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Online Consequence Analysis of Situational Awareness for Autonomous Vehicles

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Marine Technology
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MASTER THESIS IN MARINE CYBERNETICS

2018

FOR

Markus Fossdal

Title: Online Consequence Analysis of Situational Awareness for Autonomous Vehicles.

Work Description

The maritime industry is subject to a technology and business transition towards increased level of autonomy enabling lower manning or unmanned ships. The main drivers for such development can be associated with reducing construction and operational costs, as well as improved safety during operation, and reduced risk of hazardous situations potentially leading to environmental impact.

The thesis will investigate how different industries defines level of autonomy taxonomies. Furthermore, a study on which sensors that are used to perceive information about a vessel's surroundings will be conducted. A method for performing online consequence analysis (OCA) is to be developed and validated through simulation with the help of suitable computer software.

Scope of work

1. Investigate how different taxonomies for autonomy are defined, which industries they are based on, and lastly compare the different definitions.
2. Gain an overview based on literature of the main sensor platforms used in order to gain situation awareness on autonomous and non-autonomous surface vessels today.
3. Present former work on online consequence analyses for use in autonomous or higher-level control systems.
4. Propose a method for online consequence analysis.
5. Build a simulation model based on mathematical models in order to validate the proposed online consequence analysis.

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6. Validate the proposed method through a simulation study.
7. Propose a method for evaluation of risk based on the online consequence analysis.

The report shall be written in English and edited as a research report including literature review, relevant theory, description of developed methods, mathematical deductions, validation results, discussion and concluding words that include proposals for further work. Source code should be provided on a memory stick or similar. It is supposed that the Department of Marine Technology, NTNU, can use the results freely in its research work, unless otherwise agreed upon, by referring to the student's work. The thesis should be submitted within July 1, 2018.

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Project plan

Task/Time	Feb. W 6,7,8	Mar. W 9	Mar. W 10	Mar. W 11	Mar. W 12,13	Apr. W 14,15,16,17	May. W 18,19,20,21	Jun. W 22,23,24,25,26
Investigation of different taxonomies for autonomy.	X	X						
Review of sensors used to achieve situation awareness.	X	X	X					
Review previous work regarding use of OCA in marine control systems.			X	X	X			
Propose method for OCA.				X	X	X		
Build simulation model.			X	X	X			
Perform simulation study						X	X	
Propose method for evaluation of risk and simulate this.						X	X	
Report writing							X	X

Abstract

The maritime industry is undergoing substantial changes with regards to autonomy, and lately important steps has been done in realizing highly autonomous vessels for industry use. This master's thesis presents a framework for an online consequence analysis (OCA) as an approach for increased situation awareness (SA), for marine vessels in transit. It covers important steps towards this, in form of an overview of how different industries have defined autonomy, and how situation awareness currently is achieved for autonomous systems. The proposed framework is validated through simulation, and lastly a general discussion is presented, including positive outcome and challenges with the framework.

A review of how different industries have defined taxonomies for level of autonomy (LoA) is conducted, along with a review on how situation awareness is achieved for a marine vessel. Based on this, a comparison between the different taxonomies and how they fare with each other is provided, together with a visualization of how different sensors are used in order to achieve the first step of situation awareness, perception of the surrounding environment. The second and third step of SA are comprehension and projection, and this is where the OCA contributes.

The proposed framework is able to simulate the vessel's dynamics in different failure modes, when initialized at the vessel's current state and with the prevailing weather conditions. Results from the OCA simulations are evaluated with respect to the vessel's distance to obstacles, and a consequence level for each failure mode is calculated. Based on the consequence levels, a quantitative measure of the total risk of collision is presented online, which builds a foundation for further decision-making.

Furthermore, a simulation model was built in order to validate the functionality of the proposed OCA. A case study presents a set of scenarios simulated for validation, consisting of straight line transit, simple maneuvering between static obstacles and passage through a narrow channel. The results from the simulations showed promising behavior of the OCA. It was able to capture transient effects and the overall increase in risk when maneuvering in confined waters. The simulation model is flexible, as it allows for testing several failure modes and capture potential severe consequences. Initialization frequency of the OCA was important as it affected resolution of the risk indicator. A result of increasing the frequency was an earlier discovery of potential risk.

The applicability and limitations of the framework are discussed, and proposals for further work are suggested, together with a brief discussion regarding the framework's compliance with COLREGs. Based on an assessment of the research question in hindsight of the development process, it is concluded that the framework allows for increased situation awareness and that it shares capabilities of those defined as a LoA-3 management by exception autonomy level.

It is further recommended to expand the framework by implementation of moving obstacles. This will enhance the framework's capabilities to comprehend perceived information, thus making better calculations of consequence levels and associated risk.

Sammendrag

Den maritime industrien gjennomgår betydelige endringer med hensyn til autonomi, og det har den siste tiden blitt tatt viktige steg på veien mot å realisere autonome fartøy. Denne masteroppgaven presenterer et rammeverk for en online konsekvensanalyse (OCA) som en tilnærming til økt situasjonsforståelse (SA), for marinefartøy i transitt. Oppgaven dekker viktige elementer på veien mot økt situasjonsforståelse, ved å undersøke hvordan ulike næringer har definert autonomi, og hvordan situasjonsforståelse oppnås for skip i dag. Det foreslåtte rammeverket er validert ved hjelp av simulering, og det presenteres til slutt en diskusjon som tar for seg positive sider og utfordringer ved rammeverket.

En gjennomgang av hvordan ulike næringer har definert taksonomier for autonominivå (LoA) blir gjennomført, sammen med en gjennomgang av hvordan situasjonsforståelse kan oppnås for marine fartøy. Basert på dette blir det gitt en sammenligning mellom de ulike taksonomiene, sammen med en visualisering av hvordan forskjellige sensorer kan brukes for å oppnå det første trinnet i situasjonsforståelse, oppfatning av omgivelsene. Det andre og tredje trinnet i SA er forståelse og projeksjon, og det er her rammeverket bidrar til økt situasjonsforståelse.

Det foreslåtte rammeverket er i stand til å simulere fartøyets dynamikk i forskjellige feilmoduser når det initialiseres ved fartøyets nåværende tilstand og med rådende værforhold. Resultatene fra OCA-simuleringene vurderer fartøyets avstand til hindringer, og et konsekvensnivå for hver feilmodus beregnes. Basert på konsekvensnivåene presenteres et kvantitativt mål for total kollisjonsrisiko i nåtid, som bygger grunnlag for videre beslutningstaking.

En simuleringsmodell ble bygget for å validere funksjonaliteten til det foreslåtte rammeverket. En case-studie presenterer et sett av scenarier simulert for validering, bestående av rettlinjetransitt, enkel manøvrering mellom statiske hindringer og passasje gjennom en smal kanal. Resultatene fra simulasjonene viste lovende oppførsel av rammeverket. Det var i stand til å fange forbigående effekter og den samlede økningen i risiko ved manøvrering i begrenset farvann. Simulasjonsmodellen er fleksibel, da den muliggjør testing av flere feilmoduser som fanger opp potensielle alvorlige konsekvenser. Initialiseringsfrekvensen til rammeverket var viktig da det berørte oppløsning av risikoindikatoren. Resultatet av å øke frekvensen var en tidligere oppdagelse av potensiell risiko.

Rammeverkets anvendelighet og begrensninger blir diskutert, og forslag til videre arbeid foreslås sammen med en kort diskusjon om rammens overholdelse av COLREGs. Basert på en vurdering av forskningsspørsmålet i ettertid av utviklingsprosessen, konkluderes det med at rammeverket gir økt situasjonsforståelse og at det innehar egenskaper som samsvarer med et autonominivå definert som LoA-3.

Det anbefales videre å utvide rammeverket ved innføring av bevegelige hindringer. Dette vil styrke rammeverkets evne til å forstå oppfattet omgivelsene rundt seg, og dermed gi bedre beregninger av konsekvensnivå og tilhørende risiko.

Preface

This master's thesis is written at the Department of Marine Technology at the Norwegian University of Science and Technology during the spring of 2018.

This last semester has thought me a lot about how to investigate and research a topic with very little to none existing literature on previous work. That said, I have learned a lot about how different industries thrive to achieve highly autonomous systems, and I really look forward to continue learning about autonomous systems utilized in the maritime industry in the future.

Writing the thesis has been both extremely fun and challenging. I've been happy, sad, angry, tired and overtired all at once, many times. Most importantly, during the entire time, I've had a lot of helpful and encouraging friends that have helped me continue to work hard.

I would like to extend my biggest gratitude to my supervisor, Professor Asgeir Johan Sørensen. You have constantly reminded me that when everything seems to go to hell, I am most likely on a good course, and you have given me the possibility and freedom to form my own thesis based on my own interests.

I would also like to thank my two great co-supervisors, PhD Børge Rokseth and PhD Astrid H. Brodtkorb. Your guidance is unparalleled, and I would not have been able to complete this thesis without it.

Last but not least, I would like to thank my family, all of my fellow students and office buddies. My time as a student would not have been the same without you.

Trondheim, 29.06.2018

Markus Fossdal

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Markus Fossdal

Table of Contents

List of Tables

List of Figures

Nomenclature

Acronyms

AIS	Automatic Identification System
AL	Autonomy Level
AUV	Autonomous Underwater Vehicle
BASt	The German Federal Highway Research Institute
CA	Consequence Analysis
COLREGs	The International Regulations for Preventing Collisions at Sea
DOF/dof	Degree of Freedom
DP	Dynamic Positioning
GNSS	Global Navigation Satellite System
IMO	International Maritime Organization
LIDAR	Laser Imaging, Detection and Ranging
LoA	Level of Autonomy
NED	North, East, Down coordinate frame
NTHSA	US National Highway Traffic Safety Administration
NTNU	Norwegian University of Science and Technology
OCA	Online Consequence Analysis

PPM	Process Plant Model
SA	Situation Awareness
SAE	Society of Automotive Engineers
VDA	German Association of the Automotive Industry

Commonly Used Expressions

Consequence Level	Consequece level refers to the vessel's violation of a predefined distance from an obstacle
Failure Mode	Failure mode refers to a predefined failure simulated by the online consequence analysis. One OCA simulation / OCA run, simulates multiple failure modes.
Main Simulation	Main simulation referes to the simulation emulating the "real" vessel dynamics
OCA run/OCA simulation	OCA run or OCA simulation refers to the simulation conducted by the online consequence analysis.

List of Symbols

α_k	Path-tangential angle
$\bar{\tau}^b$	Constant potential damping force
$\bar{A}$	Added mass matrix
$\bar{B}$	Linear potential flow damping matrix
$\bar{O}_{rel}$	Vector holding bolean value for obstacle relevance
$\bar{r}_{O,min}$	Minimum distance between the vessel and obstacle during one OCA simulation.
$\bar{r}_{O,min}$	Vector holding the minimum distance from the vessel to each obstacle in the vessel's proximity
β	Sideslip angle
$\chi_d(e)$	Desired course angle
χ_p	Path-tangential angle
$\chi_r(e)$	Velocity-path relative angle
$\Delta(t)$	Lookahead distance
$\dot{\Theta}$	Vector holding NED angular velocities
$\dot{p}^n_{b/n}$	Vector holding NED velocities
η	Positions in NED and Euler angles.

η_{FM_n}	Simulated results η, for failure mode n (FM_n) calculated by the OCA.
μ	Fluid memory effects
ν	Vector holding body velocities and angular velocities, relative to NED
ν_c	Current velocities
ν_r	Body relative velocity and angular velocities
ν_{FM_n}	Simulated results ν, for failure mode n (FM_n) calculated by the OCA.
$\omega_{b/n}^b$	Vector holding body angular velocities relative to NED
ϕ	Euler angle, roll
ψ	Euler angle, yaw
ψ_d	Desired heading angle
ψ_{th}	Heading angle threshold
ρ	Water density
τ	External forces and moments
τ_N	Force in yaw
τ_{exc}^b	External forces and moments
τ_{wave_1}	Force and moment contribution from first order waves
τ_{wave_2}	Force and moment contribution from second order waves
τ_{wave}	Force and moment contribution from waves
τ_{wind}	Force and moment contribution from wind
θ	Euler angle, pitch
Θ_{nb}	Vector holding Euler angles.
$\tilde{\psi}$	Heading error
$\tilde{U}$	Vessel speed error
C_A	Coriolis and centrepetal added mass matrix
C_d^{2D}	Drag Coefficient (2D), (Hoerner 1965)
C_F	Flat plate friction coefficient
C_f	Combined flat plate friction coefficient and residual friction due to hull roughness
C_R	Residual friction coefficient

C_{enable}	Integral Anti-windup enabling constant
$C_{RB}(\nu)$	Rigid-body coriolis and centrepetal matrix
$CL_{FM,max}$	Maximum consequence level for each failure mode in one OCA simulation
CL_{max}	Max consequence level violation during one online consequence analysis simulation
D	Linear damping matrix
D	Position in Down direction
$d(\nu_r)$	Nonlinear resistance matrix
$D_n(\nu_r)$	Nonlinear damping matrix
E	Position in East direction
$e(t)$	Cross-track error
FM_n	Failure mode number n
$g(\eta)$	Gravitational and buoyancy force/moment matrix
g_0	Pretrimming and ballast control forces/moments
I	Identity matrix
$J_\Theta(\boldsymbol{\eta})$	6DOF Transformation matrix
k	Form factor
$K(t)$	Retardation function
K_d	Derivative gain constant
K_i	Integral action gain constant
K_p	Proportional gain constant
L	Selection matrix
L_{pp}	Length between perpendiculars
M_A	Added mass matrix
M_{RB}	Rigid-body inertia tensor matrix
N	Moment in body yaw direction
N	Position in North direction
p	Body angular velocity about body x-axis, relative to NED
$P(FM_i)$	Probability of occurrence for failure mode i

$p_{b/n}^n$	Vector relating the relative body position with respect to the North, East, Down coordinate frame.
q	Body angular velocity about body y-axis, relative to NED
R	Acceptance radius
R	Rotation matrix
R	Total risk
r	Body angular velocity about body z-axis, relative to NED
$R_b^n(\Theta_{nb})$	Rotation matrix about zyx, rotated by Θ_{nb}
$R_{x,\phi}$	Rotation matrix about x-axis, rotated by ϕ
$R_{y,\theta}$	Rotation matrix about y-axis, rotated by θ
$R_{z,\psi}$	Rotation matrix about z-axis, rotated by ψ
Re	Reynolds number
$T(x)$	Draft as a function of vessel length
$T_\Theta(\Theta_{nb})$	Angular Transformation matrix
U	Vessel speed
u	Body velocity along body x-axis, relative to NED
u_r	Relative surge velocity
U_{th}	Vessel speed threshold
v	Body velocity along body y-axis, relative to NED
v_c^b	Current velocity represented in body coordinate frame
v_c^n	Current velocity represented in inertial coordinate frame (NED)
V_c	Current velocity represented in the FLOW coordinate frame
v_r	Relative sway velocity
$v_{b/n}^b$	Body velocity relative to NED, described in body.
VL	Matrix holding consequence level violation
w	Body velocity along body z-axis, relative to NED
X	Force in body surge direction
$x(t)$	Vessel position, x-direction
x_{k+1}	Next waypoint, x-direction
Y	Force in body sway direction
$y(t)$	Vessel position, y-direction

y_{k+1}	Next waypoint, y-direction

CHAPTER 1

Introduction

The following thesis presents a new framework for increasing situation awareness(SA) for autonomous ships in terms of online consequence analysis. It covers important steps towards this, in form of an overview of how different industries have defined autonomy, and how situation awareness currently is achieved for autonomous systems. The proposed framework is validated through simulation, and lastly a general discussion is presented, including positive outcome and challenges with the framework.

1.1 Background and Motivation

Autonomous and unmanned vehicles are relatively new concepts that will challenge the way cars, ships, airplanes et cetera, are designed, tested and approved for use. The need for well defined regulations for autonomous vehicles will constantly grow, as more and more industries are pursuing the use of highly autonomous systems. Safety and reliability will be crucial if the use of autonomous vehicles is to be adapted, both by governments, but also socially accepted and trusted by the public.

The maritime industry is undergoing substantial changes with regards to autonomy, and lately important steps has been done in realizing highly autonomous vessels for industry use. Massterly is the world's first autonomous shipping company, and is planned to be fully operational from August 2018. It is a joint program between the companies Kongsberg Group and Wilhelmsen, which are pioneers within development of marine control systems and shipping, respectively (Kongsberg Group 2018). Massterly was formed in the wake of another important announcement: Yara Birkeland, will have highly autonomous capabilities, and is planned to be fully operational within 2020. It designed to replace an annual 40 000 trucks from Yara's fertilizer factory at Herøya, to Breivik and Larvik, located south-west of the Oslo fjord (TU.no 2017). A picture of Yara Birkeland's design can be seen in Figure 1.1a.

A number of different industries have started to implement autonomy on various levels. Tesla has tested their cars in what is often referred to as high automation or level 4, by SAE's definition (SAE 2016), with good results. A picture showing the Tesla's camera system, and how it observes its surroundings to gain situation awareness is shown in Figure 1.1b. Operations with the help of autonomous underwater vehicles (AUV) is another example. AUV Hugin, was recently involved in a search for the missing Malaysian Airlines flight MH370 in order to cover large seabed area in a short amount of time (Norway Today 2018). Hugin can be seen in Figure 1.1c.

(a) Yara Birkeland at Herøya. Picture: Yara/Kongsberg Group

(b) Tesla Autopilot test drive. Picture: tesla.com

(c) Hugin AUV, picture: norwaytoday.info

Figure 1.1: Autonomous vehicles and systems.

Taking a broad view, all of the above systems have similar objectives - to perform a task with very little interaction from a human operator, if any at all, in a safe and efficient way.

Personnel working in the maritime industry are often exposed to dangerous, time consuming, and tedious tasks leading to fatigue which again might lead to severe human errors. In fact, an estimated 75% to 96% of all marine accidents can be linked to human error (Allianz Global Corporate & Specialty 2012, Mazaheri 2009). The operations might be

Arctic ice management or long period transits of e.g. cargo ships, all of which could benefit from increased autonomy. In order to achieve this, a wide variety tasks will have to be masterly performed by the system on its own, and the ability to *think* and replan a situation if necessary is crucial.

To further develop autonomous systems, a thorough understanding of how different industries define autonomy is needed, but also to understand where these systems are today. A key part of this thesis is to obtain this knowledge, before proceeding with development of a framework to increase a system's situation awareness, i.e. in this case for a ship during transit, hence providing a necessary foundation for increased autonomy. A description of the core scientific question at hand is given in the following section.

1.2 Research Question and Objectives

The main research question of the following thesis is:

Is it possible to develop and utilize a continuously running online consequence analysis in order to increase the situation awareness of a vessel during transit, thus creating a better foundation for decision-making with respect to management of power system redundancy, route planning and others? The system must be applicable both as a supervisor for manned vessels, but ultimately to take direct part in decision-making for a highly autonomous vessel.

As briefly touched upon in section 1.1, some of the main objectives in order to achieve this, is the initial step of gaining knowledge of how industries define autonomy, and where we are today. Based on this, the main objectives of the thesis include:

- Thoroughly investigate how different taxonomies for autonomy are defined, which industries they are based on, and lastly compare the different definitions.
- Gain an overview based on literature of the main sensor platforms used in order to gain situation awareness on autonomous and non-autonomous surface vessels today.
- Present former work on online consequence analyses for use in autonomous or higher level control systems.
- Propose a framework for online consequence analysis.
- Build a simulation model based on mathematical models in order to validate the proposed online consequence analysis, and simulate the system.

Lastly, results from the simulations are discussed with respect to the research question, to conclude upon whether the proposed framework fulfills the objective of increasing situation awareness.

1.3 Main Contributions

The thesis main contributions consist of four parts, with a following general discussion of positive outcomes and challenges of the proposed framework:

- A rigorous comparison is made between different industry taxonomies for autonomy.
- Literature review on what situation awareness is, and some of the techniques and senors used to achieve similar for autonomous systems is presented.
- A novel framework for an online consequence analysis (OCA), for a vessel during transit, which is later validated through simulation. Such a framework has to the author's best knowledge never been developed.
- Based on the online consequence analysis, an online risk indicator is suggested, providing a quantitative measure of risk, which directly builds a foundation for autonomous decision-making.

1.4 Thesis Outline

The thesis is divided into six chapters. Necessary appendices are referred to directly from the text. The chapters include:

Chapter 2 - Background Material: This chapter consists of five sections. The first section presents a comparison study of autonomy taxonomies, arranged by industry. Secondly a literature review of situation awareness is presented, including typical sensor platforms used by maritime vehicles. Thirdly, a short literature review regarding how consequence analysis previously has been used with respect to maritime vehicles, and lastly section four and five cover the mathematical model and control theory, respectively, used by the simulator for the case study in Chapter 4.

Chapter 3 - Online Consequence Analysis: The proposed framework for how an online consequence analysis can be developed is presented in this chapter. It also gives the full mathematical deduction of the proposed framework, which is later simulated in Chapter 4. The online consequence analysis consists of a vessel dynamics simulator, a consequence level deciding algorithm, and lastly a risk indicator which is based on the consequence level from the different simulated failure modes. The chapter also includes a short discussion of further thoughts on how the risk indicator could be implemented in decision-making, before an ending section on specific challenges regarding the simulator will be discussed.

Chapter 4 - Case Study: Simulation, Online Consequence Analysis: This chapter validates the simulation model, and simulates four scenarios. Each scenario setup is explained in their respective sub sections, before the results are presented. Results that need immediate attention will be described together with the results, while a general discussion of all the scenarios will be given last.

