, slowing to pass astern, proposed by Allen (2005) could be considered by the designers of the systems.

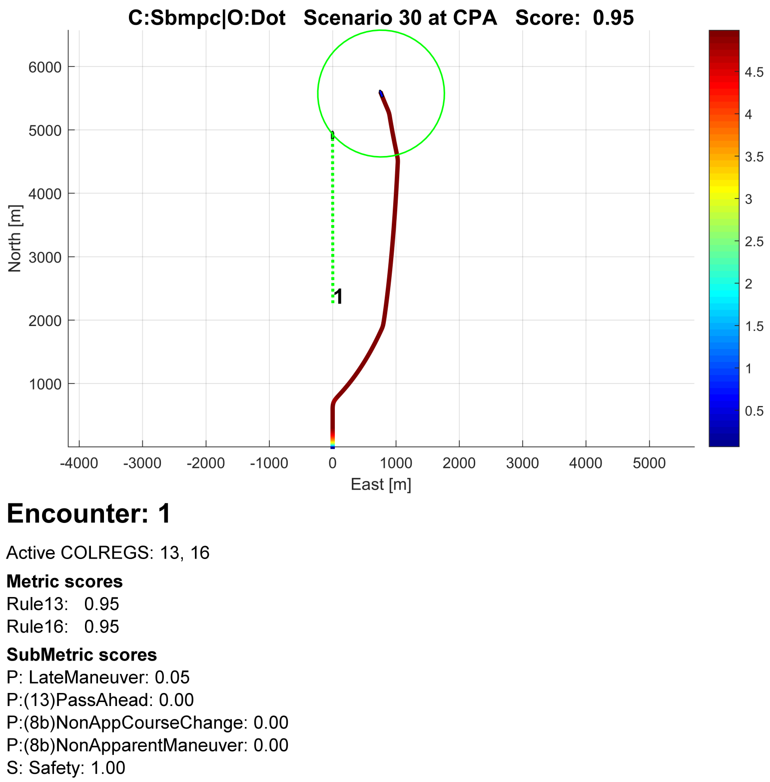

Figure 5.10: Test Case B. The SBMPC algorithm in overtaking an obstacles in compliance with the defined metrics.

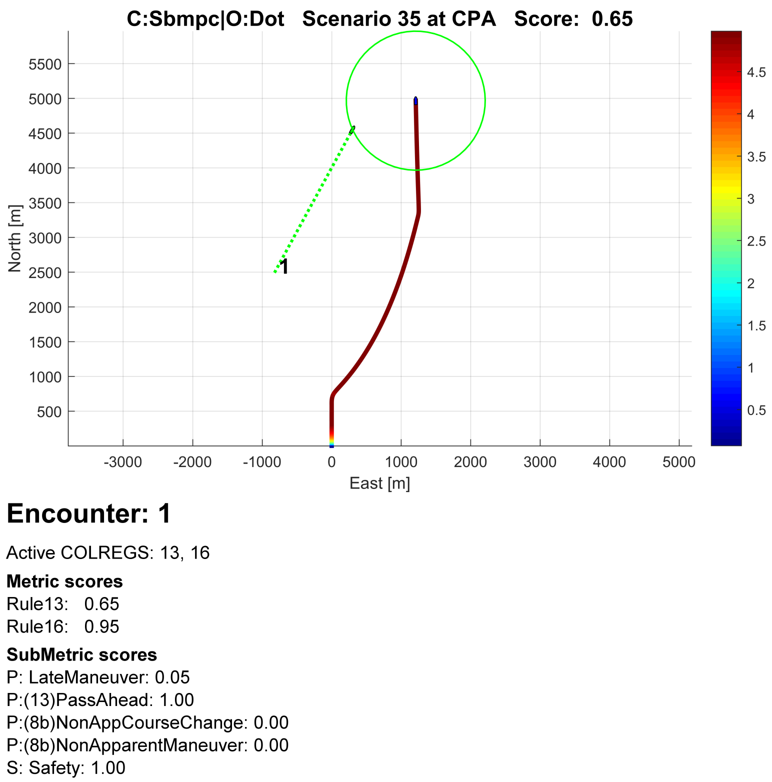

Figure 5.11: Test Case B. The SBMPC algorithm overtaking an obstacle causing a penalty for passing ahead.

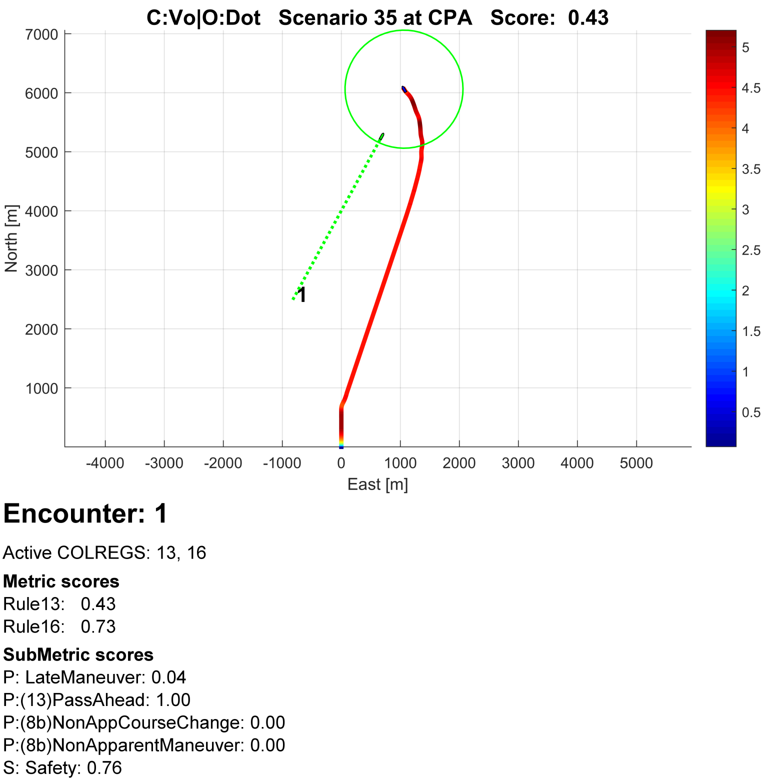

Figure 5.12: Test Case B. The VO algorithm overtaking an obstacle resulting in a penalty for passing ahead.

Non-apparent maneuvers

Figure 5.9 show that the ASV with velocity obstacles receive more penalty from non-apparent maneuvers than the ASV with SBMPC. This can also be seen in head-on and crossing encounters where the ASV is the give-way vessel. A possible reason for this penalty, is likely rooted in the way the VO-algorithm choose its desired velocity. The algorithm choose a velocity which is not in the velocity obstacle, not violating COLREGS, and deviates the *least* amount from the nominal velocity. This means that the algorithm will choose a velocity which makes it pass the obstacles at a range of no more than 1000 meters if possible. If the range to the obstacle is significant when it is detected, the course alteration does not have to be large, to pass the obstacle with a desired range between them. Figure 5.13 illustrate one such scenario where the ASV alter course only as much as necessary to pass at the desire range. This causes a penalty for a non-apparent course change.

An interesting observation with the ASV in equipped with VO, is that the non-apparent course change penalty is larger in situations with PsvObstacles than in situations with DotObstacles. Figure 5.14 illustrate one example of this. It looks like the PsvObstacles take avoiding maneuvers once they are initiated. These avoiding maneuvers “aids” the situation, such that the ASV does not have to alter the course as much as what would have been necessary if no action were taken by the PsvObstacles. This might be an undesired behavior of a maritime collision avoidance system, as it most likely is desirable to make the intentions of the ASV crystal clear to other vessels.