Chapter 5 - Discussion: A general discussion regarding the proposed framework, and potential challenges with this is provided. The discussion also covers some challenges that needs to be addressed in further work.

Chapter 6 - Conclusions and Further Work: This chapter covers the concluding remarks of the thesis, and presents the main challenges that is to be addressed in further work.

CHAPTER 2

Background Material

The following chapter is divided into five sections, covering the necessary background material in order to develop an online consequence analysis. The chapter consists of a rigorous comparison between level of autonomy taxonomies, a brief literature review on situation awareness for ships and unmanned vessels, and a short introduction to consequence analyses, and how they have been utilized in the maritime industry. The last two sections in the chapter covers the mathematical modeling and control theory, used in the case study seen in Chapter 4.

2.1 Levels of Autonomy, Industry View

Defining what autonomy is and how a system architecture should be laid out can be challenging. The need for clear definitions of what to expect from autonomous systems has become evident as different industries pursue the development of systems operating without human interaction.

The following section aims to give an overview of how different industries and their respective governmental institutions define autonomy. The represented industries are: automotive industry, maritime industry and a small section on aerospace and military. It also aims to cover some of the views these institutions have on autonomous versus automatic systems, while discussing some of the resemblance and differences between the definitions. Finally, a comparison between the different definitions on levels of autonomy is provided.

2.1.1 Automatic Systems

Distinguishing between automatic and autonomous systems is something many researchers and scientists have tried to do. Albus et al. (1998) describes autonomy as a system with the ability to make its own decisions about actions while performing different tasks. The system conducts this without the need of input from a human operator, or exogenous system. In other words, autonomy means independence from outside supervision, a ”free will” and the ability to change the initially programmed actions within limits set a priori in the system design phase (Vagia et al. 2016).

An automatic system executes predefined actions which previously were carried out by a human operator (Parasuraman & Riley 1997, Parasuraman 2000). That said, this seem to have changed over time. Tasks that were previously considered automatic, may not be seen as automatic today, as they have become part of the expected functionality of a system (Parasuraman & Riley 1997).

In the marine industry, both for surface and underwater vehicles, automation is used as a general term for computerized operations. These enables the vehicle to perform certain tasks without human interaction, while autonomy enables self-governance in the system, i.e. that different strategies are being evaluated by the system without consultation of a human operator (Rødseth & Nordahl 2017).

Summarized, automation refers to a system that will do exactly as programmed, without any possibility to act in a different way dependent on the situation, it has predefined actions and does not have the ability to change these in the future (Vagia et al. 2016).

In parallel with industries and governments beginning to see the large potential sophisticated autonomous systems bring, the importance of standards and clear definitions regarding what should be considered an autonomous system and the corresponding level of autonomy is evident.

2.1.2 Autonomous Systems and Levels of Autonomy

The differences between automatic and autonomous as described in the latter section has shown to be well defined, with some exceptions i.e. automatic tasks which has become expected functionality, rather than seen as automation. The same cannot be said about how autonomy is defined. In fact, what it is, and where it is going, is rather uncertain. A comparison of the different definition for levels of autonomy discussed in the following section, and a simplified version of the definitions, can be seen in Table 2.1 and Appendix A, respectively.

Autonomy may be divided into levels based on a system independence of input from either humans or external systems. The same levels may also depend on mission complexity and/or the environment in which the system operates. The four-level division of autonomy as seen below is just one of many suggested definitions of autonomy (Ludvigsen & Sørensen 2016)(Utne et al. 2017)(National Academy of Sciences 2005).

LoA-1 **Automatic operation:** In this mode, the system operates automatically, but is often programmed to do specific tasks and any deviations from the boundaries of the operation is controlled by a human, which also has the full responsibility of high-level planning during a mission. The mode is also referred to as **human-in-the-loop** or **human operated.**

LoA-2 **Management by consent:** Refers to a system that may prompt the human operator at important points in time for information or decisions. At this level the system might have limited communications capabilities, i.e. due to distance and may also execute mission tasks independently as delegated in advance by humans. This level stage is referred to as **human-delegated**.

LoA-3 **Semi-autonomous or management by exception:** The semi-autonomous system is able to automatically execute mission related tasks in situations where response time is too short for human intervention. At this level the human operator may intervene with the system's decision and cancel or redirect the system, however this needs to happen within a certain time limit. The human operator needs only respond to deviations from the mission. This stage is referred to as **human-supervisory control**

LoA-4 **Highly autonomous:** At this level, the system is able to execute a mission in an unstructured environment with the ability to plan and re-plan mission tasks continuously without human interaction. Humans observing the mission may be informed of any changes or deviations from the original mission plan, but may not intervene with the systems decision-making. The system is independent and intelligent. This level is referred to as **human-out-of-the-loop.**

The levels above are typically used for marine surface- and underwater vessels, but has many similarities with other definitions as well. Different industries have attempted to define levels of autonomy suitable for their respective uses, and the one presented in Ludvigsen & Sørensen (2016) is an example for marine underwater robotics. Both governmental and private institutions within the automotive, maritime, military and aerospace industry all have their own definition. Some of these are discussed below.

Automotive industry

Some of the larger car manufacturing countries have started developing level of autonomy definitions. The Society of Automotive Engineers, hereby referred to as SAE, has developed a LoA set, which consists of six levels (SAE 2016). These range from 0 to 5, and is categorized from no automation to full automation, respectively. Full automation in SAE's definition refers to a highly autonomous system w.r.t the definition in Subsection 2.1.2, and is something SAE consistently use instead of the more typical way of definition, where automation is only referred to as the lowest level of autonomy. This definition refers to specific driver tasks that is conducted by the system, and does not go into detail on how these autonomous tasks are solved.

The German Federal Highway Research Institute and the German Association of the Automotive Industry, referred to by their German acronyms BASt and VDA, has similarly to SAE also defined a set of five and six levels, respectively, to specify the range of autonomous tasks from simple automation to highly autonomous systems (Gasser et al. 2013, VDA 2015). Where VDA's definition is an almost exact replica of SAE's definition, BASt seem to have taken a step further and included specific examples on how and what type of technology that can be used to solve the different autonomous tasks to make it easier to distinguish which level a system is member of.

Lastly, the US National Highway Traffic Safety Administration (NTHSA) has defined a set og LoA containing of five levels (NHTSA 2013). The major difference in the former automotive definitions and NTHSA's definition, is the removal of the level explaining highly autonomous systems. In NTHSA's definition, this is included in level for fully autonomous system. This means the level which in SAE, BASt and VDA covers a semi-autonomus system as described in Ludvigsen & Sørensen (2016) does not exist in NTHSA's definition.

It should be noted that none of the definitions specify an exact time notice before the driver should be able to take control over the vehicle. This has been interpreted differently between car manufacturers that provide systems conducting autonomous tasks, so this is not the same in a Tesla and a Nissan.

Maritime Industry

Maritime operations tend to include many elements that can benefit from autonomous systems. Tedious work, long periods of waiting or standby, human fatigue due to environmental conditions and arctic ice management are some of the reasons why the maritime industry pursues the development of autonomous vessels.

Rødseth & Nordahl (2017) clarify some of the typical misconceptions regarding what an autonomous maritime vehicle is. Although the differences are not explicitly a part of their LoA definition which is more generalized, it is wise to recognize that there are some. Figure 2.1 shows the terminology commonly used today in form of a block diagram.

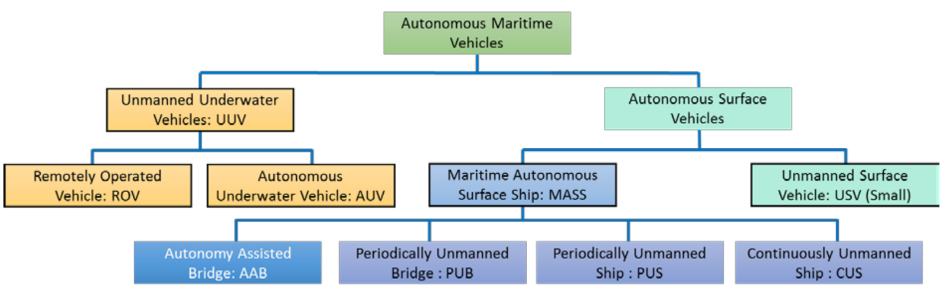


Figure 2.1: Classification of autonomous maritime systems and autonomous ship types. Figure from: (Rødseth & Nordahl 2017)

Several LoA definitions for the maritime industry has been proposed. Rødseth & Nordahl (2017) proposes an LoA definition that is divided into two sections: bridge manning level and operational autonomy level. This division is emphasized due to a shortcoming in commonly used LoA definitions, which usually includes the presence of humans in the definition. This is not always the case for autonomous vessels, hence dividing the definition into two sections, one covering the systems autonomous operational capability and the other, the operators role, is done in order to further clarify. The operational autonomy levels are defined from the lowest level, decision support, to the highest level, fully autonomous.

Lloyd's Register's seven level definition proposes two high levels that are both recognized as fully autonomous, but with a small difference between the lower and highest one. The lower level is occasionally supervised by humans, whereas at the highest level is completely unsupervised by humans (Lloyd's Register 2016).

Lastly, the US Navy Office of Naval Research proposes a six-level definition. It gives a superficial overview of what to expect from an autonomous system, where every activity described in the definition is compared against humans, making the definition highly dependent on what a human operator would do in a similar situation. As pointed out in Rødseth & Nordahl (2017), this might not be adequate for autonomous marine vessels. The definition ranges from human operated to fully autonomous (NFA 2014).

Aerospace- and Military Industry

A eleven-level definition is suggested by The Air Force Research Laboratory (Clough 2002). It provides in-depth information of expectations from the system, with regards to how the system is able to observe its surroundings, how the systems orients it self, completes decision-making, and lastly how the system acts accordingly. It provides a higher resolution than previously discussed definitions, and includes specific examples regarding missing execution. The definition is mainly used for military aerial drones. Therefore some of the levels refer to specific actions that are only applicable to aerial drones, such as transmitting radio signals, which for underwater drones would not be applicable.

2.1.3 Comparison of Definitions

In order to get an overview of the different levels of autonomy definitions, a comparison is presented in Subsection 2.1. The table presents the previously discussed definitions with respect to the definition in subsection 2.1.2. The table's color code represents how the different levels correspond to the four levels presented in Ludvigsen & Sørensen (2016), where red, blue, orange and green represents LoA-1 automatic operation, LoA-2 management by consent, LoA-3 management by exception and LoA-4 highly autonomous, respectively. As the different definitions represent a wide spectrum of industries, the comparison is likely to have some discrepancies. That said, it gives a good indication of how the different definitions compare.

Later references to specific autonomy levels will be stated in terms of the definition provided by Ludvigsen & Sørensen (2016), as seen in Subsection 2.1.2 and Appendix A.

Table 2.1: LoA definitions, comparison table. Horizontal axis: levels from lowest to highest degree of autonomy. Vertical axis: each row represents the discussed LoA definitions. Color code: Definitions are compared with the definition in Ludvigsen & Sørensen (2016), hence red, blue, orange and green represent the levels compared to LoA-1 automatic operation, LoA-2 management by consent, LoA-3 management by exception and LoA-4 highly autonomous, respectively.

(Ludvigsen & Sørensen 2016)	Automatic Operation	Management by consent	Management by exception	Highly autonomous							
(SAE 2016)	SAE 0	SAE 1	SAE 2	SAE 3	SAE 4	SAE 5					
(Gasser et al. 2013)	Driver Only	Assisted	Partial automation	High automation	Full automation						
(VDA 2015)	Driver Only	Assisted	Partial automation	Conditional automation	High automation	Full automation					
(NHTSA 2013)	No-Automation	Function Specific Automation	Combined Function Automation	Limited Self-Driving Automation	Full Self-Driving Automation						
(Lloyd's Register 2016)	AL 0)	AL 1)	AL 2)	AL 3)	AL 4)	AL 5)	AL 6)				
(Rødseth & Nordahl 2017)	Decision Support	Automatic	Constrained Autonomous	Fully Autonomous							
(NFA 2014)	Human Operated	Human Assisted	Human Delegated	Human Supervised	Mixed Initiative	Fully Autonomous					
(Clough 2002)	L0	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10

2.2 Situation Awareness for Ships and Unmanned Surface Vehicles

In order to develop autonomous systems to operate according to LoA-3 and LoA-4 (management by exception and highly autonomous), a key feature of the system is the ability to observe and more importantly *understand* its surroundings, so it can make proper decisions and actions. Endsley (1988) defines situation awareness as: *The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.* The definition has three elements, where the first element, perception, refers to the ability of perceiving the status, attributes and dynamics of relevant elements in the environment. The second element refers to the systems comprehension of the information that was perceived, and lastly the third element is the systems ability to project the future based on information gathered in the two first steps. These elements are thoroughly explained in Endsley (1995).

Achieving all three steps in an autonomous system can be challenging. The need for systems that are robust in terms of how they perceive information of their surroundings is evident, as a lack of this could lead to dangerous situations of severe extent, on the environment, personnel and/or materials. The different sensors in a system are responsible for the perception of surrounding elements, but to properly *understand* the surroundings i.e. comprehension and projection, the need for advanced models for analyzing risk and consequences becomes necessary. Subsection 2.3 will briefly discuss how consequence analyses are used in marine control systems, while Chapter 3 thoroughly explain how an online consequence analysis can be utilized for a ship in transit.

Some of the typical sensor platforms used as a foundation for situation awareness for marine vessels are global navigation satellite system (GNSS), radar, laser imaging, detection and ranging (LIDAR), automatic identification system (AIS), stereo cameras and acoustic positioning systems in form of transponders. The previously mentioned are further investigated, as they are a good match for perceiving information about a marine vessels surroundings. Sensors used by the system purely to estimate its own position will not be discussed.

Situation Awareness Visualization

Inspired by Nilssen et al. (2015), covering spatial versus temporal domain for different vehicles that use autonomy, a similar visualization is was made for the different sensor platforms used to achieve situation awareness. Figure 2.2 shows this visualization, and the figure gives a good representation of how the range information can be perceived and at which rate, with regards to autonomous systems and obstacles in close proximity.

It is noticeable from Figure 2.2 that in order to cover both close range (0-15m) and up to a larger range (10 km+), a combination of computer vision (cameras), LIDAR and Radar is a minimum required sensor package. An example where this might not be sufficient, is during interaction with high-speed vessels that might intercept the autonomous systems path.

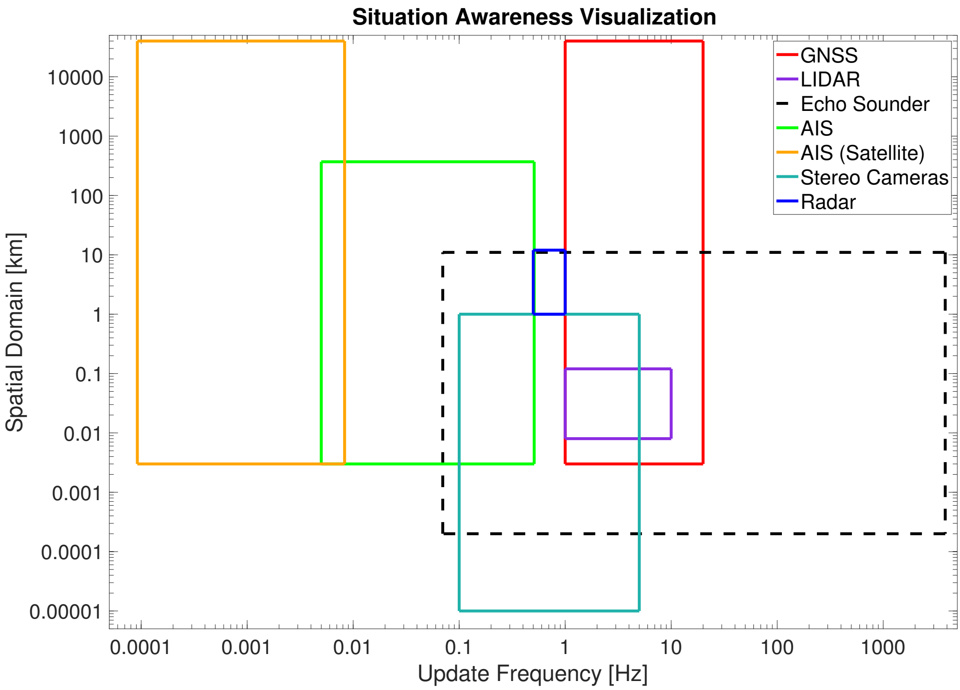


Figure 2.2: Illustration of sensors and technologies used in order to achieve situation awareness for marine vessels. The dashed lines represent sensors applicable for underwater use only.

In this case, a sensor package covering a higher update rate might be necessary.

Figure 2.2 gives a brief overview of the first step in situation awareness, the perception of elements in the systems proximity. However, to fully achieve the last two steps, comprehension and projection, the development of more sophisticated methods are needed. This is some of what an online consequence analysis could contribute with, thus achieving a higher situation awareness.

In the following, a brief description of the different sensors and their range/frequency properties is given.

Global Navigation Satellite System

Navigation with the help of satellites was developed for military use during the 20th century. Scientists were able to measure the frequency of transmitted and received signals from the satellites, thus calculating position of a vehicle based on the Doppler shift in frequency (NASA 2017). Several dedicated GNSS systems are operative today: GPS, GLONASS, Gallileo and BeiDou are the most commonly used, belonging to the U.S., Russia, European Union and China, respectively (Kartverket 2018). GNSS can estimate position and velocity, and has a typical update rate of 1 Hz (Toledo-Moreo et al. 2009), but may also be as frequent as 10-20Hz for some GNSS receivers (SX Blue 2018). The range og GNSS is considered to be global, however there are signal dead zones near the poles and at certain parts of the great oceans, which are not covered by the satellites.

Radar

Radar is typically used to aid personnel aboard ships, it uses radio frequency signals, and measures the elapsed time from the signal is transmitted until it's received again. The beam of radio signals are able to give a representation of how large and how far away from the vessel an object is. A marine radar has a typical range of 1 to 12 km, and update frequency of 0.5 Hz for x-band radars, to 1 Hz for Ka-band radars, however this may vary (Elkins et al. 2006).

LIDAR

LIDAR stands for "Laser Imaging, Detection and Ranging". The technology uses one or multiple lasers and measures the time of flight of reflected light. This can be used for mapping the environment around a vessel with at high frequency. Elkins et al. (2006) used a Velodyne HDL-64E S2, which consists of 64 lasers, and spins at a rate of 10 Hz. It generates a three-dimensional map based on the point measurements, which is sampled at a rate of approximately one million points per second. The LIDAR is usable between 8 and 120 m, and is meant to complement the radar in close proximity to the vessel. The wavelength of the lasers is such that the radiated energy does not reflect well from the water surface. Thus, most points that are returned are not water, making it suited for object and obstacle detection.

AIS

Automatic Identification System, or AIS collects transmitted data from other AIS-equipped ships. Similar to the military "identification-friend-or-foe" system (IFF), the AIS collects data such as maritime mobile service identity (MMSI), vessel name, radio call sign, status (anchored, in transit), speed, heading, type of ship/cargo, destination, estimated time of arrival and vessel turn rate. The AIS system uses very high frequency (VHF) and satellites to transmit information, and is a requirement for all vessels of 300 tonnage and upwards (IMO 2003, 2009). The range and update frequency of the AIS system varies based on location of the land based AIS antenna, obstacles, elevation of antenna, and/or weather conditions. The max range may vary from a distance of 15 to 200 nautical miles (Marine Traffic 2018*b*). Furthermore, the update frequency of the VHF based AIS is dependent on the vessel speed, and varies from three minutes while anchored, to being updated every two seconds for vessel during high-speed transit. For AIS transmitting data over satellite, this frequency drops to between a few minutes and up to several hours, however the coverage of satellites is near global. (Marine Traffic 2018*a*). AIS may be a great contribution to increased situation awareness, as it covers most large vessels that have slow maneuvering dynamics, contributing to a higher risk of collision. However it should be mentioned that AIS can never be a primary tool for perceiving information about a vessel's surroundings, as it might miss smaller vessels and does not cover other obstacles.

Stereo Camera Assembly

Cameras have shown to be valuable for autonomous systems, as they are able to capture details where e.g. radar and LIDAR struggle. Testing of cameras for detecting and tracking objects on an unmanned surface vehicle was conducted, and multiple objects were tracked using a 360° camera assembly, able to detect obstacles at every bearing (Wolf et al. 2006). A Bayesian approach was used to probabilistically track the objects, even when they were outside of the sensors range. The 360° assembly is used together with the vessel compass, thus it becomes easy to determine at which bearing the object is detected. An approach of combining the 360° camera assembly with a set of four cameras, two and two working in stereo was done by Elkins et al. (2006), further increasing the vessels ability to perceive its surroundings.

Accurate information regarding range and update frequency of camera systems used for object tracking has proven to be rather difficult to find. This is mostly because it depends on several factors, such as computational power, type of cameras, weather, light and size of the object to be tracked. The range of such a camera system has a best case of approximately 1 cm to 1 km distance, and and update frequency of 0.1 to 5 Hz. As mentioned, this will vary, and can only be used as a coarse estimate.

Echo Sounder

Acoustic echo sounders are used by marine vessels to measure water depth or to map the sea bed (bathymetry), with either a single acoustic beam or multiple acoustic beams, often called multibeam. The range and update frequency is highly dependent on the sound speed in water, which depends on temperature, salinity and hydrostatic pressure. Typical echo sounders used by marine vessels have range capability from 0.2 to 11000 m, and a frequency range of 12 kHz to 500 kHz (Kongsberg Maritime 2018). The speed of sound in water is approximately 1540 m/s at 20°C (Fox et al. 2012). Based on this, the actual update frequency is equal to 0.07 to 3850 Hz, taken into consideration that the acoustic signal travels to the seabed and returns.