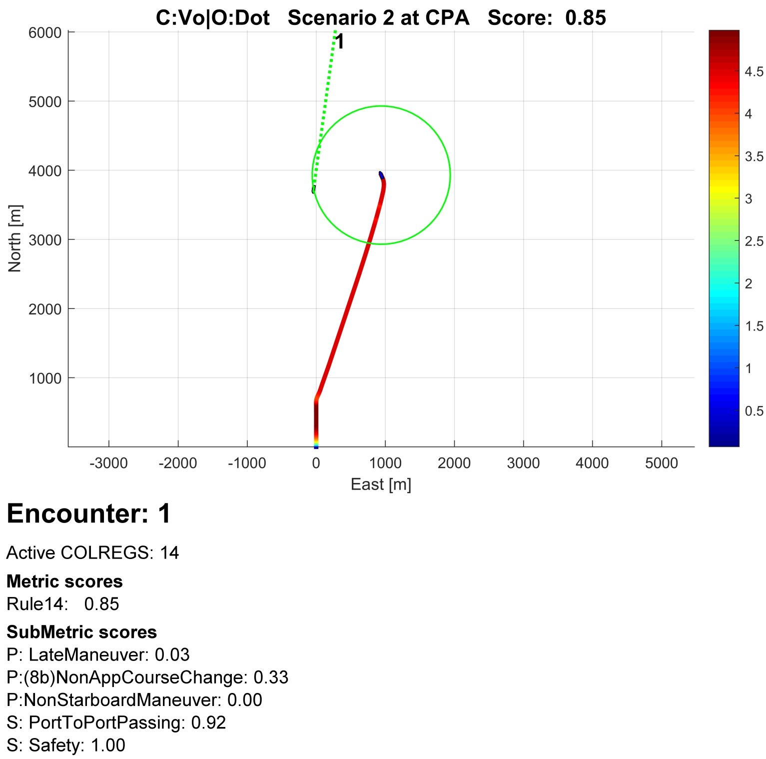

Figure 5.13: Test Case B. Scenario where the ASV is using Velocity Obstacle and receive penalty for a non-apparent course change.

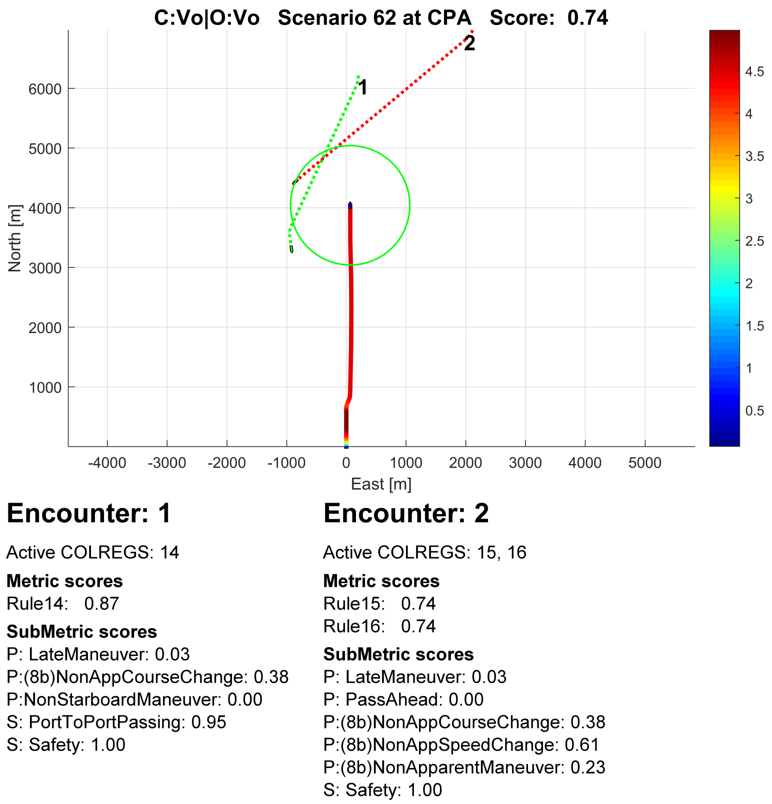

Figure 5.14: Test Case B. Non-apparent course change in situation where the ASV is equipped with the Velocity obstacle, in a scenario with two PsvObstacles.

5.3.3 Test Case B: Rule 14, head-on

Figure 5.15 show the mean score and penalties received by the algorithms in head-on encounters. The algorithms seem to handle this scenario well. The only detectable problem in Rule 14 encounters, is as discussed in the previous section, related to the ASV equipped with the Velocity Obstacle. This algorithm receive some penalty due to non-apparent course changes.

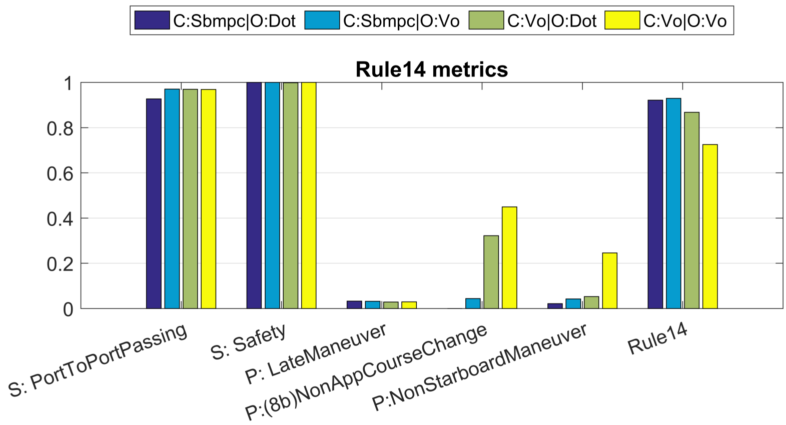

Figure 5.15: Score and penalties for Rule 14 in Test Case B.