2.3 Consequence analysis

As described in Section 2.2, situation awareness is not achieved only by perceiving information about a systems' surroundings. Thorough *understanding* of the perceived information is necessary, and development of methods to achieve this is needed. The last two steps defined by Endsley (1988), comprehension and projection, covers the missing elements in order to achieve SA, and as the thesis research question suggests, a consequence analysis implemented directly in the control system may contribute to increase it.

Consequence analyses are commonly used to estimate the physical effects of an accident by use of various models. They are used to predict the damage outcome of an event caused by one or multiple failure modes. If the consequence is quantified and combined with the probability of occurrence for the event, a quantitative measure of risk can be calculated (Varde & Pecht 2018).

In the maritime industry, consequence analyses are found on vessels equipped with dynamic positioning (DP) systems. Such vessels are often used in the oil and gas industry, where operations requiring precise positioning often occur, and are obligated to have a consequence analysis embedded in their control system. It should be able to simulate the worst case failure mode of the system, and if the vessel is not able to maintain its position in the prevailing weather conditions, it should raise an alarm (DNV GL 2014). Estimation of the environmental forces is typically provided by the bias estimate in the control system observer. The observer bias gives an estimate of the steady state forces acting on the system. As many consequence analyses are based on a static equilibrium of the estimated forces, they lack the ability to capture the failure dynamics during transient behavior of the system.

Bø et al. (2016) implemented a dynamic consequence analysis for a vessel during DP operation, which showed that the current static consequence analyses that is used by the maritime industry may overestimate the systems ability to withstand the prevailing weather. In a real life application, the system might not be able to maintain its position as well as estimated by the consequence analysis, due to a shortcoming in the analysis during transient behavior.

A suggested system architecture which includes an online risk model was presented in Utne et al. (2017). The risk model uses historical data, measurements from the sensors and experience data, including weather forecasts, in order to calculate the associated risk. The method proposed in Utne et al. (2017) emphasizes the importance of the research objective of this thesis, as a development of an online consequence analysis that is able to simulate different failure scenarios, would build a better foundation for projection into the future, thus increasing the vessel's situation awareness.

Lastly, the developed method presented in Chapter 3 is applicable for a vessel in transit. As it is developed for the purpose of increasing situation awareness, and to better avoid potential hazardous situations, it makes sense to mention the International Regulations for Preventing Collisions at Sea, better known by its acronym COLREGs. It consists of 38 rules, some of which will be presented later in Section 5.7, as they are relevant for the development of the online consequence analysis (IMO 1972).

2.4 Mathematical Modeling of Marine Vessels and Environmental Forces

The following section aims to provide the necessary theoretical foundation used in the ship simulator, which is later used for validation of the online consequence analysis. The model is a maneuvering model based on NTNU's research vessel R/V Gunnerus. Relevant information regarding R/V Gunnerus can be seen in Appendix B. The full nonlinear model may also be referred to as Process Plant Model, or by its abbreviation, PPM (Sørensen 2011). The model assumes that the vessel is operating in deep water at all times, and the body is considered rigid. Lastly the modeling of environmental forces acting on the vessel is described.

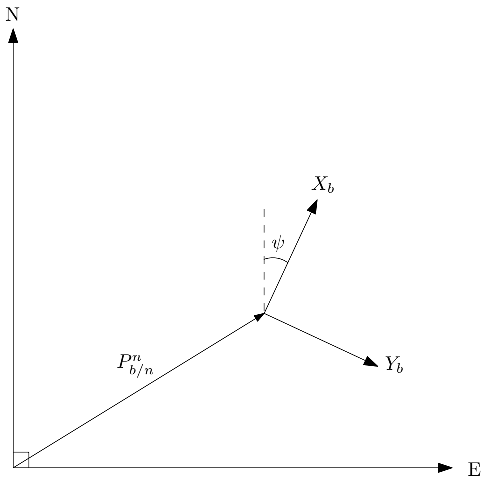


Figure 2.3: 2D illustration showing relationship between NED frame and body-frame.

2.4.1 Kinematics

This section will provide the theoretical foundation and deduction of the PPM's kinematics. The notation will follow the vectorial six degree of freedom (6DOF) notation as presented in Fossen (2011). The vector $\boldsymbol{p}^n_{b/n}$ relates the relative body position with respect to the North, East, Down (NED) coordinate frame, which is assumed inertial, and is defined as:

$$\boldsymbol{p}^n_{b/n} := \begin{bmatrix} N \\ E \\ D \end{bmatrix} \in \mathbb{R}^3 \tag{2.1}$$

Note that $\mathbb{R}^3$ is the Euclidean space with three dimensions. Further, $\boldsymbol{\Theta}_{nb}$ is a vector defining the orientation of the body relative to NED, holding the Euler angles ϕ, θ and

ψ which represents the angle about the body x_b, y_b and z_b respectively:

$$\boldsymbol{\Theta}_{nb} := \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} \in \mathcal{S}^3, \tag{2.2}$$

$\mathcal{S}^3$ is a sphere with three Euler angles defined between $[0, 2\pi]$. Combining (2.1) and (2.2) gives the 6DOF generalized position:

$$\boldsymbol{\eta} := \begin{bmatrix} \boldsymbol{p}^n_{b/n} \\ \boldsymbol{\Theta}_{nb} \end{bmatrix} \tag{2.3}$$

Figure 2.3 illustrates how (2.3) relates the body frame to NED for the special case of 2DOF.

The body-fixed velocities u, v and w representing the body velocities in x_b, y_b and z_b direction respectively, are defined by:

$$\boldsymbol{v}^b_{b/n} := \begin{bmatrix} u \\ v \\ w \end{bmatrix} \in \mathbb{R}^3 \tag{2.4}$$

Lastly the body-fixed angular velocities are defined by:

$$\boldsymbol{\omega}^b_{b/n} := \begin{bmatrix} p \\ q \\ r \end{bmatrix} \in \mathcal{S}^3, \tag{2.5}$$

where p, q and r are the rotational velocities around the body axis x_b, y_b and z_b, in that order. The combined body-fixed velocity vector from (2.4) and (2.5) defines the generalized 6DOF velocity vector:

$$\boldsymbol{\nu} := \begin{bmatrix} \boldsymbol{v}^b_{b/n} \\ \boldsymbol{\omega}^b_{b/n} \end{bmatrix} \tag{2.6}$$

To describe the motion and velocities of a vessel precisely, it is necessary to relate these between the body-fixed coordinate frame and the earth-fixed coordinate frame, being the body and NED frame. This is done through a series of $SO(3)$ matrices. These matrices are orthogonal and has a determinant $det(R) = 1$. Consequently, the inverse rotation matrix $R^{-1} = R^T$. The matrices are within the *special orthogonal group of order 3*, and also holds the properties of $O(3)$ matrices:

$$O(3) := \{\boldsymbol{R} | \boldsymbol{R} \in \mathbb{R}^3, \quad \boldsymbol{R}\boldsymbol{R}^{\boldsymbol{T}} = \boldsymbol{R}^{\boldsymbol{T}}\boldsymbol{R} = \boldsymbol{I}\} \tag{2.7}$$

The principal rotations about x_b, y_b and z_b and the angles in (2.2) can be used to decompose the body velocities into NED frame. The principal rotations are given by (2.8):

$$\boldsymbol{R}_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\phi) & -sin(\phi) \\ 0 & sin(\phi) & cos(\phi) \end{bmatrix} \tag{2.8a}$$

$$\boldsymbol{R}_{y,\theta} = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix} \tag{2.8b}$$

$$\boldsymbol{R}_{z,\psi} = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.8c}$$

In guidance and control it is normal to represent the matrices decomposing the velocity vectors from body to NED frame as one matrix multiplication:

$$\boldsymbol{R_b^n(\Theta_{nb})} \coloneqq \boldsymbol{R_{z,\psi} R_{y,\theta} R_{x,\phi}} \tag{2.9}$$

The multiplication results in the following matrix, where the inverse matrix is equal to it's transpose ($\boldsymbol{R^{-1} = R^T}$), and can be used to represent opposite transformation from NED to body.

$$\boldsymbol{R_b^n(\Theta_{nb})} = \begin{bmatrix} cos\psi cos\theta & -sin\psi cos\phi + cos\psi sin\theta sin\phi & sin\psi sin\phi + cos\psi cos\phi sin\theta \\ sin\psi cos\theta & cos\psi cos\phi + sin\phi sin\theta sin\psi & -cos\psi sin\phi + sin\theta sin\psi cos\phi \\ -sin\theta & cos\theta sin\phi & cos\theta cos\phi \end{bmatrix} \tag{2.10}$$

With the use of (2.10), we can express the velocities from (2.4) in NED:

$$\boldsymbol{\dot{p}_{b/n}^n = R_b^n(\Theta_{nb}) v_{b/n}^b} \tag{2.11}$$

As for transforming angular velocity, this follows the transformation matrix $\boldsymbol{T_\Theta(\Theta_{nb})}$ as shown in Fossen (2011):

$$\boldsymbol{T_\Theta(\Theta_{nb})} = \begin{bmatrix} 1 & sin\phi tan\theta & cos\phi tan\theta \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi/cos\theta & cos\phi/cos\theta \end{bmatrix} \tag{2.12}$$

Note that (2.12) is not defined for $\theta \pm 90°$, and that it is not a member of the *special orthogonal group*, hence $\boldsymbol{T_\Theta^{-1}(\Theta_{nb})} \neq \boldsymbol{T_\Theta^T(\Theta_{nb})}$. (2.12) enables the body angular velocities to be represented in terms of NED frame following:

$$\dot{\boldsymbol{\Theta}} = \boldsymbol{T}_{\Theta}(\boldsymbol{\Theta}_{nb})\boldsymbol{\omega}^b_{b/n} \tag{2.13}$$

Being able to relate both linear and angular velocities in NED, the combined is represented in matrix form as in (2.14) and in compact form as in (2.15):

$$\begin{bmatrix} \dot{\boldsymbol{p}}^n_{b/n} \\ \dot{\boldsymbol{\Theta}}_{nb} \end{bmatrix} = \begin{bmatrix} \boldsymbol{R}^n_b(\boldsymbol{\Theta_{nb}}) & \boldsymbol{0}_{3\times3} \\ \boldsymbol{0}_{3\times3} & \boldsymbol{T}_{\Theta}(\boldsymbol{\Theta_{nb}}) \end{bmatrix} \begin{bmatrix} \boldsymbol{v}^b_{b/n} \\ \boldsymbol{\omega}^b_{b/n} \end{bmatrix} \tag{2.14}$$

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}_{\Theta}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{2.15}$$

This concludes the necessary kinematics in order to describe the motion and velocity of the vessel in body and NED frame.

2.4.2 Kinetics

This section covers the rigid-body kinetics typically used for ship simulators, and follows a Newtonian approach. From Sørensen (2011) and Fossen (2011) a process plant model describing the kinetic relationship is given as:

$$\begin{aligned} &\boldsymbol{M}_{RB}\dot{\boldsymbol{\nu}} + \boldsymbol{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{M}_A\dot{\boldsymbol{\nu}}_r + \boldsymbol{C}_A(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{g}(\boldsymbol{\eta}) + \boldsymbol{g}_0 = \\ &\boldsymbol{\tau} + \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{wave} \end{aligned} \tag{2.16}$$

Where the left-hand side consist of: $\boldsymbol{M}_{RB}$ and $\boldsymbol{M}_A$ are the system inertia- and added mass matrix, respectively, $\boldsymbol{C}_{RB}(\boldsymbol{\nu})$ and $\boldsymbol{C}_A(\boldsymbol{\nu}_r)$ are the Coriolis-centripetal matrix and Coriolis-centripetal contribution matrix from added mass, $\boldsymbol{D}(\boldsymbol{\nu}_r)$ is the damping matrix, $\boldsymbol{g}(\boldsymbol{\eta})$ is the vector of gravitational and/or buoyancy forces and moments, and lastly $\boldsymbol{g}_0$ is the vector for pretrimming and ballast control forces and moments. Further, the right-hand side consists of the external force contributions from environmental forces and input forces from the control system, where: $\boldsymbol{\tau}$ is the control input vector, $\boldsymbol{\tau}_{wind}$ is the contribution from wind forces, and lastly $\boldsymbol{\tau}_{wave}$ is the force contribution from waves. Note that the contribution from waves is in some cases divided into first and second order wave forces ($\boldsymbol{\tau}_{wave} = \boldsymbol{\tau}_{wave_1} + \boldsymbol{\tau}_{wave_2}$), depending on application of the model. The contribution from current is implemented in the relative velocity, $\boldsymbol{\nu}_r = \boldsymbol{\nu} - \boldsymbol{\nu}_c$, where $\boldsymbol{\nu}_c$ is the current velocity in the body frame.

2.4.2.1 Linear Maneuvering Model

The model used for validation in this thesis follows the same denotation as described above, but with some modifications. It is based on a linear maneuvering model presented in Perez & Fossen (2007). The model can be seen in (2.17).

$$
\begin{aligned}
&\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}_{RB}\boldsymbol{\nu} + \boldsymbol{C}_{A}\boldsymbol{\nu} + \bar{\boldsymbol{B}}\boldsymbol{\nu} \\
&\quad + \int_0^t \boldsymbol{K}(t-t')[\nu(t') + U\boldsymbol{L}\boldsymbol{\eta}(t')]dt' \\
&\quad + \boldsymbol{G}\boldsymbol{\eta} = \boldsymbol{\tau}^b_{exc} + \bar{\boldsymbol{\tau}}^b
\end{aligned}
\tag{2.17}
$$

The included terms are: $\boldsymbol{M} = \boldsymbol{M}_{RB} + \bar{\boldsymbol{A}}$ is the system inertia- and added mass matrix, $\boldsymbol{C}_{RB} := \boldsymbol{M}_{RB}U\boldsymbol{L}$ is the linearized Coriolis-centripetal force matrix, which consists of the rigid-body mass matrix $\boldsymbol{M}_{RB}$, the vessel speed U, and a selection matrix $\boldsymbol{L}$. $\bar{\boldsymbol{B}}$ is the linear potential flow damping. The Coriolis-centripetal contribution from added mass $\boldsymbol{C}_A := \bar{\boldsymbol{A}}U\boldsymbol{L}$, the convolution term $\int_0^t \boldsymbol{K}(t-t')[\nu(t') + U\boldsymbol{L}\boldsymbol{\eta}(t')]dt'$ represents the fluid memory effects, here the $\boldsymbol{K}(t)$ is a retardation function. The fluid memory effects is the change in fluid momentum due to motion of the vessel hull at a particular time instant, which affects motion of the vessel at all subsequent times (Cummins 1962). $\boldsymbol{G}\boldsymbol{\eta}$ includes gravitational and buoyancy forces, $\boldsymbol{\tau}^b_{exc}$ is the external forces which consits of environmental forces and control input, and lastly $\bar{\boldsymbol{\tau}}^b := \bar{\boldsymbol{B}}\bar{\boldsymbol{\nu}}$ is constant potential damping force, which it later moved to the left-hand side of the equation, and embedded in a linear damping matrix.

It should be mentioned that the model is valid for small deviations from the equilibrium heading, which means that there will be discrepancies during large turning rates. However, this is not of great importance with respect to validation of the online consequence analysis. Equation 2.17 is based on potential flow theory, thus it does not include any viscous forces. Three important effects, which are added to the left-hand side of (2.17) are linear viscous damping, nonlinear surge damping and cross-flow drag.

Linear Viscous Damping

Linear viscous damping is added to the left-hand side of (2.17). A main contributor to this is hull skin friction, and is typically added together with the linear potential damping, as seen in the linear maneuvering model. The linear viscous damping may be modelled as: $\boldsymbol{B}_v\boldsymbol{\nu}$, where $\boldsymbol{B}_v$ is the linear damping coefficient. The total damping in a vessel model is typically divided into a linear and nonlinear part:

$$
\boldsymbol{D}(\boldsymbol{\nu_r}) = \boldsymbol{D} + \boldsymbol{D}_n(\boldsymbol{\nu_r}), \tag{2.18}
$$

where $\boldsymbol{D}$ is the contribution including potential and linear viscous damping, while $\boldsymbol{D}_n(\boldsymbol{\nu_r})$ includes the nonlinear contributions, as described below (Fossen 2011).

Nonlinear Surge Resistance

Nonlinear surge resistance (also referred to as nonlinear surge damping) can be modeled as (Lewis 1989):

$$X = -\frac{1}{2}\rho S(1+k)C_f(u_r)|u_r|u_r, \tag{2.19}$$

where ρ is the density of water, S is the wetted surface area of the hull, k is the form factor, typically $k = 0.1$ for a vessel in transit (Hoerner 1965), u_r is the relative velocity in surge between the vessel and current. Lastly $C_f(u_r)$ is the combined flat plate friction coefficient (C_F) and residual friction due to hull roughness, pressure resistance, wave-making and wave breaking resistance (C_R):

$$C_f(u_r) = \underbrace{\frac{0.075}{(log_{10}Re - 2)^2}}_{C_F} + C_R \tag{2.20}$$

Re is the Reynolds number.

For a vessel at higher speed, it is important to include nonlinear surge resistance in the model, as this dominates at higher speed, while the linear damping term ($\bar{\boldsymbol{B}}$ in (2.17)) is important for low speed and station keeping. A figure explaining this can be seen in Fossen (2011), p.138. Note that the linear damping term is still useful to the model, as it secures exponential velocity convergence to zero.

Cross-Flow Drag

In order to calculate the nonlinear damping force and moment in sway and yaw, respectively, a cross-flow drag model is implemented. Implementation of such model is relevant for current angles $|\beta_c - \psi| >> 0$, where β_c is the current angle of attack, and ψ is the vessel heading (Fossen 2011). This is a strip theory approach where each longitudinal section contributes to the integral (Faltinsen 1990). The implemented integral equation can be written as:

$$Y = -\frac{1}{2}\rho \int_{-\frac{L_{pp}}{2}}^{\frac{L_{pp}}{2}} T(x)C_d^{2D}|v_r + xr|(v_r + xr)dx \tag{2.21}$$

$$N = -\frac{1}{2}\rho \int_{-\frac{L_{pp}}{2}}^{\frac{L_{pp}}{2}} T(x)xC_d^{2D}|v_r + xr|(v_r + xr)dx, \tag{2.22}$$

where Y and N is the force and moment in sway and yaw, respectively, ρ is the density of water, L_{pp} is the length between the vessel perpendiculars, $T(x)$ is the draft as a function of length, C_d^{2D} is the 2D drag coefficient (Hoerner 1965), and lastly v_r is the relative velocity in sway between the vessel and current. The cross-flow principle is based on the assumptions that (i) the flow separates because of cross-flow past the vessel, (ii) the longitudinal components do not influence the transverse forces on a cross section and lastly (iii) the transverse force the main force contribution on a section is caused by separated flow effects on the pressure distribution around the vessel (Faltinsen 2005).

Complete model

Combining (2.17), with (2.21) and (2.22), while following the denotation of Sørensen (2011) and Fossen (2011), we obtain the complete model composed by the kinematic and kinetic model as:

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}_{\Theta}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{2.23a}$$

$$\begin{aligned}(\boldsymbol{M}_{RB} + \boldsymbol{M}_A)\dot{\boldsymbol{\nu}} - \underbrace{\boldsymbol{M}_{RB}U_r\boldsymbol{L}}_{\boldsymbol{C}_{RB}}\boldsymbol{\nu} - \underbrace{\boldsymbol{M}_A U_r \boldsymbol{L}}_{\boldsymbol{C}_A}\boldsymbol{\nu_r} - \boldsymbol{D}\boldsymbol{\nu_r} - \boldsymbol{d}(\boldsymbol{\nu_r})\boldsymbol{\nu_r} \\ - \boldsymbol{G}\boldsymbol{\eta} - \boldsymbol{\mu} = \boldsymbol{\tau^b_{exc}}\end{aligned} \tag{2.23b}$$

where (2.23a) represent the same kinematics model as seen in (2.15), $\boldsymbol{D\nu}$ includes both linear potential damping and linear viscous damping, the convolution term in (2.17) is represented as $\boldsymbol{\mu}$, and the nonlinear surge resistance and cross-flow drag is included in $\boldsymbol{d(\nu_r)}$. The rest of the parameters are described in the sections above.

The two latter equations complete the vessel dynamics used for simulating the vessel in the simulation study.

2.4.3 Current

A model for 3D irrotational current is implemented acting as environmental force in the simulation model, and during simulation of the failure modes according to Fossen (2011). The current is given in a separate coordinate frame, often referred to as the flow frame. The current velocity is given along the x-axis of the flow frame, and can be rotated to NED as follows:

$$\boldsymbol{v}_c^n = \begin{bmatrix} cos(\alpha_c) & 0 & sin(\alpha_c) \\ 0 & 1 & 0 \\ -sin(\alpha_c) & 0 & cos(\alpha_c) \end{bmatrix} \begin{bmatrix} cos(-\beta_c) & -sin(-\beta_c) & 0 \\ sin(-\beta_c) & cos(-\beta_c) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_c \\ 0 \\ 0 \end{bmatrix} \tag{2.24}$$

where β_c and α_c are the side-slip angle and angle of attack, respectively. For the purpose of simulation in this thesis, the angle of attack is assumed zero, $\alpha_c = 0$, hence the equations reduces to 2D. The NED current can further be rotated into body frame by:

$$\boldsymbol{v_c^b} = \boldsymbol{R_b^n}(\boldsymbol{\Theta_{nb}})^T \boldsymbol{v}_c^n \tag{2.25}$$

where $\boldsymbol{R_b^n}(\boldsymbol{\Theta_{nb}})$ is the rotation matrix as seen in subsection 2.4.1.