5.3.4 Test Case B: Rule 15 + 16. Give-way crossings

Figure 5.16 show the scores in encounters where the ASV is the give-way vessel. Both of the tested performs well according to the metrics. However, again can the problem with non-apparent maneuvers of the Velocity Obstacle algorithm be seen.

5.3.5 Test Case B: Rule 15 + 17. Stand-on crossings

Figure 5.17 show the scores in encounters where the ASV is the stand-on vessel. Here the penalty related to stand-on maneuvers is quite large. One could say that this is as expected, as the stand-on responsibility is not considered in the design of neither the SBMPC or the velocity obstacle. This is an aspect that is probably more important for larger vessels, such as the PSV considered in this thesis. In Kuwata et al. (2014) and Hagen (2017), where the Velocity Obstacle and the SBMPC algorithms have been tested on sea, significantly smaller and more maneuverable vessels are considered. Here a risk of collision might not

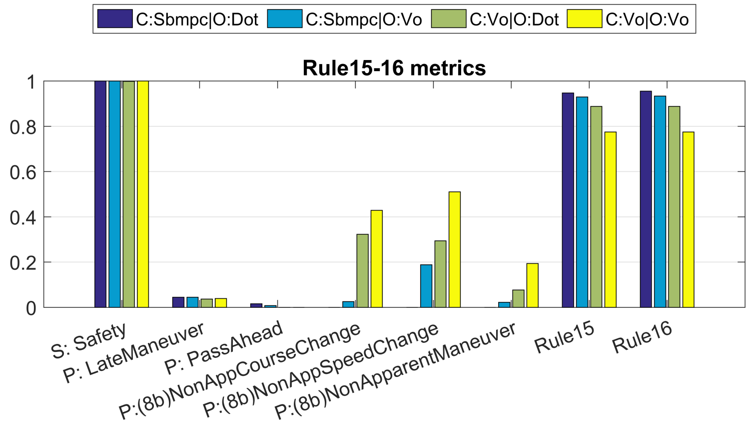

Figure 5.16: Score and penalties for Rule 15 + 16. Crossing with the ASV as give-way vessel in Test Case B.

be considered to exist, before the vessel are so close that the operators can claim to take action as permitted in stage 3 (as discussed in Section 3.9.

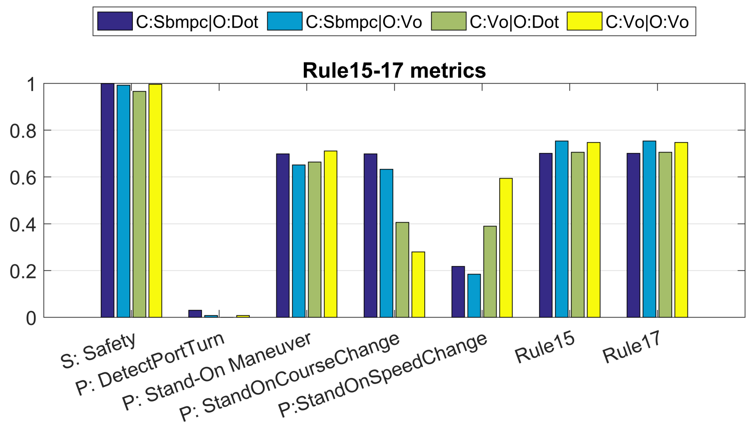

Figure 5.17: Score and penalties for Rule 15 + 17. Crossing with the ASV as stand-on vessel in Test Case B.

5.3.6 Test Case B: Difficult scenarios

After all scenarios have been analyzed with the aggregated metrics, the scenarios with the lowest scores can be identified and inspected manually. The aggregated results are useful for detecting trends and identify characteristics of the collision avoidance algorithms. However, difficult scenarios that the ASV handles particularly bad can be identified by manually inspecting scenarios that have received particularly low score.

One interesting scenario identified in this way is shown in Figure 5.18. Here the ASV has give-way responsibility for a crossing vessel which almost resembles an overtaking encounter. At the same time the ASV is approaching a second vessel on nearly reciprocal courses, causing Rule 14 to apply. The contact geometry force the SBMPC to violate Rule 14 of the COLREGS, causing a starboard-starboard passing. Although this is a rather unrealistic scenario, it does highlight that there is room for improvement. If the ASV had put its engines on full speed in reverse, for then to alter course to starboard, this scenario would have been handled in a way that does not violate the COLRES. This could be achieved with a different tuning of the SBMPC algorithm. For example by reducing the cost of altering speed.

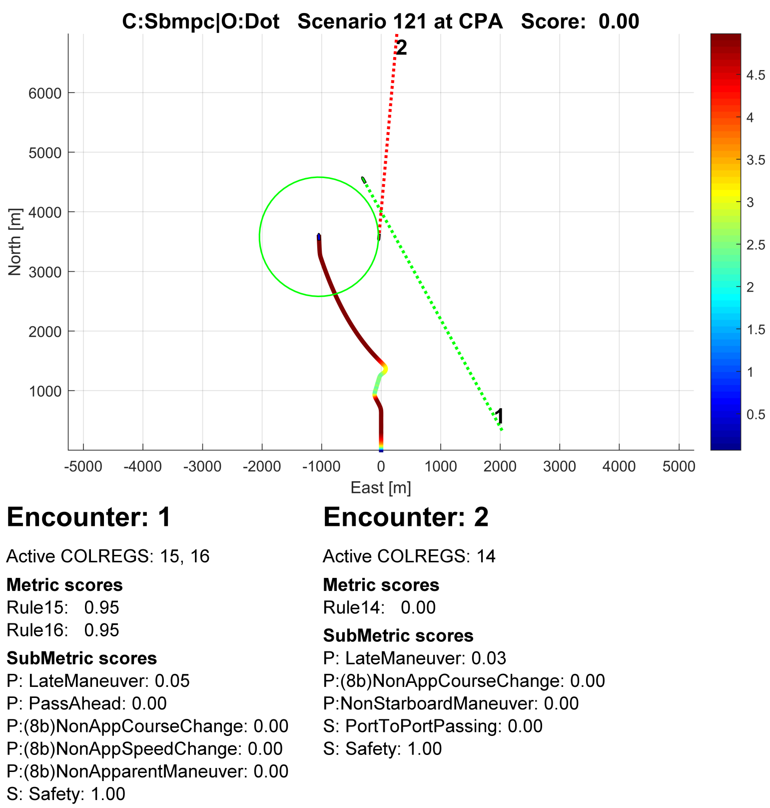

Figure 5.18: Test Case B. A problematic scenario for the SBMPC algorithm.

5.4 Test Case C - Less time to maneuver

Test Case C is similar to Test Case B, but it has been generated aiming to be tougher. This is done by generating scenarios where the ASV has less time to maneuver. Additionally, Test Case C has been generated with up to three simultaneous encounters. The parameters used to generate the scenarios in Test Case C are similar to those used to generate Test Case A, given in Table 5.3. The parameters that are altered and the values used are listed below.

- $t_{ttc} = 400s$
- $P_{col} = (2500, 0)$
- $v_{min} = 3m/s$

Scenarios are generated with both DotObstcles and PsvObstacles The SBMPC algorithm and the VO algorithm are tested in 396 scenarios with DotObstacles, and 401 scenarios with PsvObstacle. The number of different encounter types are listen in Table 5.6

Table 5.6: Encounter types in Test Case C

	DotObstacles	*PsvObstacles*
Scenarios	396	401
Rule 13 + 16	32	39
Rule 13 + 17	6	0
Rule 14	42	47
Rule 15 + 16	126	120
Rule 15 + 17	131	131

5.5 Aggregated results for Test Case C

Figure 5.19 show the mean scenario score of different sets of simulations. It shows that the performance of the SBMPC is degraded in Test Case C, compared to Test Case B. The velocity obstacle can be seen to achieve a better performance in this Test Case compared to Test Case B. To determine whether it is the reduced time to collision, or the third