2.5 Control Theory

How a vessel is controlled can be divided into several layers, based on system complexity, purpose and location. Ludvigsen & Sørensen (2016) shows how this can be divided for an underwater vehicle, this is similar to how a ship or USV can be controlled, hence Figure 2.4 can be used to introduce the following section.

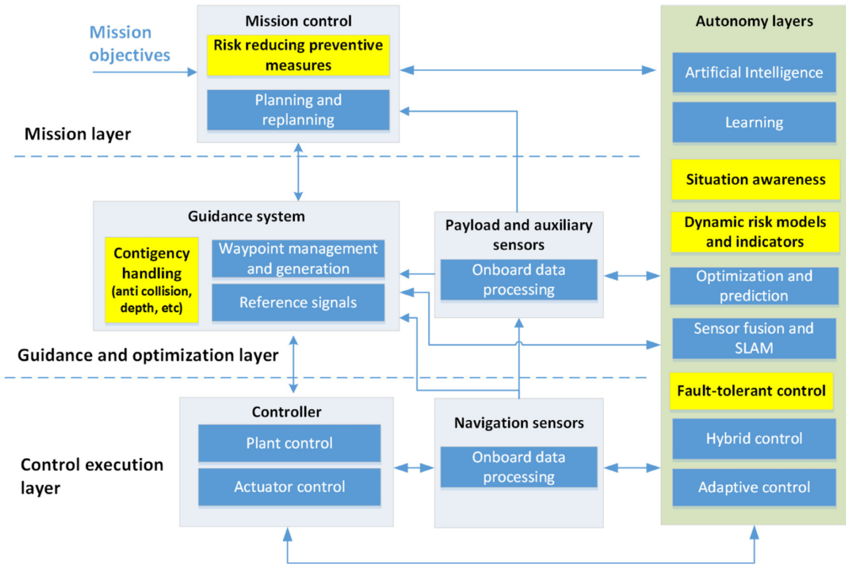


Figure 2.4: Control Architecture, Source: Ludvigsen & Sørensen (2016)

The two controllers described below are the autopilot and speed controller. As it is not part of the thesis scope, there are no actuator models included in the simulation model, thus both controllers are considered "plant controllers" according to the figure, and belong in the control execution layer. Moreover, the guidance system as seen in Subsection 2.5.3 is a lookahead-based steering guidance law, which according to the figure belongs in the guidance and optimization layer. Lastly, the online consequence analysis, which is dependent on the previously described controllers and guidance system to function, is arguably positioned in-between the guidance and optimization level, and mission layer. This, due to its purpose of increasing situational awareness, but also taking part in replanning of mission strategy.

2.5.1 Autopilot

For maneuvering purposes, the two main properties of a control system is the ability to maintain a desired speed and heading, explained in this and the next subsection. There are multiple control laws that can achieve this, but the most commonly used is the PID algorithm, or some variation of it.

The autopilot applied in simulations is given by the PID control law:

$$\tau_N = -K_p\tilde{\psi} - C_{enable}\left(K_i\int_{t_0}^{t}\tilde{\psi}(\tau)d\tau\right) - K_d\dot{\tilde{\psi}} \qquad K_p, K_i, K_d > 0 \tag{2.26}$$

where $\tilde{\psi} = \psi - \psi_d$. In order to avoid integral windup during large step inputs in the desired heading, ψ_d, for instance during switches between waypoints in the guidance system, a constant C_{enable} is added to the algorithm. This is defined by:

$$C_{enable} := \begin{cases} 1, & \text{if} \quad |\tilde{\psi}| \leq \psi_{th} \\ 0, & \text{otherwise} \end{cases} \tag{2.27}$$

where ψ_{th} is a specified threshold, which is set to be larger than the steady state error of the system. t_0 in (2.26) is set equal to the current time when $C_{enable} = 1$ in order to reset the integral term. This results in a controller which for large transients is controlled by the proportional and derivative term, while the integral term is active only in steady state, thus removing potential windup of the integral term.

2.5.2 Speed controller

As for the autopilot design in Subsection 2.5.1, a PI variation of the PID controller is utilized for speed control:

$$\tau_X = -K_p\tilde{U} - C_{enable}\left(K_i\int_{t_0}^{t}\tilde{U}(\tau)d\tau\right) \qquad K_p, K_i, K_d > 0 \tag{2.28}$$

where $\tilde{U} = U - U_d$, and U is the total speed, calculated by:

$$U = \sqrt{u^2 + v^2} \tag{2.29}$$

where u and v is the velocity in surge and sway, respectively. (2.28) is also modified with an anti-windup algorithm in form of C_{enable}, with a specified threshold U_{th} for the speed U, in order to avoid overshoot in the system during large step changes in U_d:

$$C_{enable} := \begin{cases} 1, & \text{if} \quad |\tilde{U}| \leq U_{th} \\ 0, & \text{otherwise} \end{cases} \tag{2.30}$$

2.5.3 Guidance system

For a vessel to be able to steer through a path containing a specified set of waypoints, a guidance law is implemented. The guidance law is used to generate the appropriate input to the autopilot, based on north-east position, distance from the desired path and based on environmental forces acting on the vessel.

A summarized version of the ”Lookahead-Based Steering” covered in (Fossen 2011) is given, as this is essential for the online consequence analysis to function.

The desired course angle $\chi_d(e)$ can be calculated according to:

$$\chi_d(e) = \chi_p + \chi_r(e) \tag{2.31}$$

where $e(t)$ is the cross-track error and the path-tangential angle α_k is the angle between desired path and the north-axis, given by:

$$\chi_p = \alpha_k \tag{2.32}$$

Further on, the velocity-path relative angle is calculated according to:

$$\chi_r(e) := arctan\left(\frac{-e}{\Delta}\right) \tag{2.33}$$

where $\Delta(t)$ is the lookahead distance of the vessel. Both which are illustrated in Figure 2.5. A constant acceptance radius (R) is composed by:

$$e(t)^2 + \Delta(t)^2 = R^2 \tag{2.34}$$

It is possible to use a constant lookahead distance $\Delta(t)$, however allowing this to be time dependent and only restrained by (2.34) allows for a varying control algorithm which behaves more aggressively at large values of $e(t)$ as this results in a smaller $\Delta(t)$, and vice versa. This is easily seen by increasing $e(t)$ or lowering the value of $\Delta(t)$ in (2.33). The lookahead distance can be calculated according to (2.36), while the cross-track error is calculated according to (2.35).

$$e = -(x(t) - x_k)sin(\chi_p) + (y(t) - y_k)cos(\chi_p) \tag{2.35}$$

$$\Delta(t) = \sqrt{R^2 - e(t)^2} \tag{2.36}$$

When the vessel approaches a waypoint $[x_k, y_k]$ switching logic needs to be implemented in order to smoothly transition on to the next waypoint. This logic is performed according to (2.37). As soon as the radial distance from the vessel to the waypoint is smaller than

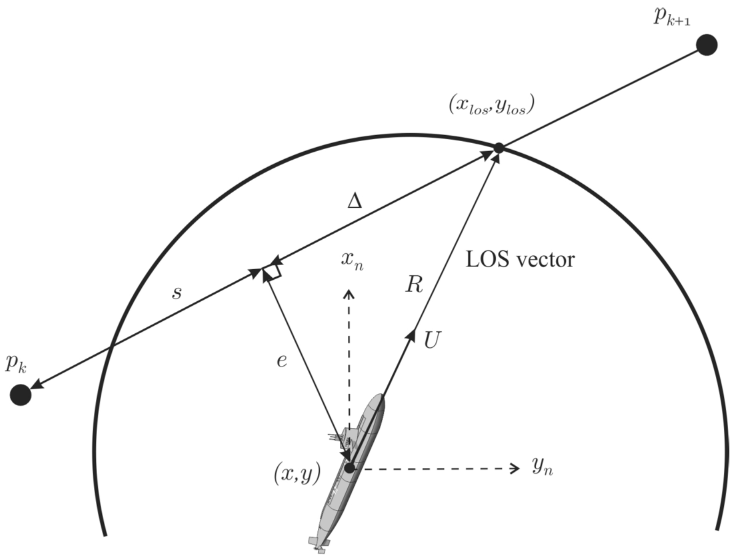


Figure 2.5: Lookahead-Based Steering illustration figure, Source: Fossen (2011)

a specified radius of acceptance. The radius of acceptance is usually set to $R = 2L_{pp}$, which is the case in validation simulations for this thesis.

$$[x_{k+1} - x(t)]^2 + [y_{k+1} - y(t)]^2 \leq R_{k+1}^2 \tag{2.37}$$

Lastly, since the commanded course is given by (2.33), and not by a saturation control law, the desired heading which is used in the previously explained autopilot will be calulated by:

$$\psi_d = \chi_d - \beta \tag{2.38}$$

where ψ_d, χ_d and β are the desired heading angle, desired course and sideslip angle, in that order. The sideslip angle β occurs if the vessel is exposed to transverse current, resulting in a course angle that is different from the vessel heading. The sideslip angle β can be calculated according to (2.39), and is referred to as sideslip compensation,

$$\beta = arcsin\left(\frac{v}{U}\right) \tag{2.39}$$

where v is the sway velocity of the vessel, and U is the total speed.

CHAPTER 3

Online Consequence Analysis - An Approach for Increased Situation Awareness for Autonomous Vessels

This chapter describes the mathematical model and the strategy for developing a novel framework for online consequence analysis (OCA). Bø et al. (2016) has developed a dynamic consequence analysis for vessels in DP operations, but to the author's knowledge this has not been developed for vessels in transit. The dynamic consequence analysis for DP vessels simulates possible failure modes, with the main goal of determining if the vessel can maintain its position and map the transient phase of each failure mode. The framework presented in the following, simulates a selection of failure modes, and determines the consequence level and associated risk, with respect to collision.

Prior to the development of the online consequence analysis, a preliminary specification was developed. This was necessary in order to formalize the expected outcome of the development process, and identify requirements for validation of the concept i.e. requirements for the simulation model and so forth. Parts of these requirements were presented in Section 2.4. The specification can be seen in Section 3.1, and OCA source code is provided in Appendix C.

Figure 3.1 shows a proposed system overview for use in control of marine vessels. It consists of the plant, which represents the vessel dynamics, sensors which measure the different states of the vessel, the observer which combines information from the sensors and the actuator input in order to provide estimates of both the measured and observable states. It also consists of the feedback controllers, which provide the necessary control commands in each degree of freedom, the actuator system allocates the control commands correctly to the different actuators. Lastly, there is a collision avoidance system (CAS) which provides offset values for the controller in order to avoid collisions, and the online consequence analysis (OCA) as described in the following chapter. The CAS is not discussed further, but is included in the figure for illustration purposes and later discussion.

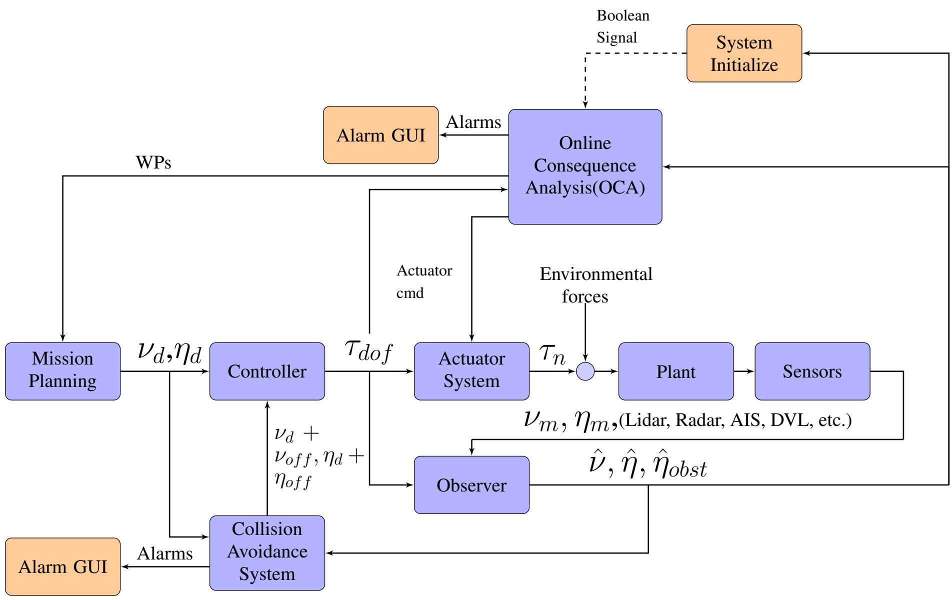


Figure 3.1: System overview, included collision avoidance and online consequence analysis.

Not all of the blocks in Figure 3.1 are necessary in order to simulate the system. The relevant selection of blocks from the figure were presented in Section 2.4 and 2.5, with the exception of the collision avoidance system and online consequence analysis. The collision avoidance system is added in the figure for later discussions, and will not be further described. The online consequence analysis procedure proposed in the thesis is summarized in Figure 3.2, which also serves as an outline for the rest of the chapter (Sections 3.1-3.6).

In addition to Figure 3.1, two figures to help visualize the process are presented in the chapter. One system overview sketch of the online consequence analysis, seen in Figure 3.2, and a flow chart describing the step by step progress of the OCA seen in Figure 3.5. The thesis scope is shown both figures.

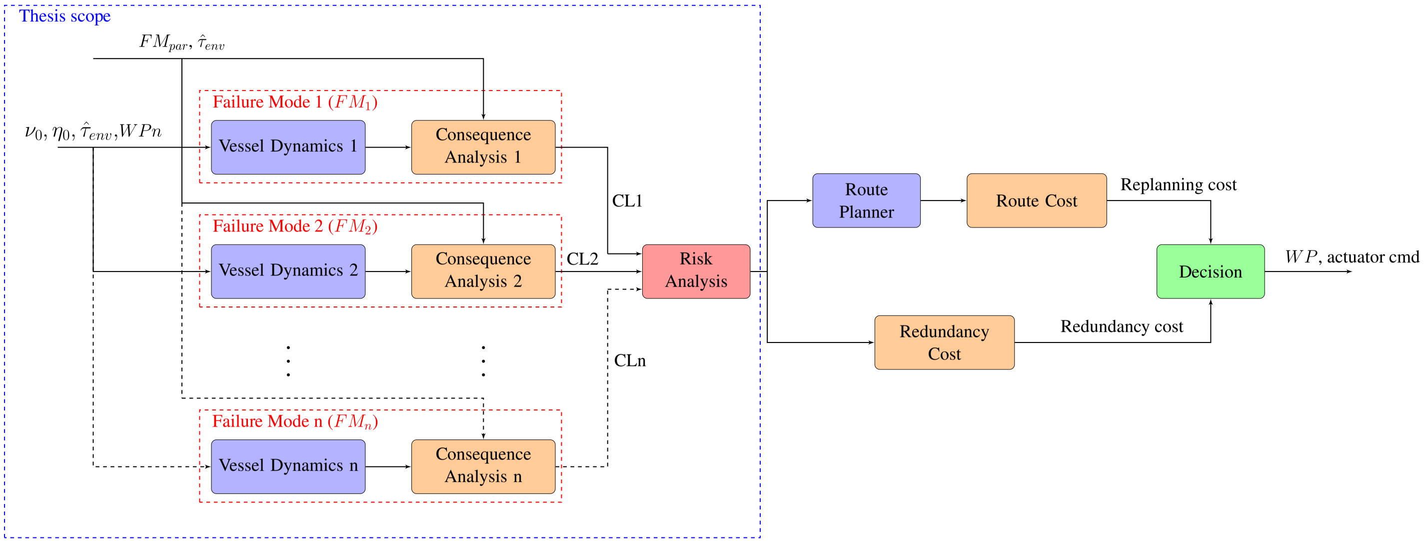


Figure 3.2: Overview, online consequence analysis. The figure illustrates the process executed within the online consequence analysis. The blue blocks represent a result giving analysis, the orange blocks represent post processing of data, the red block is a risk calculation and lastly the green block represents a decision block. Note that the thesis scope includes Vessel dynamics, Consequence Analysis and Risk Analysis. This is marked by the blue rectangle.

3.1 Online Consequence Analysis Specification

An online consequence analysis is to be developed for an autonomous vessel. The consequence analysis should be able to simulate possible failure modes online, and give the operator direct feedback regarding collision risk with surrounding static objects in the event of a partly or total loss of power for a period of time, and while influenced by external environmental forces. The ultimate purpose of such an analysis is to implement it for decision-making purposes in an autonomous system, which operates without human interaction. It is necessary to develop high-level control architecture that is able to evaluate the outcome of an event, in order for an autonomous vessel to perform its operations in a safe and efficient manner.

A consequence analysis can be utilized in different aspects of an autonomous operation. A likely way to utilize this is in the event of information loss, or loss of ability to perform a task. Information loss can be due to sensor failure or the signal can be contaminated by noise for periods of time, which again leads to a decreased situation awareness. Ability loss might be in the instance of a potential power loss during operation, which may lead to collision or other dangerous situations. In both cases, a decision must be made on how to act based on the event.

3.1.1 Example scenario

The following section gives a brief introduction to a simulation scenario which is used to develop and verify the functionality of the online consequence analysis. The example scenario includes all elements from simulation of vessel dynamics through the OCA, to the final decision. This is done to highlight the problem at hand, and it should be noted that some of the elements discussed below are not a part of the thesis scope, but included to give better understanding.

A sketch is provided in order to give a clear explanation of a specific case where such analysis could be of importance in a decision-making process, both by operators or in an autonomous system. Figure 3.3 shows a transit path from point A to B. The black dotted line is the direct path between the two points, the black cross markings with dotted circles around are foreign obstacles that should be avoided (O1-O3), the green line is the desired path with the obstacles and the safety margin (dotted circles) taken into consideration, and the red dotted lines illustrates the vessel path in the event of power loss. Moreover the red circles shows the vessel position, and the red crosses shows where the power loss occurs. Lastly, at point C it is illustrated how the vessel re-plans its path as a possible collision with object O3 might occur.

If the consequence analysis indicates that a collision occurs in the event of power loss, the system shall automatically raise an alarm. This can further be utilized for decision-making. To avoid a collision, the system shall then evaluate the situation and act upon the decision made, e.g. the system checks whether it is better to increase redundancy in the machinery or to re-plan the route, with respect to fuel usage, time or other costs.

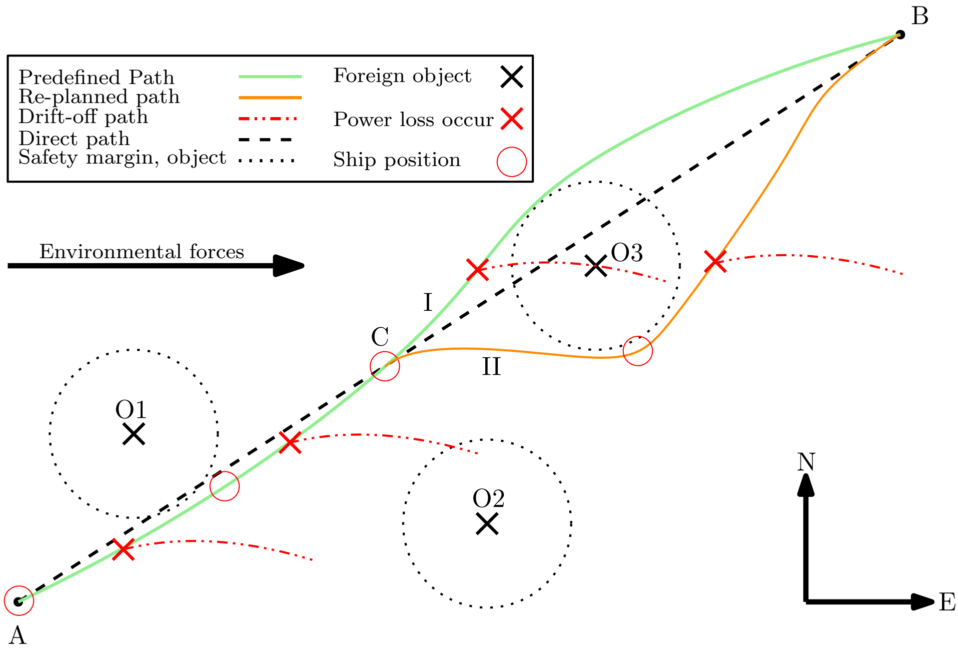


Figure 3.3: Example figure of vessel in transit from A to B.

3.1.2 Simulator Requirements

In order to simulate the above scenario, a simulation model that fulfills the following requirements should be developed:

- The simulation model should capture both steady state and transient maneuvering dynamics of the vessel.
- The model should include an environmental model of current.
- The vessel control system should be able to maintain speed and heading, with compensation for side-slip caused by current.
- It should include a sufficient guidance law so that it is able to follow a predefined path with waypoints.
- Lastly, the simulator should be able to simulate failure scenarios i.e. a percentage power loss, for a given period of time before recovering.

The requirements above are necessary in order to implement a high-level consequence analysis, and it is key that these are functioning properly, before developing the online consequence analysis.

3.2 Failure Modes

As explained by the specification in Section 3.1, the online consequence analysis must be able to simulate a specified number of failure modes (FM_n), and analyze the consequence of each mode. For simulation purposes, a set of four ($n = 4$) failure modes have been implemented.

The modes are:

FM_1: Full power blackout for a specified duration of time. This failure mode simulates a worst case scenario, and does not recover.