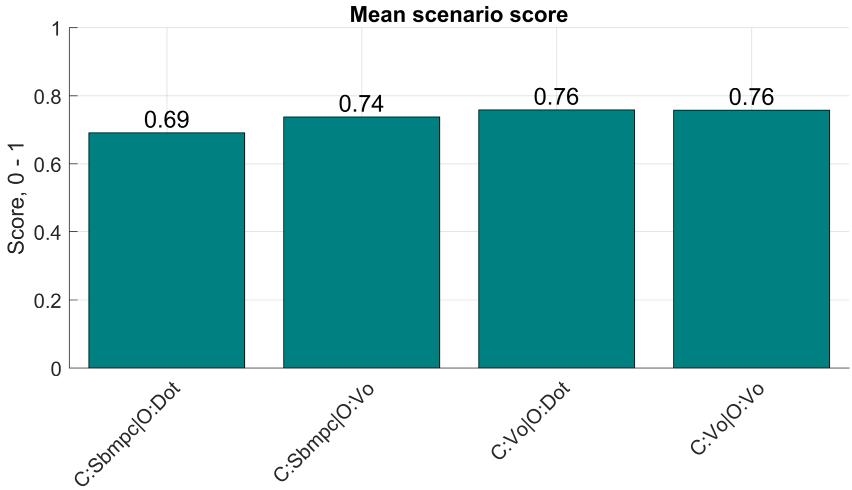

Figure 5.19: The mean scenario scores for the CAS tested in Test Case C.

obstacle which is the root cause of the reduction in score; the mean score for Test Case C where all scenarios with three obstacles are filtered away, are shown in Figure 5.20. Little difference can be seen in the mean score, which could indicate that it is the reduced time to collision which is the greatest contributing factor for the reduction in score of the SBMPC algorithm.

Figure 5.19 show the mean encounter type score in the different sets of simulations. Figure 5.22 to Figure 5.25 show the penalties and scores in the different encounter types. In this Test Case, the late maneuver penalty gets larger than in Test Case B. This is because the range to the obstacles at t_{detect} is shorter than in Test Case B. It is also interesting to notice that the algorithms receive less penalty from maneuvers when the ASV have stand-on responsibility in crossing situations. This is probably because action is taken when vessel is closer to the obstacles.

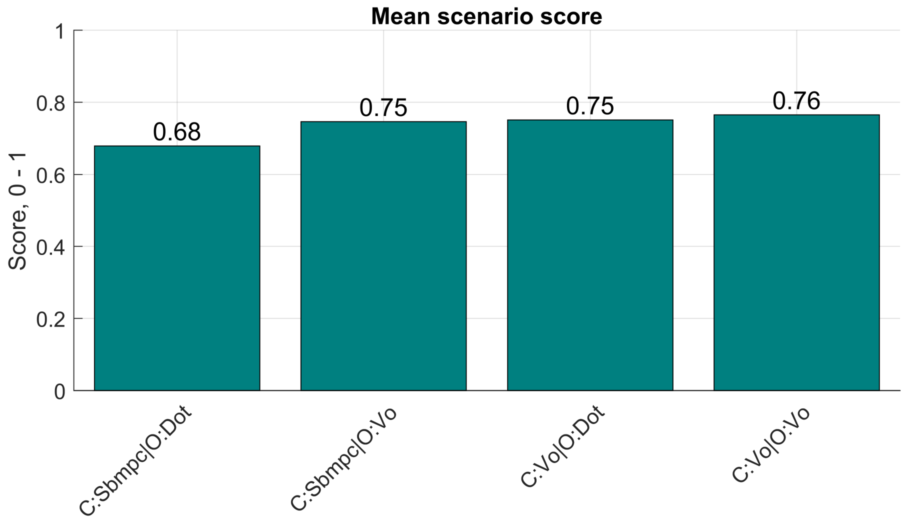

Figure 5.20: The mean scenario scores in Test Case C, with one and two obstacles.

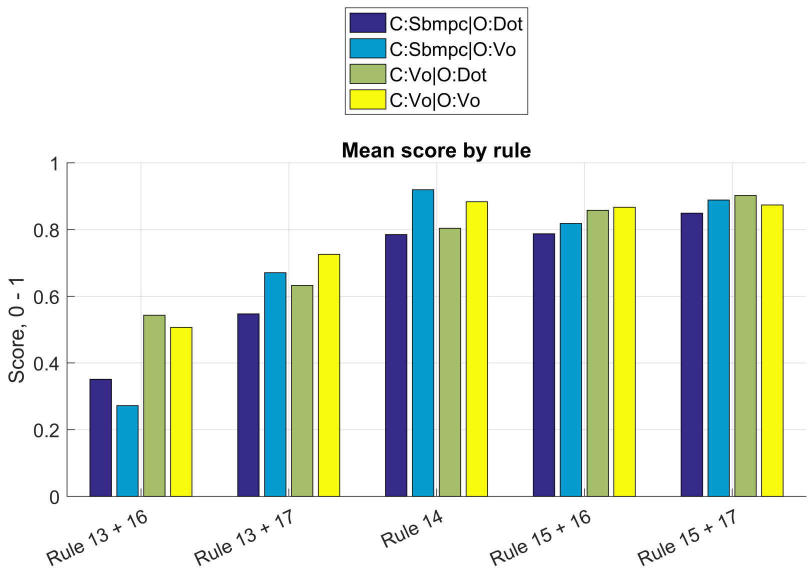

Figure 5.21: Mean encounter score grouped by the applicable COLREGS rule, in Test Case C.

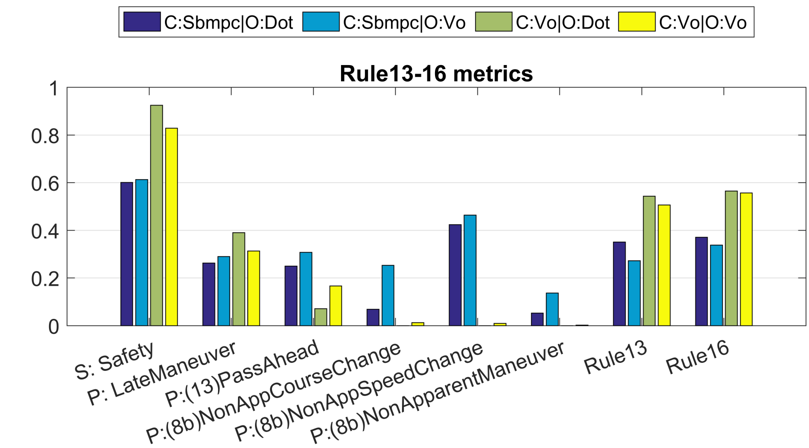

Figure 5.22: Score and penalties for Rule 13 where the ASV is the give-way vessel, in Test Case C

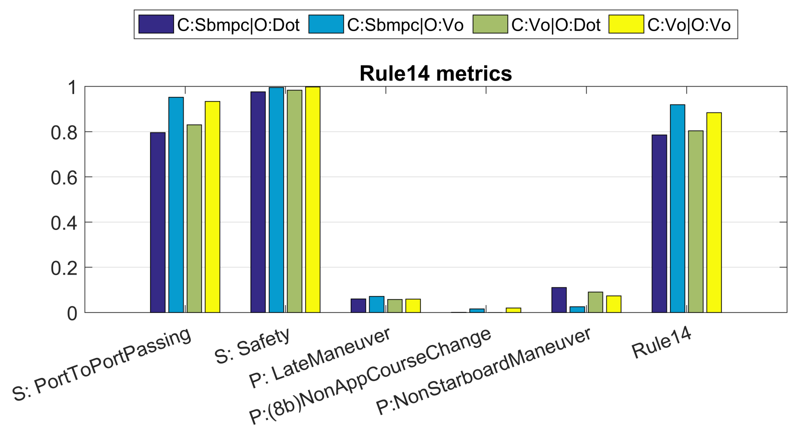

Figure 5.23: Score and penalties for Rule 14 in Test Case C.

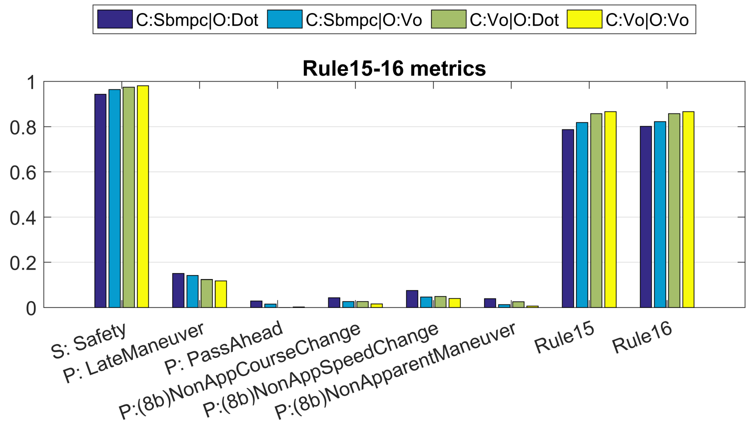

Figure 5.24: Score and penalties for Rule 15 + 16. Crossing with the ASV as give-way vessel in Test Case C.