FM_2: 80% power loss for a specified duration of time, before the system recovers and continues its mission.

FM_3: 50% power loss for a specified duration of time, before the system recovers and continues its mission.

FM_4: Rudder freeze. In this failure mode the yaw moment is held constant for a period of time, as there are no actuator modeled. Note that a discrepancy in the model occurs during this mode, as movement in surge and sway would change the in-flow on the rudder, making the yaw moment vary. However, this does not affect the ability to showcase the OCA's abilities, thus it is neglected.

The failure mode simulation duration is a parameter which will have to be defined based on each particular vessel's setup. As the OCA may be implemented on any vessel, this would have to be dependent on the specific machinery, power system or in a more general term, the system's ability to recover after a fault occurs. In this thesis, the duration is defined based on the Rules for Classification of Ships, Part 6 Chapter 7 - Dynamic Positioning Systems, which requires a thrust recovery within 45 seconds of a black-out (DNV GL 2014). During simulations in the thesis, this is valid for all the failure modes excluding the 100% black-out, which is simulated longer. The failure scenarios are constructed as examples to showcase the OCA. Others may be relevant as well.

From Figure 3.2 it can be seen that each failure mode is divided into two parts. One covering the simulation of vessel dynamics during the failure mode, and the other covering interpretation of consequence.

3.3 Vessel Dynamics

The vessel dynamics within the online consequence analysis is simulated with the same model as in Equation 2.23, excluding the fluid memory effects[1]. This gives the new model:

[1]The fluid memory effects are removed in the model as they are complicated to implement in the online consequence analysis, and does not take away from the demonstration of the framework proposed in this chapter.

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}_{\Theta}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{3.1a}$$

$$\begin{aligned}(\boldsymbol{M}_{RB} + \boldsymbol{M}_{A})\dot{\boldsymbol{\nu}} - \underbrace{\boldsymbol{M}_{RB}U_r\boldsymbol{L}}_{\boldsymbol{C}_{RB}}\boldsymbol{\nu} - \underbrace{\boldsymbol{M}_{A}U_r\boldsymbol{L}}_{\boldsymbol{C}_{A}}\boldsymbol{\nu_r} - \boldsymbol{D}\boldsymbol{\nu_r} - \boldsymbol{d}(\boldsymbol{\nu_r})\boldsymbol{\nu_r} \\ - \boldsymbol{G}\boldsymbol{\eta} = \boldsymbol{\tau}^{\boldsymbol{b}}_{\boldsymbol{exc}}\end{aligned} \tag{3.1b}$$

When the system is initialized, it samples the initial data from the current position, velocity, information about the environmental forces acting on the vessel, and both active and remaining waypoints from the guidance system. This is seen from Figure 3.2, and can also be seen as the second process in the flow chart of the analysis, Figure 3.5. The OCA simulates the vessel dynamics assuming the environmental forces are constant. This is a reasonable assumption, as the environmental forces acting on the vessel are not likely to change within the relatively small time span simulated by the OCA. A mathematical description of the initial condition sampling is defined as:

$$\boldsymbol{\eta}_{0,FM_n} \coloneqq \boldsymbol{\eta}(T_{0,OCA}) \tag{3.2a}$$

$$\boldsymbol{\nu}_{0,FM_n} \coloneqq \boldsymbol{\nu}(T_{0,OCA}) \tag{3.2b}$$

$$\boldsymbol{WP}_{0,FM_n} \coloneqq \boldsymbol{WP}(T_{0,OCA}) \tag{3.2c}$$

$$\boldsymbol{\tau}_{env,0,FM_n} \coloneqq \boldsymbol{\tau}_{env}(T_{0,OCA}) \tag{3.2d}$$

Once the initial conditions are set, the vessel dynamics in the OCA is simulated for T_{sim} seconds, for each of the failure modes. These are solved in parallel, and the results are presented simultaneously. The plant dynamics are implemented as a for-loop which iterates through an Euler integration of the vessel plant equations, controllers and guidance system. It is necessary to include the controller and guidance system, in order to capture the behavior once it recovers from the failure modes.

Implementation of the Euler integration is done according to Appendix B in Fossen (2011):

$$\begin{aligned}\boldsymbol{\nu}(k+1) = \boldsymbol{\nu}(k) + h(\boldsymbol{M}_{RB} + \boldsymbol{M}_{A})^{-1}[\boldsymbol{M}_{RB}U_r\boldsymbol{L}\boldsymbol{\nu}(k) + \boldsymbol{M}_{A}U_r\boldsymbol{L}\boldsymbol{\nu_r}(k) \\ + \boldsymbol{D}\boldsymbol{\nu_r}(k) + \boldsymbol{d}(\boldsymbol{\nu_r}(k))\boldsymbol{\nu_r}(k) + \boldsymbol{G}\boldsymbol{\eta}(k) + \boldsymbol{\tau}_{exc}]\end{aligned} \tag{3.3a}$$

$$\boldsymbol{\eta}(k+1) = \boldsymbol{\eta}(k) + h[\boldsymbol{J_\Theta}(\boldsymbol{\eta}(k))\boldsymbol{\nu}(k+1))], \tag{3.3b}$$

where k is the integration step number, and h is the step size. After completion of one failure mode simulation, the resulting vessel positions in NED, and body velocities, are given as a fixed-size vector:

$$\boldsymbol{\eta}_{FM_n} = [\boldsymbol{\eta}(h) \;\; \boldsymbol{\eta}(2h) \;\; \boldsymbol{\eta}(3h) \;\; \ldots \;\; \boldsymbol{\eta}(nh)] \tag{3.4a}$$

$$\boldsymbol{\nu}_{FM_n} = [\boldsymbol{\nu}(h) \;\; \boldsymbol{\nu}(2h) \;\; \boldsymbol{\nu}(3h) \;\; \ldots \;\; \boldsymbol{\nu}(nh)] \tag{3.4b}$$

Once the results of each failure mode is obtained, the consequence analysis calculates the consequence level of each failure mode, as explained in the next section. As Figure 3.2 shows, there is one vessel dynamics simulation occurring per failure mode that is included in the online consequence analysis. The main model initiates the OCA, which then pauses the main simulation, simulates all the failure mode dynamics, before proceeding the main simulation in the next time step. This way of simulating the system is assumed to be sufficient as the dynamics of a vessel in a real life scenario would be slow compared to the computation time of the simulation models. Ideally, the online consequence analysis should be simulated in parallel with the main simulation, however, this requires extensive knowledge of software development, and is not a part of the thesis scope.

The model is built and simulated with the help of the computer software MATLAB, Simulink and MSS toolbox (MathWorks 2018, Fossen & Perez 2004). The system dynamics are simulated within Simulink, with the help of an embedded MATLAB function. In order to initialize the system at any time, extensive use of the ”enable” block in Simulink was done, as this allows for a subsystem (in this case the embedded matlab function) to be triggered, preventing this from running at every time step. This also opens for further work in terms of creating a sophisticated way of initializing the system, and determining what frequency the OCA should run at. This will be discussed further in the general discussion, seen in Chapter 5.

3.4 Consequence Level

In order to calculate the highest consequence level a single failure mode produces, a definition of how the levels are to be interpreted is needed. The interpretation of consequence level is chosen to be dependent on radial distance from the vessel to a known object. The objects and their positions are assumed to be known at all times. For convenience during implementation of the simulation model, a set of three circles are defined around the object, to function as three levels of consequence. The levels range from $L1$ to $L3$, where $L1$ is the circle with largest radius and $L3$ the smallest. The consequence levels are arranged such that $L1$ corresponds to the lowest consequence level and $L3$ to a worst case scenario: collision. Even though a consequence level where the vessels position is within $L1$ or $L2$ does not result in collision, it is fair to evaluate these as consequence levels, as a situation might change rapidly, and where the end goal is to avoid even coming close to a collision.

An illustration of the vessel position and consequence levels can be seen in Figure 3.4. The process of evaluating the consequence levels consists of four steps:

Step: 1 Iterate through the simulated possible future scenarios (3.4a) and calculate the smallest distance between the objects and vessel. This can be done according to:

$$\bar{\boldsymbol{r}}_{O,min} = min([\bar{\boldsymbol{r}}_O(h) \;\; \bar{\boldsymbol{r}}_O(2h) \;\; \dots \;\; \bar{\boldsymbol{r}}_O(nh)]), \tag{3.5}$$

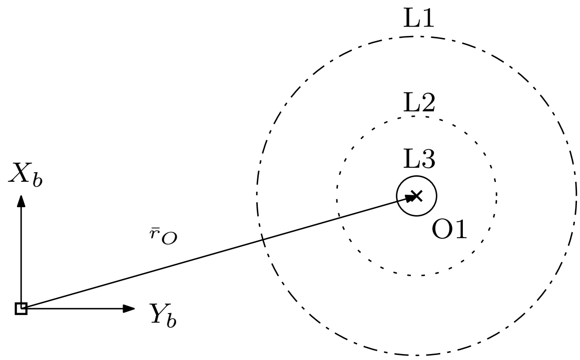


Figure 3.4: Illustration of the distance between vessel and object, including distance levels interpreted as consequence levels. The vessel position is at the origin of the body frame.

where $\bar{\boldsymbol{r}}_{O,min}$ is the smallest distance between an object and the vessel from the possible future positions provided by (3.4a). The distance can be calculated according to:

$$\bar{\boldsymbol{r}}_O = \sqrt{(\boldsymbol{\eta}_N(h) - \boldsymbol{\eta}_{O,N})^2 + (\boldsymbol{\eta}_E(h) - \boldsymbol{\eta}_{O,E})^2}, \tag{3.6}$$

$\boldsymbol{\eta}_N$ and $\boldsymbol{\eta}_{O,N}$ is the vessel position and object position respectively, in North direction. $\boldsymbol{\eta}_E$ and $\boldsymbol{\eta}_{O,E}$ is the corresponding positions in East.

The calculation above is done for all the known objects surrounding the vessel. The output from **Step 1** is a vector containing the smallest distance between the vessel and each object:

$$\bar{\boldsymbol{r}}_{O,min} = [\bar{\boldsymbol{r}}_{O1,min} \;\; \bar{\boldsymbol{r}}_{O2,min} \;\; \dots \;\; \bar{\boldsymbol{r}}_{Oq,min}] \tag{3.7}$$

Step: 2 The second step checks if and which of the objects that need to be analyzed further based on (3.7). By comparing the smallest distances with the largest radial level of each object, the relevance of further analysis is determined:

$$\bar{\boldsymbol{r}}_{Oq,min} < R_{L1}, \tag{3.8}$$

where R_{L1} is the radius defining consequence level 1. A vector containing a boolean high for each relevant object and vice versa for non-relevant objects is defined, which is also the return from step 2:

$$\bar{\boldsymbol{O}}_{rel} := [O1_{bool} \;\; O2_{bool} \;\; \dots \;\; Oq_{bool}] \tag{3.9}$$

Note that the process of sorting the relevant objects to investigate is strictly not necessary. However, as the remaining analysis may include nested for-loops, the analysis becomes a

$O(N^2)$ computation, hence increasing the runtime (Savitch 2016). By keeping the number of iterations low as of only evaluating relevant objects, this decreases runtime.

Step: 3 Investigates the relevant objects based on (3.9). By iterating through the results from (3.4a) a matrix containing information about level violation, and when it occurs is defined:

$$\boldsymbol{VL} := \begin{bmatrix} \boldsymbol{CL}_{O1}(h) & \boldsymbol{CL}_{O2}(h) & \dots & \boldsymbol{CL}_{Oq}(h) \\ \boldsymbol{CL}_{O1}(2h) & \boldsymbol{CL}_{O2}(2h) & \dots & \boldsymbol{CL}_{Oq}(2h) \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{CL}_{O1}(mh) & \boldsymbol{CL}_{O2}(mh) & \dots & \boldsymbol{CL}_{Oq}(mh) \end{bmatrix}, \tag{3.10}$$

where the violation matrix ($\boldsymbol{VL}$) is an $m \times q$ matrix, where h is still the step size, m is the row number representing the time step index, and q is the column number, representing the corresponding objects, e.g. $\boldsymbol{CL}_{Oq}(mh)$ is the consequence level in time step m, for object q.

The consequence levels are determined by the same approach as in (3.8), but is performed for all predefined radial levels (R_{L1}, R_{L2} and R_{L3}) to determine the max violation level.

Step: 4 Lastly, the consequence levels as seen in (3.10) are evaluated to determine the maximum consequence level that occurs during the failure mode analysis. This is given by:

$$\boldsymbol{CL}_{max} = max(\boldsymbol{VL}) \tag{3.11}$$

where $\boldsymbol{CL}_{max}$ is the maximum level during the simulation, among all relevant objects. By defining VL as shown in (3.10) it is possible to determine when each level is violated, since it includes consequence level for each time step. This is not further implemented, but is included for further implementation work.

Summarizing the steps for evaluating the maximum consequence level for each failure mode, it starts with determining the smallest distance from the vessel to all known objects, the relevant objects for further analysis are then sorted in a vector. Further, a violation matrix is provided, which includes the violation level of all relevant objects, in every time step of the dynamics analysis. Lastly, the maximum violation level of the analysis is returned.

3.5 Online Risk Indicator

Once the previous sequence of simulating the failure modes and calculating their respective consequence levels (if any), an online risk indicator is developed by assigning a level for probability of occurrence for each failure mode, and further use these in combination with the provided consequence levels. A vector containing the maximum consequence level for each failure mode is defined:

$$\boldsymbol{CL}_{FM,max} \coloneqq [CL_{FM_1,max} \;\; CL_{FM_2,max} \;\; \dots \;\; CL_{FM_n,max}] \tag{3.12}$$

Varde & Pecht (2018) defines a quantitative measure of the total risk as:

$$R \coloneqq \sum_i P(FM_i)CL_{FM_i,max} \tag{3.13}$$

where $P(FM_i)$ is the probability of occurrence for failure mode i and $CL_{FM_i,max}$ is the associated consequence level, given by (3.12). The probabilities will in this thesis be assumed, and is provided as a vector defined as:

$$\boldsymbol{P}(FM_i) \coloneqq [P(FM_1) \;\; P(FM_2) \;\; \dots \;\; P(FM_n)] \tag{3.14}$$

Lastly, the risk level related to each failure mode is calculated, and the failure mode that is associated with the largest risk is presented. This is useful information in terms of decision-making, which will be discussed in the next section.

3.6 From Risk to Decision: A Brief Discussion

Figure 3.5 gives a summary of the OCA procedure that has been introduced. Notice that the thesis scope ends with realization of the risk indicator, (3.13), as seen in Figure 3.2 and Figure 3.5. The remaining steps from risk to decision will briefly be discussed in the following.

As the consequence analysis is meant to be either a supervision tool or ultimately a tool that can take direct part in decision-making, it makes sense to mention further thoughts regarding this. Figure 3.5 also consists of a route planner and a route- and redundancy cost function. It is suggested that the risk indicator is evaluated against a risk threshold, and by violation of this, initiate replanning of the mission strategy, i.e. a route with lower associated risk or increased redundancy in power system. Once the route is replanned, a simultaneous evaluation of cost functions for the new route, and a cost of increased redundancy e.g. running more generators, will be performed. The cheapest option when comparing the costs, will function as the decision-maker and a command should be returned to either the machinery and actuator system or the mission planning block, as seen in Figure 3.1. Deciding what these cost functions are based on remains for further work, but the author suggests evaluating maximization of fuel efficiency, minimization of time, or minimizing deviation from the original path. The returned command from the OCA will for autonomous systems (LoA-3/4) be an input in the following analysis conducted by the OCA, thus always using the most recent and accurate information when analyzing.

In cases where the risk indicator may fluctuate, the OCA may return similar fluctuating commands to the machinery of mission planning system. This is particularly relevant for the machinery system as startup procedure may take long, which could potentially damage components in the machinery system. If this behavior occurs a criteria that the total risk should be lower than a threshold, for a specified time duration, before readjusting the number of generators/machineries running. Such a criteria will lower the risk of damage in the machinery system.

As briefly mentioned in the previous section, the risk indicator also returns information regarding which failure mode results in the highest risk. This information might be important in the decision-making process. If for example the outcome of a rudder freeze is associated with a higher risk compared to a partial power loss, the foundation for making a correct decision might include this information in the process, instead of solely making the decision based on the cheapest cost.

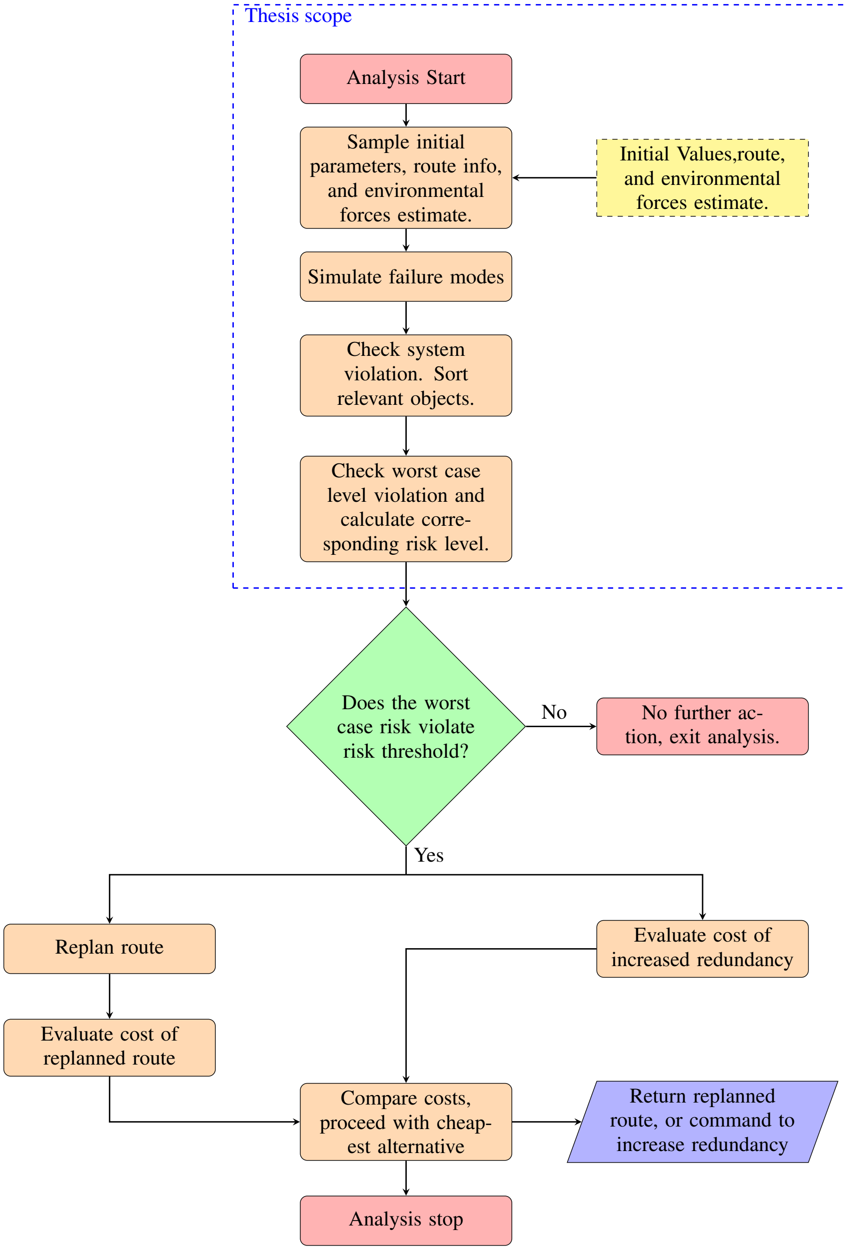


Figure 3.5: Online Consequence Analysis, Flow chart. The flow chart explains the full procedure from start to decision-making. The red blocks are describing start and finish, the orange are processes, the green diamond is a decision block, the yellow an input block and lastly the blue block is an output. The thesis scope is marked by the blue rectangle.

CHAPTER 4

Case Study: Simulation, Online Consequence Analysis

To better illustrate the functionality of the proposed framework for the online consequence analysis, as described in Chapter 3, a case study was conducted. The case study is divided into five sections in total, one section that briefly validates the model behavior and four sections that illustrates the different scenarios.

As previously mentioned, the simulator is built using MATLAB, Simulink and MSS toolbox, and is based on the NTNU-owned and operated research vessel R/V Gunnerus (MathWorks 2018, Fossen & Perez 2004). The vessel's cruising speed is assumed to be $U = 5.1$ m/s $\approx$ 10 knots, as seen in Appendix B. The results from the scenarios considered in the case-study are presented in terms of the same five plots each, making it easy to compare and contrast the results. A general description of the five plots follows below. The setup and layout of each scenario is thoroughly explained in their corresponding subsections. The two first scenarios are in open water, while scenario 3 and 4 consider a narrow channel passage.

The five plots presented consist of:

1. North-East plot of the vessel's path and position, as well as objects known to the vessel throughout the main simulation (the simulation emulating the "real" vessel dynamics). The plot also highlights when the failure modes occur, and the simulated path conducted by the online consequence analysis. Also marked in the figure are the recovery points from each failure mode, as described in Section 3.2. Lastly, the plot shows the consequence levels in proximity of the obstacles, and the different desired waypoints that the vessel follows. The different details are annotated in the figure legends. In order to keep the plot readable a selection of the consequence

analyses are plotted. The dynamics simulated by the online consequence analysis will be referred to as OCA-n (X s), where n is the number of the online consequence analysis during the main simulation, and (X s) is the corresponding time of the OCA in the main simulation.

2. A zoomed selection of the North-East plot. It highlights a single result from the online consequence analysis, which is the basis for discussion.

3. The third plot shows the consequence level evaluation done by the OCA, with respect to time in the main simulation. The figure includes four subplots corresponding to each failure mode. Each spike in the plot corresponds to the consequence level at that time in the main simulation, e.g. OCA-n (X s) is the consequence level from analysis number n, which occurs at X seconds in the main simulation. Note that the online consequence analysis returns negative one (-1) if no consequence levels are violated during that failure mode simulation. This is done in order to easily distinguish each analysis performed by the OCA, and to validate that the OCA returned a result.

4. Two subplots make the fourth figure. The first subplot shows the relative total risk with respect to time. This plot displays the current risk level, divided by the maximum possible risk. The second subplot shows which failure mode during the OCA run that corresponds to the highest risk, amongst the simulated failure modes in the OCA.

5. The last plot is a risk matrix presenting the one failure mode from each OCA run which has the highest risk amongst the failure modes in that OCA run. All the OCA runs during one main simulation (the simulation emulating the ”real” vessel dynamics) are presented as a diamond marker in the risk matrix, which plots the consequence level against probability of occurrence. The consequence level and probability of occurrence are scaled to fit within axes from 0 and 1.

Note that τ_{env} indicated by the black arrow in the North-East plots represent the environmental forces acting on the vessel, in this case, current. The current velocity is set to $U_c = 1.5$ m/s, which is higher than one would normally expect. The exaggeration is done to better illustrate the environmental force effect during simulation of the failure modes, but also to compensate for the fact that wind and wave forces are not included in the model. It should also be noted that the consequence level radii are predefined and kept constant. These are equal to 50 m, 25 m, and 5 m, corresponding to the first, second and third level, respectively. The probability of occurrence for each failure mode, as described in Section 3.5, is assumed equal to $\boldsymbol{P}(FM_i) = [0.05 \;\; 0.15 \;\; 0.38 \;\; 0.25]$. The probability values are exaggerated for the purpose of illustrating the framework, and should be considered merely as relative levels between the failure modes.

The online consequence analysis is initiated every 15 seconds ($T_{init} = 15$), and the failure modes as described in Chapter 3 are simulated for 45 seconds before recovering, with the exception of 100% power loss, also referred to as black-out, which is simulated for 250 seconds.

A general discussion regarding the case study results is given in Chapter 5.

4.1 Simulator Validation

Before results from the online consequence analysis are presented, a brief discussion of the simulation model's validity is necessary. A scenario was simulated in order to see how the model behaves, and to clarify any anomalies.

The scenario which is simulated in order to validate the behavior of the simulation model is a straight line path from $[0, 0]$ m to $[1000, 0]$ m, where the coordinates represent the North and East coordinate in NED, respectively. The main simulation model is programmed to experience a full power black-out when the vessel passes $[500, 0]$ m.

Figure 4.1 shows that the vessel immediately after initialization, experiences a trajectory offset as it initially does not compensate for the current force. The vessel parameters are deliberately not initialized at their equilibrium values in order to cause a transient response during the first part of the simulation. The offset is corrected by sideslip compensation, which takes some time to stabilize as it depends on sway velocity and total speed of the vessel (see (2.38)).

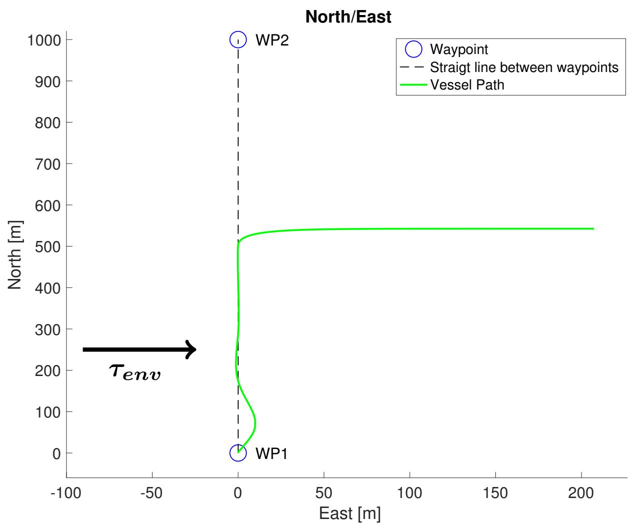


Figure 4.1: North/East plot, validation scenario.

Figure 4.2 shows the North, East position, heading, surge and sway velocity, and lastly the turning rate of the main simulation. Once the vessel passes $[500, 0]$ m at approximately 100 s into the simulation, the online consequence analysis starts to simulate the power loss scenario. Both main and OCA simulation starts to drift with the current at this point. This means that it is expected that the surge velocity decays exponentially due to the linear damping. The online consequence analysis is able to simulate the same dynamics. Furthermore, the equilibrium heading stabilizes at a constant value, as expected, due to viscous forces and moments acting on the hull. It is noted that the Munk moment which may contribute to the equilibrium heading of the vessel, is not included in the simulator. However, cross-flow drag is most likely the dominant nonlinear contribution at low forward speed in this simulator (Faltinsen 2005). In other words, the equilibrium heading when the vessel is moving along with the current might have been different if the Munk moment was implemented, however, it does not affect the results in terms of showcasing the OCA framework. Notice that the sway velocity is also different from zero, as the vessel compensate for sideslip.

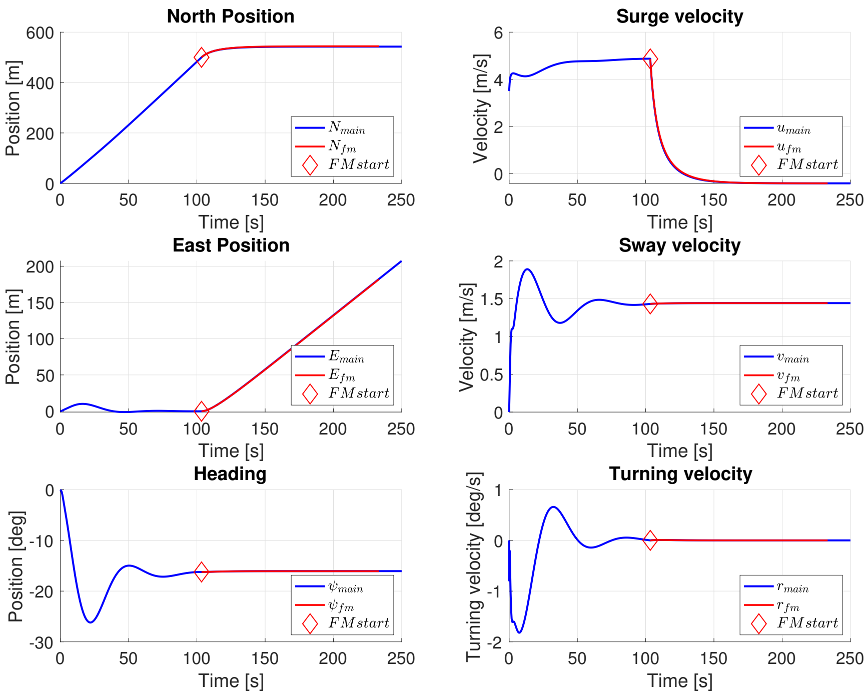


Figure 4.2: 3DOF η and ν comparison, validation scenario. The blue line shows the main simulation results, while the red line indicates the dynamics simulated by the OCA. The diamond marker indicate the start of each OCA simulation.

The largest error between the main simulation (emulating the “real” vessel dynamics) and the OCA simulation has in this validation showed to be negligible, and is not presented in a separate figure. This is error magnitude is considered ok, as the OCA would never be able to represent the real world dynamics perfectly. Lastly the total vessel speed is presented in Figure 4.3. The result from the total speed is as expected, an exponential decrease converging towards the current speed of $U_c = 1.5$ m/s.

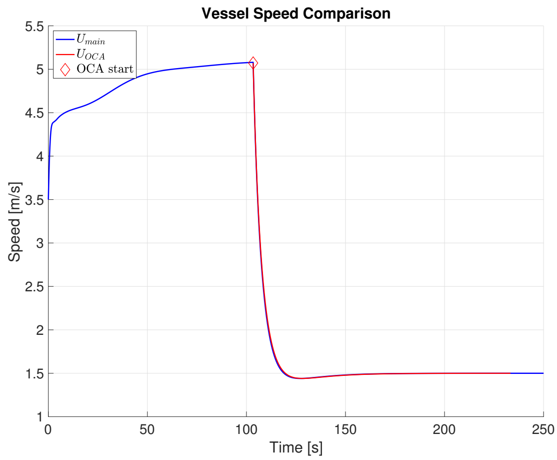


Figure 4.3: Vessel speed for main simulation and OCA simulation, validation scenario. The blue line shows the main simulation speed, while the red line indicates the speed simulated by the OCA. The diamond marker indicate start of the OCA simulation.

4.2 Scenario 1: Straight Line Transit

Simulation Setup

An overview over Scenario 1 is shown in Figure 4.4. It consists of a path made up of the waypoints $[0, 0]$, $[150, 0]$ and lastly $[500, 0]$. One obstacle is placed at $[275, 50]$. The current direction is along the positive East-axis, indicated by the black arrow in Figure 4.4.

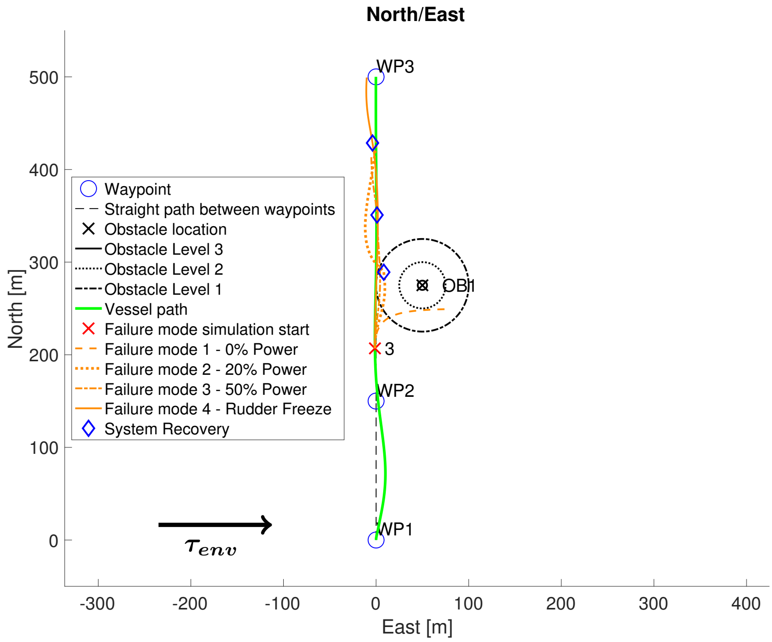


Figure 4.4: Scenario 1: North East plot of the vessels path, with a selection of consequence analysis results. The results from OCA run number 3 (45 s) are shown.

Results

Figure 4.4 shows that the system has an offset value in the positive East direction in the beginning. This is caused by the current, which is present and constant during the entire simulation. This behavior is to be expected by the model, as the current is introduced as a step function, and not a gradually increasing one. The autopilot depends on sideslip compensation in order to follow a straight path while influenced by current. It takes some time for the sideslip compensation to stabilize, as it is dependent on sway velocity and vessel speed (see (2.39)). The rather large offset is caused by the exaggerated current velocity.

Looking closer at the zoomed portion of the plot in Figure 4.5, it is observed that none of the failure modes simulated by OCA-3 (45 s) violates a higher consequence level than level one. Based on observations from Figure 4.5, it is expected that each of the failure modes show a consequence level of one when in the proximity of the obstacle, and negative one otherwise. Recall that each spike in Figure 4.6 represent the OCA runs, where during the OCA runs, the main simulation is paused.

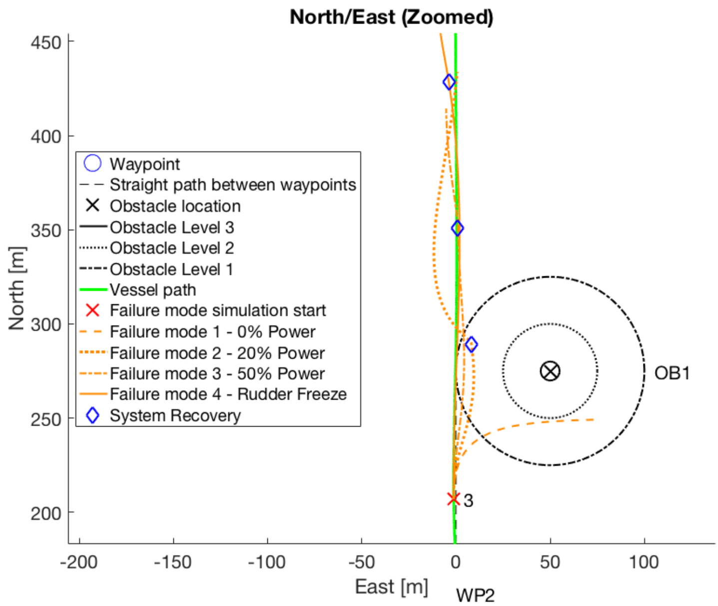


Figure 4.5: Scenario 1: Zoomed portion of the North East Plot

It is observed that OCA-2 (30 s) violates consequence level 1, caused by failure mode 3.

Figure 4.6 shows that OCA-2 (30 s) (not shown in Figure 4.4) indicates a level 1 violation. The number of failure modes that indicates violation is expected to increase, as the vessel is approaching the obstacle with cruising speed, and given the position of the obstacle with respect to the vessel path. OCA-3 (45 s) in Figure 4.6 shows that each of the failure modes does indeed signal a level one violation, which is in accordance with the observations made in Figure 4.5. It is also observable from Figure 4.6 that failure mode 1 in OCA-4 (60 s) results in a level 1 violation. Note that OCA-4 (60 s) is not shown in Figure 4.4. The remaining of OCA runs in the main simulation does not show any violation of consequence levels, which is expected since the vessel has passed the obstacle and given the direction of the current, risk of collision should disappear.

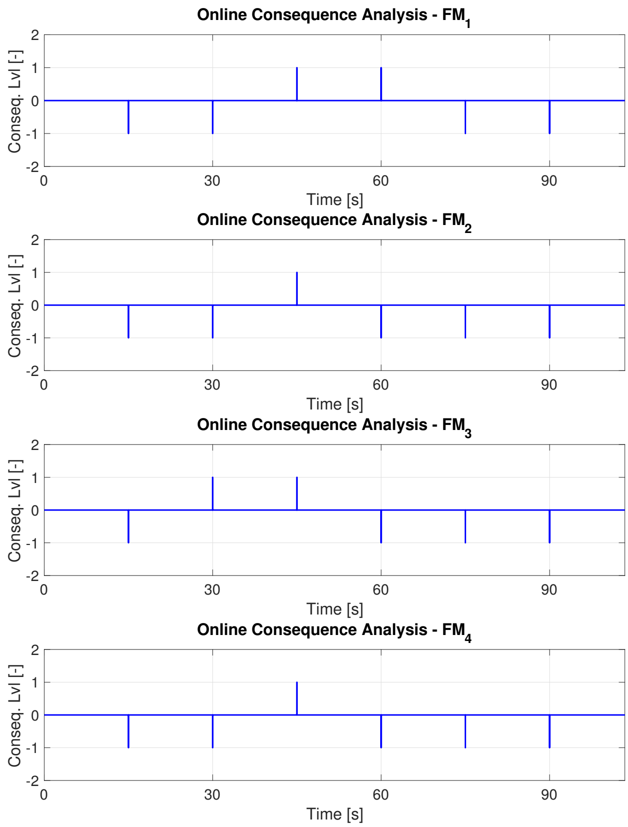


Figure 4.6: Scenario 1: This figure shows how the different failure modes in the consequence analysis and the corresponding consequence level, versus time. Each spike on the plot y-axis illustrates the consequence level from the consequence analysis carried out at that time (referred to in the text as OCA-n (X s), where n is the online consequence number and X is seconds into the main simulation). If the result is equal to -1, it indicates that failure mode simulation did not violate any of the consequence levels.

Examining Figure 4.7, the online risk indicator follows a similar trend as the consequence levels in Figure 4.6. The difference is that the risk indicator is dependent on the probability level for each failure mode, $\boldsymbol{P}(FM_i) = [0.05 \;\; 0.15 \;\; 0.38 \;\; 0.25]$, where the first element in the vector corresponds to the probability level of failure mode one, and so forth. Due to fact that OCA-2 (30 s) had a level 1 violation in failure mode 3, the total risk slightly increases as a function of this. Furthermore, the risk indicator is drastically increased at 45 seconds. This is due to the fact that all the failure modes violate consequence level 1 in OCA-3 (45 s). It is also observed from the figure that the failure mode that causes the highest risk is failure mode 3, which is to be expected, as it has the highest probability of occurrence. Lastly, OCA-4 (60 s) shows a decrease in total risk due to only violating consequence level 1 in failure mode 1 which corresponds to a total power black-out with the lowest probability of occurrence, thus the total risk level reduces drastically.

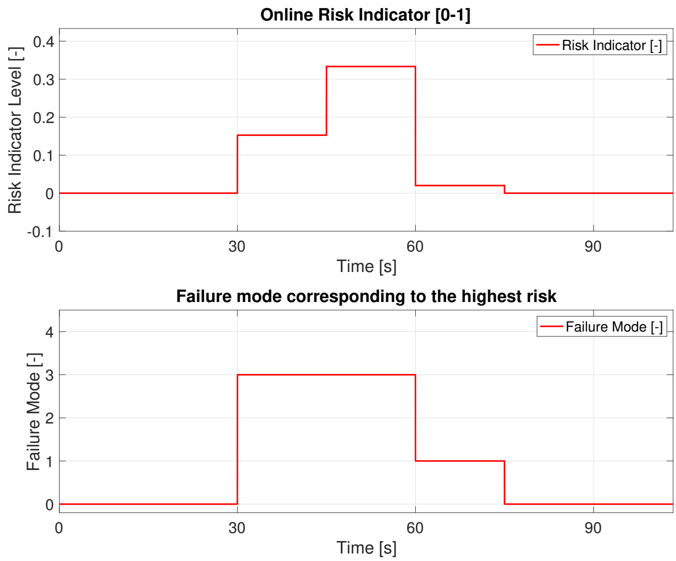


Figure 4.7: Scenario 1: The upper plot shows the online relative total risk indicator, defined from 0 to 1. The lower plot shows the failure mode corresponding to the highest risk.

The last figure, Figure 4.8, shows the risk matrix containing results from each OCA run. Each of the diamond markers presented in the matrix corresponds to the consequence level and probability of occurrence for the failure mode during a single OCA run that generates the largest risk. In accordance with Figure 4.5 and Figure 4.6, it is observed that the highest risk is caused during OCA-2 (30 s) and OCA-3 (45 s), which makes sense considering that failure mode 3 has a higher probability of occurrence, compared to the others. In other words, although the total risk based on OCA-3 (45) is higher compared to OCA-2 (30 s) it is still failure mode 3, 50% power loss, that has the highest probability of occurrence thus the single failure mode risk is equal for OCA-2 (30 s) and OCA-3 (45 s).

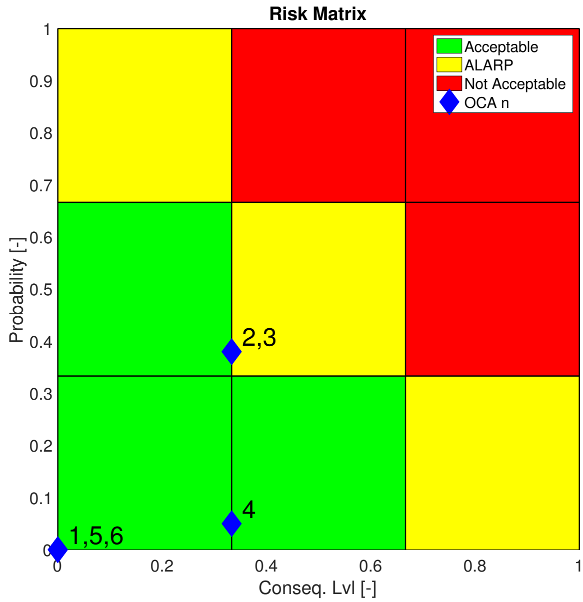


Figure 4.8: Scenario 1: Risk matrix showing the consequence level and probability of occurrence corresponding to the failure mode with the highest risk from each consequence analysis run. The numbering corresponds to consequence analysis n (OCA-n) as referred to in the text.

4.3 Scenario 2: Maneuvering

Simulation Setup

An overview of the second scenario can be seen in Figure 4.9. The second scenario consists of a path with the waypoints $[0, 0]$, $[100, 100]$, $[1000, 100]$ and lastly $[1200, -300]$. Known to the vessel are four obstacles, which it navigates between. The obstacles are placed at $[400, 175]$, $[800, 175]$, $[600, -175]$ and $[1150, 100]$. Similar to the first scenario, the current direction is along the positive East-axis, indicated by the black arrow in Figure 4.9.