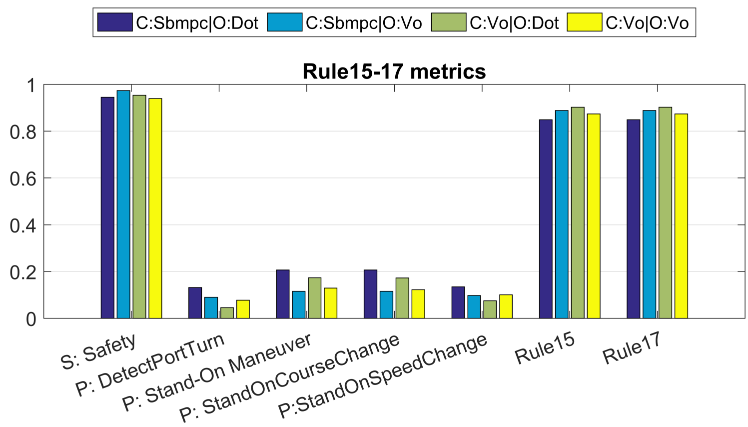

Figure 5.25: Score and penalties for Rule 15 + 17. Crossing with the ASV as stand-on vessel in Test Case C.

CHAPTER 6

Conclusion and future work

6.1 Conclusion

In this thesis, a framework for automatic testing of collision avoidance algorithms has been implemented. The framework consist of a simulated environment, with two types of obstacles to be avoided by the ASV and the algorithms subject to testing. The framework allows a large set of scenarios to be generated and simulations are conducted automatically with the system being tested. When all scenarios have been simulated, the logs can automatically be evaluated with the metrics developed by Woerner (2016), to quantify safety and compliance with the COLREGS. In this thesis two implemented collision avoidance algorithms have been tested and analyzed.

6.2 Future work

Restricted waters

The current implementation of the metrics and the developed simulator environment does not include testing in restricted waters. Extending the metrics and the simulated environment to include situations close to shore, and in shallow waters, is crucial to enable evaluation of an in important type of possible collision situations.

Generate scenarios based on rules

In Section 5.2, it was shown that the scheme used for generating scenarios was successful in generating a wide range of encounter geometries. However, this resulted in small sample sizes for some encounter types. It is of interest to inspect how a collision avoidance algorithms solves different encounter types. The author does not know of procedures solving this problem automatically.

Environmental disturbances

The collision avoidance systems developed in this thesis, and the metrics are not tested in situations with environmental disturbances. This might play an important role on the performance of the collision avoidance algorithms. The ASV hull model provided by DNV GL is already modeled with environmental disturbances, this could be included in the obstacle models.

Obstacle detection and a testing of a full collision avoidance system

As mentioned in the introduction, obstacle detection is essential for the collision avoidance algorithms. In future work, the obstacle tracking module presented in Section 4, could be redesigned to include a full sensor fusion and tracking system. This module could then be connected to other modules in CyberSea, modeling the sensors on the vessel. Models which provides realistic measurements from radar and AIS can be implemented in CyberSea as modules, and be connected to the Obstacle Tracking module. This way realistic uncertainty could be added to the state of the obstacles provided to the collision avoidance algorithm.

COLAV while following a path

The system implemented in this thesis follows a path along the north axis. Investigating how a collision avoidance system handles conflicting priorities, regarding the goal of the mission while avoiding collisions in a COLREGS compliant manner could be important for detecting dangerous behavior. For this to be enabled in the implemented framework for automatic testing, additional functionality needs to be implemented before this type of situations can be inspected.

Simulation Based Collision avoidance system

The tested SBMPC implementation is somewhat limited compared to what is possible with the algorithm. Inspecting more control-behaviors and different predicted obstacle paths might improve its performance. Additionally, the method allows for seamless integration of environmental disturbances. This is also a topic that should be investigated.

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