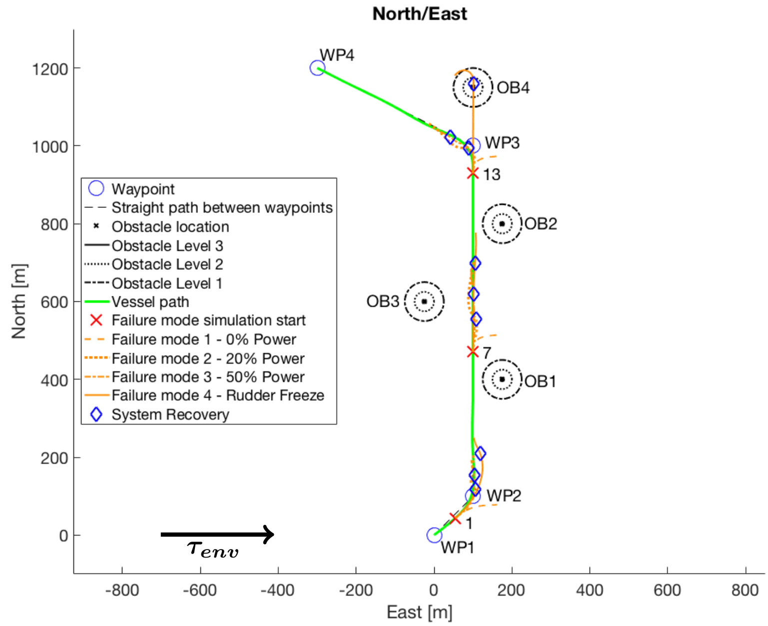


Figure 4.9: Scenario 2: North East plot of the vessels path, with a selection of consequence analysis results. The different OCA runs are numbered, where each number n represent OCA-n, as described in the text.

Results

As the scenario consists of more complex maneuvering compared to the first scenario, the fourth failure mode, which corresponds to the rudder freezing for a period of 45 seconds, is considered the most severe type of failure. Therefore the discussion in this section evolves around rudder freeze. Similar to the first scenario, the vessel experiences an offset along the positive East-axis, due to the immediate presence of current. It is also observed from Figure 4.9 that failure mode 4 in OCA-1 (15 s) causes the vessel to overshoot the intended path, as the rudder freezes. OCA-7 (105 s) in the figure shows to have no violation at all, thus it is reasonable to expect zero total risk at 105 s in the main simulation, which is later confirmed by Figure 4.12.

OCA-13 (195 s), zoomed in Figure 4.10, shows a level 3 violation for failure mode 4, rudder freeze. It is observed from the figure that if a 45 seconds long rudder freeze were to take place, the recovery would happen too late. This would lead to a collision given that the vessel maintains speed. This is brought to the readers attention because the rudder freeze in this case follows a completely straight line, where you would expect the vessel to gain an offset or turn in either directions. The reason for this is that the fluid flow dynamics around the rudder are not modeled, and the current is completely uniform. In a real scenario, the current and other environmental forces would not be constant and the rudder would not behave perfectly. An implementation of rudder dynamics and a varying current in the model, could make this more realistic. The variable current may be implemented as a Gauss-Markov stochastic process (Fossen 1994).

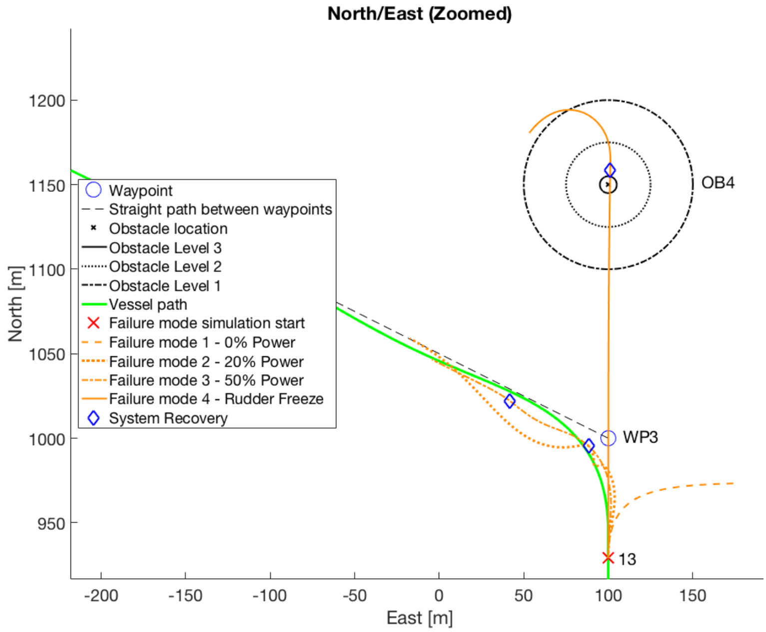


Figure 4.10: Scenario 2: Zoomed portion of the North East Plot

OCA-1 (15 s) in Figure 4.11 shows the expected outcome as discussed based on Figure 4.9. The vessel is at this stage far away from any obstacles in the vessel's proximity, hence the online consequence analysis returns negative one (-1) for all failure modes. It was mentioned earlier that in a case of rudder freeze, the vessel would overshoot its desired path. However, this is not important in terms of risk of collision. OCA-7 (105 s) shows a similar consequence level as OCA-1 (15 s), the vessel will at this time have passed obstacle 1 (OB1) in Figure 4.9, this the OCA returns no consequence level violation for OCA-7 (105 s). Keeping in mind that the vessel have just passed obstacle 1 (OB1) when OCA-7 (105 s) is conducted, it is expected that there might be a violation level from the consequence analyses performed just in front of OB1 and while the vessel is along side it. This is true, and Figure 4.11 shows that OCA-5 (75 s) and OCA-6 (90 s) both violates consequence level 1, in failure mode 1. Note that OCA-5 (75 s) and OCA-6 (90 s) are not shown in Figure 4.9.

Shown in Figure 4.9, OCA-13 (195 s) simulates a collision with obstacle 4 (OB4). This is confirmed by Figure 4.11, in failure mode 4, rudder freeze. It can also be seen that OCA-12 (180 s) returns a level 1 consequence level violation in the same failure mode. This illustrates that the frequency of the OCA may be to low. An increase in frequency would most likely capture the violation of level 2 in a separate OCA run, which could show to be important in decision-making, as the risk level would increase earlier, thus a replanning of the mission strategy could be initiated earlier. This is thoroughly discussed in Chapter 5.

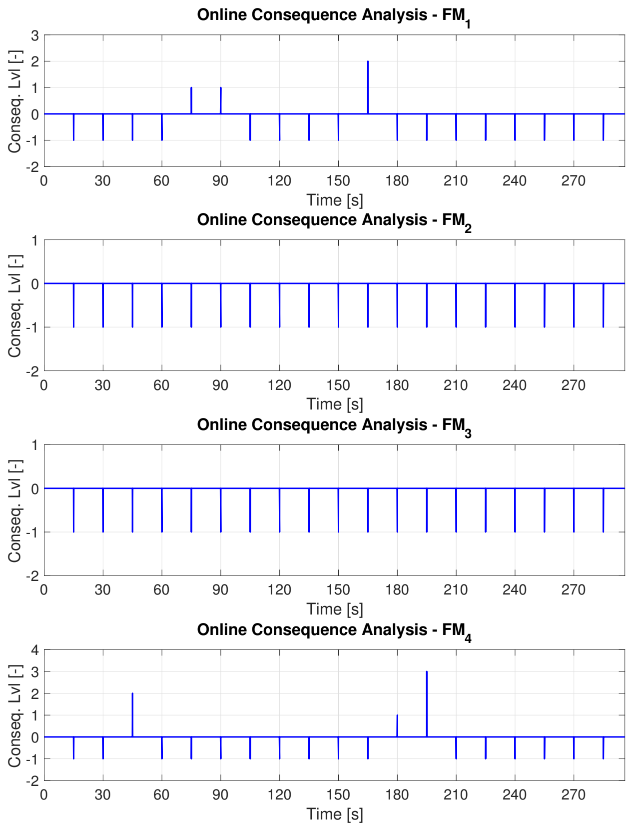


Figure 4.11: Scenario 2: This figure shows how the different failure modes in the consequence analysis and the corresponding consequence level, versus time. Each spike on the plot y-axis illustrates the consequence level from the consequence analysis carried out at that time (referred to in the text as OCA-n (X s), where n is the online consequence number and X is seconds into the main simulation). If the result is equal to -1, it indicates that failure mode simulation did not violate any of the consequence levels.

The risk indicator in Figure 4.12 confirms the previous observations from the North-East plot (Figure 4.9) and the consequence levels in Figure 4.11. OCA-1 (15 s) shows zero indication in the total risk, as expected. OCA-3 (45 s) has not previously been discussed, however this OCA run causes a level 2 violation in failure mode 4, rudder freeze, as the vessel passes obstacle 1 (OB1) as seen in Figure 4.9. This causes the first increase in total risk from 45 s to 60 s. The next increase in total risk between 75 s to 105 s is cause by failure mode 1 in OCA-5 (75 s) and OCA-6 (90 s). Since the second increase is caused by failure mode 1, total power black-out, the associated risk is small due to the low probability of occurrence ($P(FM_1) = 0.05$).

From 165 s to 210 s in risk indicator (Figure 4.12), there is a substantial increase in risk. The first step is caused by OCA-11 (165 s) (not shown in Figure 4.9) as failure mode 1, total power black-out, simulates a consequence level violation 2 when the vessel passes obstacle 2 (OB2). Furthermore, the previously discussed OCA-12 (180 s) and OCA-13 (195 s) further increase the risk level as failure mode 4, rudder freeze, simulates the hazardous situation with obstacle 4 (OB4) as seen in Figure 4.9. The rest of the simulation has a risk level zero, which is expected, since there are no more obstacles in close proximity. This does not mean that none of the remaining OCA runs after OCA-13 (195 s) will simulate a direction towards an obstacle, but it means that since the vessel recovers after 45 s it will most likely not collide with the obstacle.

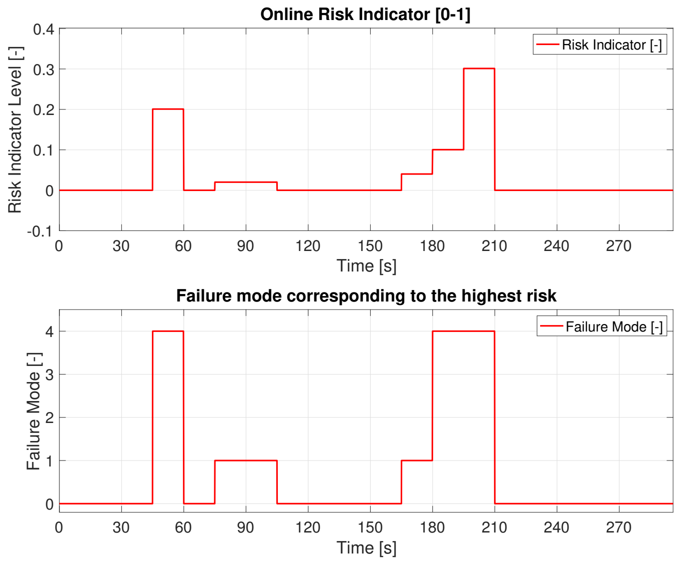


Figure 4.12: Scenario 2: The upper plot shows the online relative total risk indicator, defined from 0 to 1. The lower plot shows the failure mode corresponding to the highest risk.

Figure 4.13 shows that the majority of the conducted consequence analyses do not generate any risk for individual failure modes. The exceptions are that OCA-3 (45 s), OCA-11 (165 s) and OCA-13 (195 s) indicates substantial risk, as previously discussed. Note that the risk levels according to Figure 4.13 are low. This is because figure only represents the worst case of a single failure mode. A similar risk matrix which plotted the total consequence against total probability would probably consist of a higher risk level.

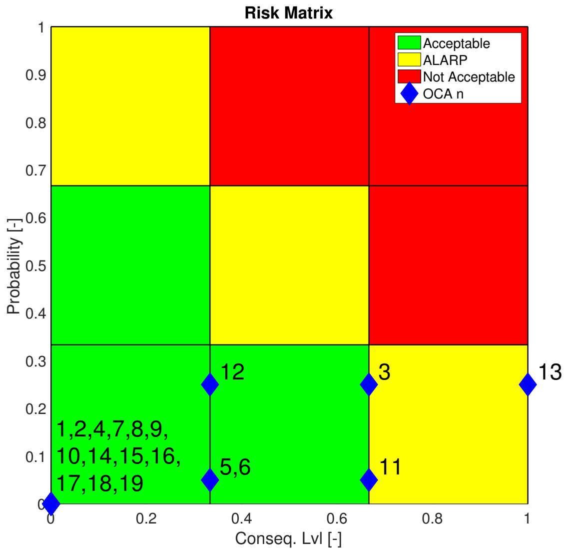


Figure 4.13: Scenario 2: Risk matrix showing the consequence level and probability of occurrence corresponding to the failure mode with the highest risk from each consequence analysis run. The numbering corresponds to consequence analysis n (OCA-n) as referred to in the text.

4.4 Scenario 3: Narrow Channel Passage

Simulation Setup

The third scenario consists of a narrow channel passage, see Figure 4.14. The vessel follows the path specified with waypoints: $[200, 0]$, $[140, 480]$, $[140, 950]$, $[900, 1625]$ and $[1600, 1350]$. There is one obstacle known to the vessel, located at $[230, 100]$. The channel is modeled by a large number of obstacles densely placed along a line, thus creating a wall. Similar to single obstacles, the consequence levels are modeled as the distance perpendicular to the wall. The current direction is $135°$ in the clockwise direction from the North-axis, making the current flow in the negative North direction, and positive East direction. The current direction in this scenario is not realistic considering the channel geometry, however wind is, and as current is used to compensate for lack of a wind model, the direction is thought appropriate for illustration. The current direction is indicated by the black arrow marker in Figure 4.14. Consequence analyses OCA-1 (15 s), OCA-8 (120 s), OCA-15 (225 s), OCA-22 (330 s) and OCA-29 (435 s) are highlighted in Figure 4.14, out of a total of 35 analyses conducted during the simulation.

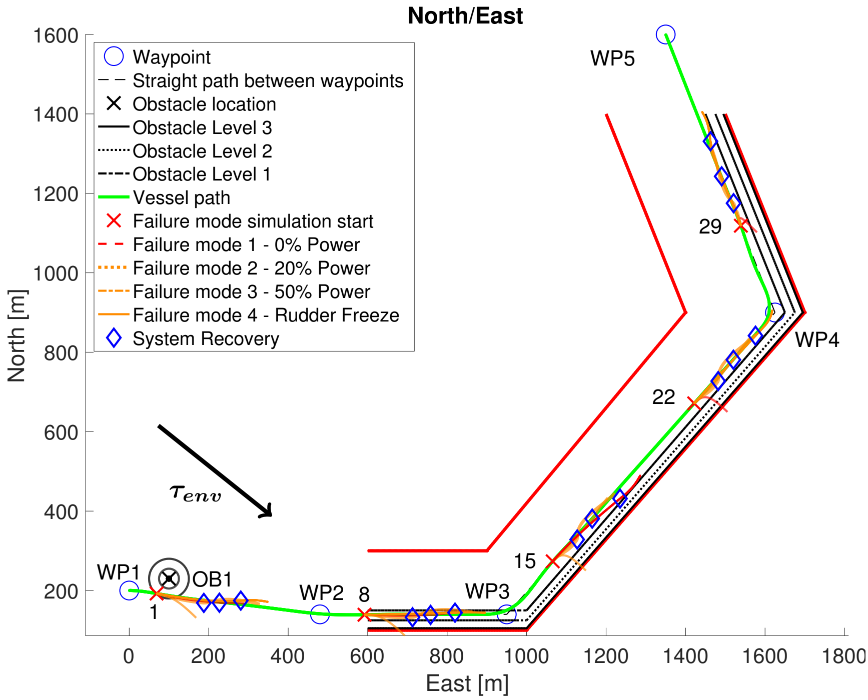


Figure 4.14: Scenario 3: North East plot of the vessels path, with a selection of consequence analysis results. The different OCA runs are numbered, where each number n represent OCA-n, as described in the text.

Results

The main difference between this and scenario 1 and 2 is that instead of the vessel operating in open water, it now navigates through a narrow channel passage. The scenario was constructed in order to open for a discussion of the OCAs capabilities in a channel passage with respect to COLREGs, which was introduced in Section 2.3. A thorough discussion of the OCA's compliance with COLREGs is given in Chapter 5, while direct observations with respect to the scenario are made here.

The general expected outcome of the scenario is a low risk level at the beginning and as the vessel enters the channel passage, it is expected that the risk will increase due to the direction of the current forces, and the fact that the vessel navigates close to the channel wall on its starboard side. This is illustrated in Figure 4.14, which shows that amongst the highlighted OCA runs, OCA-1 (15 s) is the only one which is not affected by the channel passage. Due to the current direction it is expected that failure mode 1, total power black-out, in OCA-8 (120 s) will result in a consequence level 3 violation: collision. Similar results are also expected for OCA-15 (225 s) and OCA-22 (330 s) as the current is in beam direction on the vessel. Figure 4.15 verifies the expected behavior, and it is observed from the figure that OCA-22 (330 s) would in fact reach a consequence level 3. Lastly, and similar to OCA-8 (120 s), the highlighted OCA-29 (435 s) shows that the power black-out is the failure mode which visually from Figure 4.14 may cause a hazardous situation.

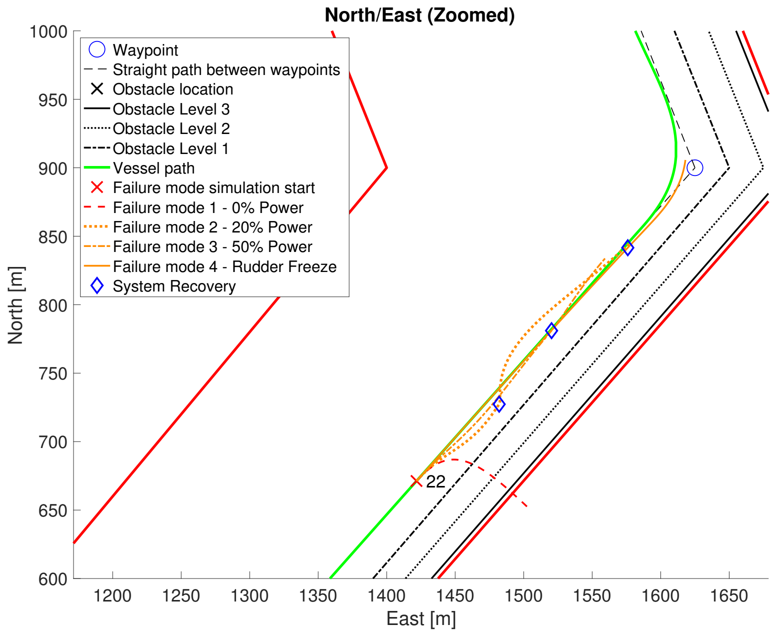


Figure 4.15: Scenario 3: Zoomed portion of the North East Plot

The main information to note from Figure 4.16 and Figure 4.17 is the increased number of consequence level violations and the overall increase in total risk during the vessels journey through the channel. A key capability of the online consequence analysis is the ability to capture this increased risk, enabling it to be used as a foundation for decision-making in the future. Figure 4.16 confirms the previously expected results, and it becomes clear that especially failure mode 1 continuously violates one of the three consequence levels while the vessel is inside the narrow channel passage.

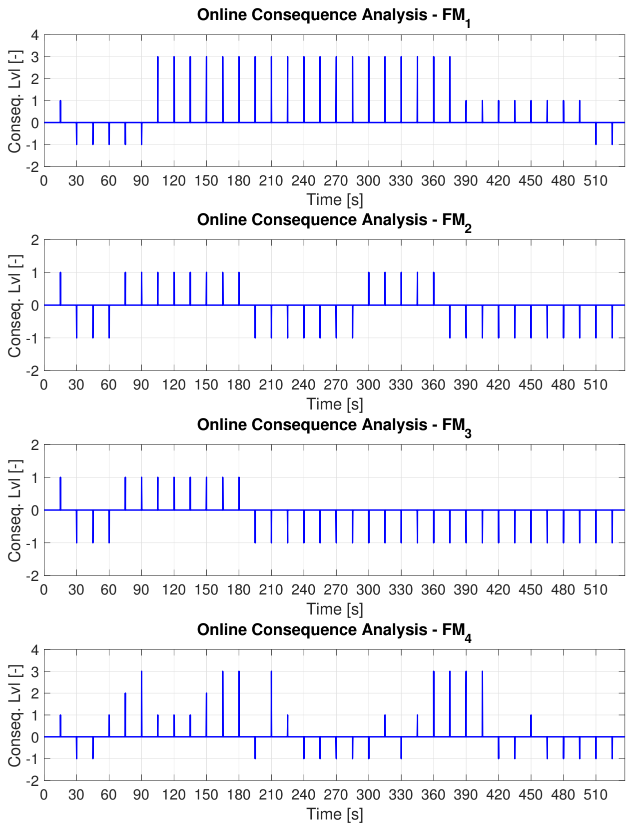


Figure 4.16: Scenario 3: This figure shows how the different failure modes in the consequence analysis and the corresponding consequence level, versus time. Each spike on the plot y-axis illustrates the consequence level from the consequence analysis carried out at that time (referred to in the text as OCA-n (X s), where n is the online consequence number and X is seconds into the main simulation). If the result is equal to -1, it indicates that failure mode simulation did not violate any of the consequence levels.

The risk indicator in Figure 4.17 shows an increase in risk from 15 s to 30 s, which occurs due to obstacle 1 (OB1) as seen in Figure 4.14. The indicator then settles at zero for a short duration of time, and at 75 s the vessel enters the channel, raising the risk level substantially. Also contributing to the raised risk level is failure mode 4, rudder freeze, as seen from Figure 4.16, this occasionally violates consequence levels, which also creates a fluctuating behavior of the risk indicator. The fluctuation may be beneficial as it allows for a finer resolution of the total risk, thus increasing situation awareness. However, this should be further investigated further, as a high-resolution risk indicator that fluctuates a lot, may give contradictory commands when/if replanning the mission strategy occurs.

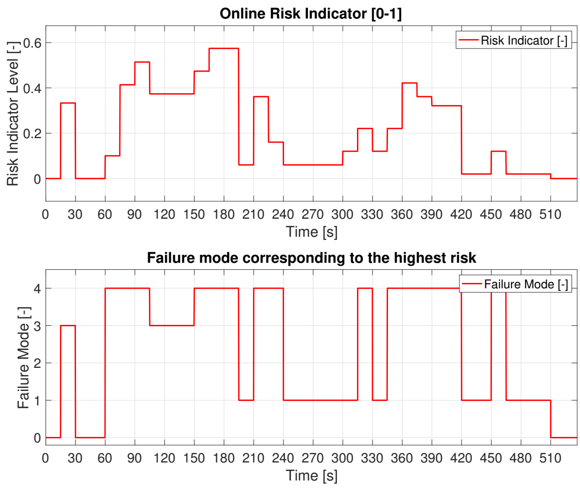


Figure 4.17: Scenario 3: The upper plot shows the online relative total risk indicator, defined from 0 to 1. The lower plot shows the failure mode corresponding to the highest risk.

Lastly, the risk matrix shows the general increase in risk for many of the consequence analysis simulations, as seen in Figure 4.18. It is observed that a large portion of the conducted OCA runs give a worst case result with consequence level 3 violation results. Intuitively, collision should indicate a risk in the red section of Figure 4.18. This is not the case due to a low probability of occurrence. The results are in accordance with the observations made in Figure 4.14 and Figure 4.16, many of the conducted consequence analyses returned violation in failure mode 1, total power black-out and 4, rudder freeze.

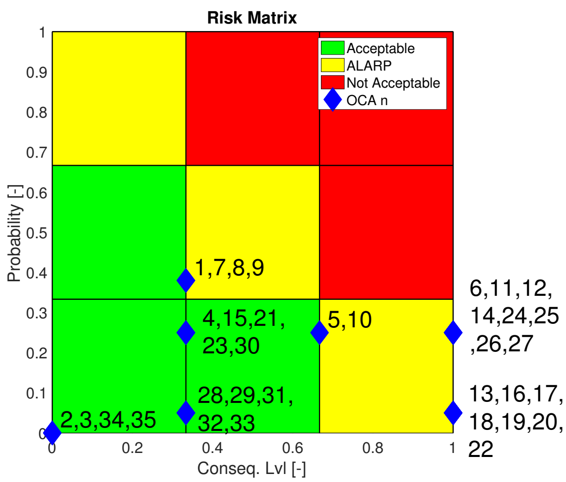


Figure 4.18: Scenario 3: Risk matrix showing the consequence level and probability of occurrence corresponding to the failure mode with the highest risk from each consequence analysis run. The numbering corresponds to consequence analysis n (OCA-n) as referred to in the text.

4.5 Scenario 4: Narrow Channel Passage

Simulation Setup

The fourth and last scenario is equal to the third scenario, except that the online consequence analysis is run at an interval of $T = 3.75$ s, instead of $T = 15$ s. This is conducted solely to investigate the difference in resolution of the online consequence analysis and risk indicator, thus only the consequence analysis results and risk indicator plots described in the chapter introduction are presented.

Results

Figure 4.19 shows an obvious increase in number of consequence analyses conducted here compared to in the third scenario. The results of this, is an increase in resolution for the risk indicator, which can both be beneficial and have a negative impact on a later decision-making process. A clear and beneficial result of the increased resolution can be observed when comparing the risk indicators in Figure 4.17 and Figure 4.20. The readers attention is directed towards the interval 45 s to 75 s in both risk indicators. A clear difference between the two, is that the one corresponding to scenario 4 increases the total risk earlier compared to the one in scenario 3. When studying the interval between 360 s and 390 s it is seen that the risk indicator from scenario 4 detects a large reduction in risk for a short period of time. It may be argued that not being able to detect a decrease in risk may be regarded as conservative, however as the previous example (interval 45 s to 75 s) indicated, the earlier raise in total risk was not captured in scenario 3, thus increasing the frequency seems to increase the overall understanding of risk associated with the mission. How to determine a correct frequency for the OCA will be further discussed in Chapter 5.

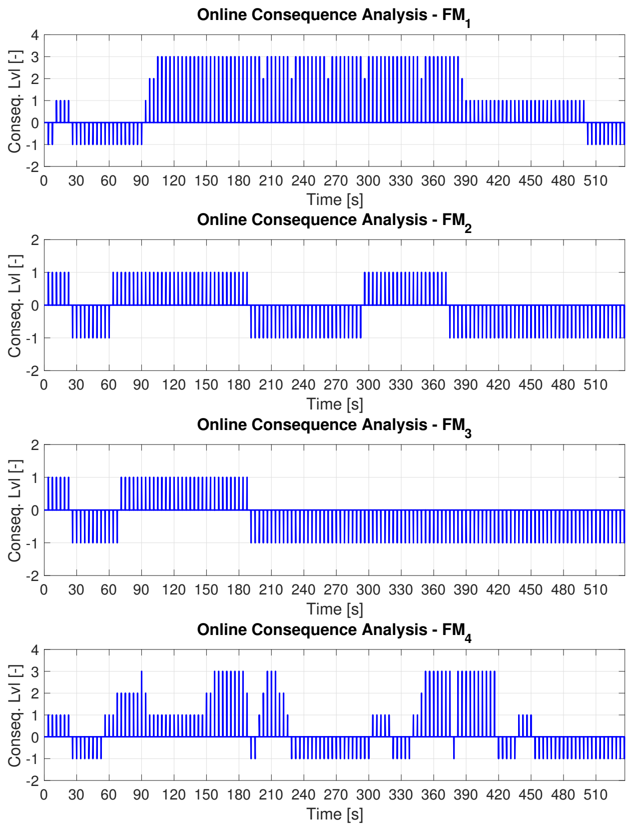


Figure 4.19: Scenario 4: This figure shows how the different failure modes in the consequence analysis and the corresponding consequence level, versus time. Each spike on the plot y-axis illustrates the consequence level from the consequence analysis carried out at that time (referred to in the text as OCA-n (X s), where n is the online consequence number and X is seconds into the main simulation). If the result is equal to -1, it indicates that failure mode simulation did not violate any of the consequence levels.

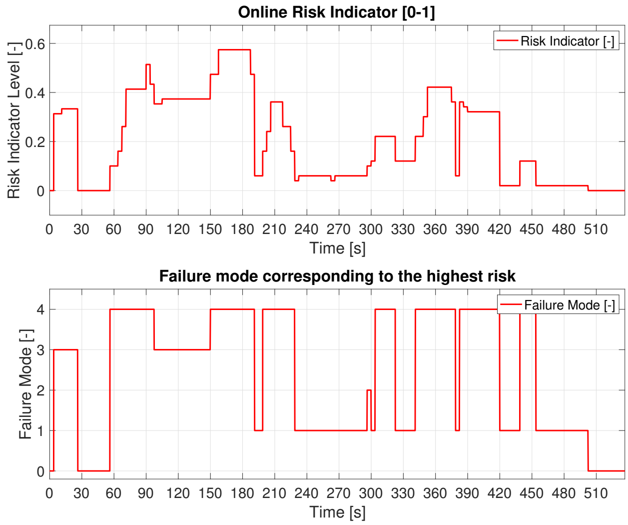


Figure 4.20: Scenario 4: The upper plot shows the online relative total risk indicator, defined from 0 to 1. The lower plot shows the failure mode corresponding to the highest risk.

CHAPTER 5

Discussion

This chapter provides a discussion about the proposed framework for the online consequence analysis, and how a vessel employing the proposed framework would position itself with respect to level of autonomy taxonomies (LoA). It also covers a discussion regarding the importance of how the vessel perceives information about its surroundings, a discussion of how to best initialize the system and how to determine the different consequence levels. Another discussed topic is the OCA's role and placement in a control system hierarchy. We further discuss how decision-making may be conducted by the OCA before ending the discussion by considering how the developed framework may cope with the COLREGs regulation.

The above mentioned discussion topics are chosen amongst an immense selection. There are other topics that could have been discussed as well. There is a lack of literature on the topic, and a lot of questions have emerged during the thesis. The following discussion will only cover the most relevant ones.

5.1 Main Outcome

The main outcome of this thesis is the proposed framework for an online consequence analysis for a manned or unmanned surface vessel. The framework contributes to increased situation awareness, and a better foundation for decision-making. As previously covered by Section 2.1, a lot of different taxonomies has been developed for autonomous systems, based on different industries. The taxonomy used as a reference during this thesis is the one proposed by Ludvigsen & Sørensen (2016), which is divided into four levels.

It is difficult to precisely position a vessel equipped with the online consequence analysis within a specific level of autonomy. However, if the proposed framework is implemented together with systems that are designed to utilize the output of the analysis, such as: route planner, route cost, redundancy cost and decision block, as seen in Figure 3.2, this positioning will be easier. A system containing all these steps would allow for decision-making which directly influences the mission strategy of an autonomous operation, based on the associated risk. Such a system could be considered to belong to an autonomy level of LoA-3 to LoA-4. It is likely that a framework like the online consequence analysis would be implemented on a vessel, and monitored by a surveillance center which either would be placed onboard the vessel, or on land. LoA-3, management by exception corresponds well with the explained functionality of the OCA. The flowchart in Figure 3.5 underlines this, as the system makes a decision on its own, then returns a command based on the decision to the mission planning part of the control system, as seen from Figure 3.1. A key factor that allows for LoA-3 categorization compared to LoA-2, management by concent, is the decision-making process. An LoA-2 system would do the same calculations, but it would not conduct the last decision call without confirmation from a human operator, while the LoA-3 system would, unless canceled within reasonable time by the operator.

As the proposed OCA framework simulates failure modes in order to calculate the associated risk with respect to collision, the vessel's ability to perceive information about its surroundings is a premise, which will be further discussed in the following section.

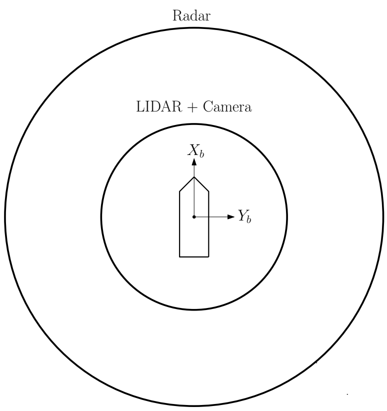
5.2 Perception of the Vessel Surroundings

A requirement for the online consequence analysis to efficiently increase situation awareness, is the vessel's ability to perceive detailed information about its surroundings. Background material on situation awareness was presented in Section 2.2, which covered a definition made by Endsley (1995). The definition is divided into three elements, where perception is the first element to master in order to obtain situation awareness. The second and third element are comprehension and projection of the perceived information. The online consequence analysis framework will help with the second and third element. It will contribute to the systems comprehension of its surroundings with the help of the online risk indicator, but also in a way help with projection of the future as the system simulates the outcome of possible future failure that may occur.

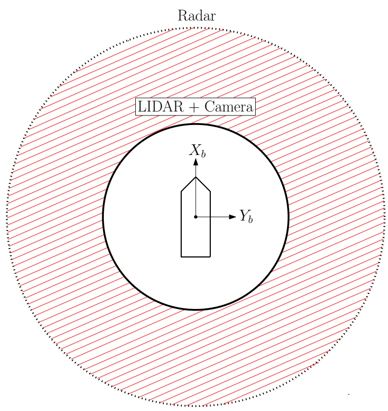
Figure 2.2 illustrates which sensor platforms that are necessary in order to adequately obtain information regarding the vessel's surroundings. It quickly becomes clear by investigating the Figure 2.2 that in order for a vessel to have a clear perception of its surroundings, a package of different sensors is necessary. An obvious but important comment regarding the sensor package on an autonomous vessel, is that the online consequence analysis will never be able to contribute to higher situation awareness unless it receives information from a robust sensor system.

Figure 5.1 illustrates a case where loss of radar signal occurs. The left figure (Figure 5.1a) shows the sensor coverage in close proximity to the vessel consisting of cameras, LIDAR and radar. The right figure (Figure 5.1b) shows the same picture, but illustrates the lower coverage due to radar signal loss, as marked by the red lines, thus leaving only information within the inner circle available to the system. This case causes an interesting question to arise: In the event of a radar signal loss, how should the online consequence analysis behave during the signal loss? Figure 2.2, illustrating sensor range against update frequency, shows that a loss of radar signal should not be an immediate problem to the OCA, as GNSS and AIS will be able to cover the same range. The frequency however is not the same, and the sampling of information from the sensors will decrease due to this.

If the vessel loses the radar signal for an unknown duration of time, the OCA would still have information about most of the static environment in proximity of the vessel from GNSS. Historical data saved locally on the vessel may also be an information source in this case, AIS would give information about vessels equipped with this, and echo sounder may give information about the risk of grounding. Any obstacles not covered by the previously mentioned sensors will not be perceived by the vessel before it is within range of LIDAR and/or camera systems. For a large vessel with slow dynamics, this might be too late.



(a) Illustration of perception ability, with radar



(b) Illustration of perception ability, without radar

Figure 5.1: Autonomus vessel's ability to perceive information about its surroundings

One of the ways the OCA may behave based on the event described above might be to increase the frequency of which the online consequence analysis is initialized, in order to gain the maximum resolution for the risk indicator. This does not solve the problem, but it will be able to initiate a replanning process earlier, as the risk indicator reacts quicker if a collision simulated through the OCA. Scenario 3 and 4 in Section 4.4 and 4.5, respectively, illustrates this for a vessel maneuvering through a narrow channel passage, and shows how the risk indicator increased earlier due to an larger OCA initiation frequency.

Another way the OCA could behave during radar signal loss is to not simulate any of the failure modes outside of the perceived area of the vessel. In that way, the system assures that no decisions are made based on missing information about the surroundings, but on the other hand, the system greatly reduces the OCA's ability to increase situation awareness.

A scenario where the OCA would most likely not be of use, is if an unknown object, possibly a small high-speed vessel without AIS, appears from behind a larger object. In this case, the sensor systems might not be able to identify the object, and the OCA will most likely not manage to simulate any failure modes based on that obstacle. Hopefully, a refined collision avoidance system would react to the obstacle. How the collision avoidance system interacts with the OCA will be briefly discussed below, when discussing the OCA's position in a control system hierarchy.

The above examples emphasizes the importance of the first element of situation awareness, perception of the surrounding environment. The examples highlight that the OCA is dependent on adequate input from the sensor system.

5.3 Initialization of the Online Consequence Analysis

Correctly determining the initialization time period of the online consequence analysis is a discussion topic not addressed in detail earlier in the thesis. It is easy to think that the OCA should be initiated with the highest possible frequency. However, this is only partly true. If the OCA is initiated often the result is a higher resolution risk indicator, but an example where the vessel is operating in open water might not require the same resolution as a vessel operating within a channel, fjord, or close to shore. In case of open water missions, a priority may be to simulate the failure scenarios longer, thus each OCA run takes more time to conduct. Utilization of computers with high computational power will of course influence the highest achievable frequency, but the OCA failure mode simulation time and overall frequency of the OCA will always depend on each other, and in the pursue of the highest possible frequency and the largest covered spatial domain, there will always be a trade-off.

A suggested way calculating the initialization period for the OCA is given in (5.1), which is both dependent on the vessel's own speed, and its range to the nearest obstacle.

$$T = \left(T_{U,min} - \frac{K_U}{U_{max}} U \right) + (T_{\bar{\boldsymbol{r}}_O,min} - K_O sat(\bar{\boldsymbol{r}}_O)\bar{\boldsymbol{r}}_O) \tag{5.1}$$

Here $T_{U,min}$ is a strictly positive constant value that assures a minimum frequency of the OCA, $K_U < T_{U,min}$ is a linear gain constant that should appropriately scale the initialization period based on the vessel's speed, U_{max} is the vessel's maximum speed, U is the vessel speed, $T_{\bar{\boldsymbol{r}}_O,min}$ is a time constant which ensures that the range dependent initialization period is never equal to zero, K_O is a gain constant similar to K_U which scales how the initialization period decreases (thus increasing the frequency) with respect to the vessel's range to the obstacle, and $\bar{\boldsymbol{r}}_O$ is the distance between the vessel and obstacle.

Furthermore, the saturation function $sat(\bar{\boldsymbol{r}}_O)$ is defined by (5.2)

$$sat(\bar{\boldsymbol{r}}_O) := \begin{cases} 1, & \text{if} \quad \bar{\boldsymbol{r}}_O \leq \bar{\boldsymbol{r}}_{O,min} \\ 0, & \text{otherwise} \end{cases} \tag{5.2}$$

where $\bar{\boldsymbol{r}}_{O,min}$ is a constant distance from the obstacle, which is also a foundation for setting $T_{\bar{\boldsymbol{r}}_O,min}$. The constant $\bar{\boldsymbol{r}}_{O,min}$ defines a minimum radius from an obstacle to the vessel, before increasing the initialization frequency.

The example presented in (5.1) above was not tested during simulation, and is just one of many ways that the initialization period could be defined. It is strongly encouraged that this is further researched. Parameters not mentioned that might be important when defining the initialization period are: size of obstacles, type of obstacle (AIS equipped, unknown, etc.), weather conditions, maneuverability of own ship, and many more.

5.4 Determination of Consequence Levels

During development of the online consequence analysis framework, the consequence levels were defined based on a radial distance from the center of an obstacle. Level 1 being the least severe one, and Level 3 seen as a collision. During simulations in the case study (Chapter 4), this definition functioned well, but more sophisticated methods for utilizing dynamic consequence levels are encouraged to investigate.

A possible way to determine the consequence levels used by the OCA, may be to define them based on parameters such as obstacle velocity (if the obstacle is moving) and/or based on their physical size. If a moving obstacle with a significant velocity comes within near proximity of the vessel, the consequence levels could be set larger compared to a static object of the same size. This method of defining the consequence levels makes sense as a moving object is unpredictable compared to a static object, thus having larger consequence levels would automatically increase the risk level at a larger distance from the object. The total risk could also have been increased by increasing the probability level as a function of the obstacle's velocity, however this would not be a tidy way of increasing the risk as probability levels are dependent on the probability of occurrence for a specific failure, and not the obstacle.

Basing the consequence levels on physical size of an obstacle is also one method that may be useful. The physical size of static objects may be received from GNSS data, while for moving obstacles this may be obtained from AIS or radar. The radar may be unreliable in terms of estimation of an obstacles size, as it may be disturbed by prevailing weather conditions and/or misses information due to signal shadow zones, however in these cases a predefined conservative definition of the consequence levels may be used.

Lastly, if a vessel is operating close to a shore line, or within a channel as simulated in the case study (Chapter 4), Scenario 3 and 4, the need for an accurate definition of the consequence levels increase. An example on how to solve this is presented in Figure 5.2. The figure represents a vessel following a shore line on its starboard side. The question at hand is how far from the shore line the vessel should steer? A possible way to determine this is with the use of a multibeam echo sounder, as described in Section 2.2. The echo sounder would be used to determine the closest distance from shore which has a depth equal to the vessel's draught, thus the most severe consequence level, L3 will then be based on this distance, as it is directly associated with vessel grounding. The other levels will be defined as based on L3.

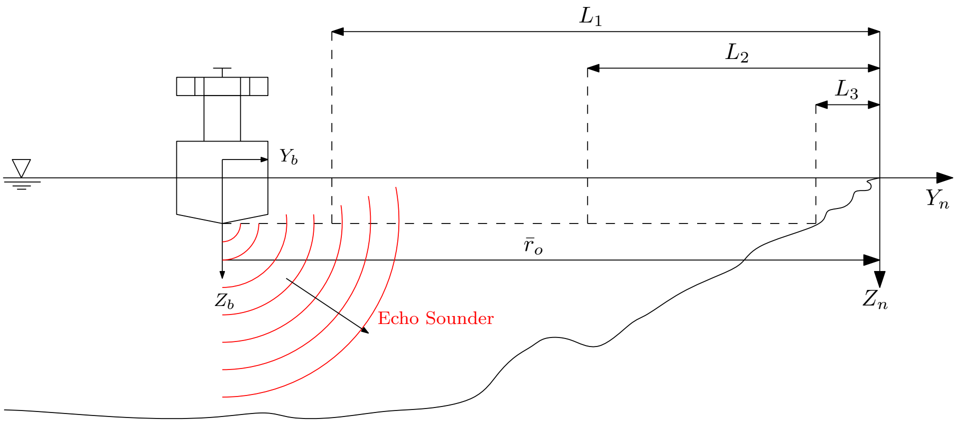


Figure 5.2: Illustration of consequence level determination of a vessel close to shore, with the use of echo sounder.

If the consequence levels are defined based on the above, this would give a dynamic consequence level definition, enabling the vessel to navigate close to the shore line, without exceeding a risk level that could potentially lead to grounding or collision.

5.5 The Online Consequence Analysis' Position in a Control System Hierarchy

When introducing a new element to a control system, it is important to reflect on its position, including if and how it fares with an already existing control system hierarchy. Ludvigsen & Sørensen (2016) presented a figure explaining some of the main group divisions typically used for underwater vehicles, but which also have a lot in common with the systems used on surface marine vessels. The groups are: Control execution layer, guidance and optimization layer and lastly the mission layer. Relevant to the model used in this thesis the control execution layer is responsible for the autopilot and speed control. An even lower level compared to these is the actuator control, however as no actuator models were implemented in the model used in this thesis, hence no further discussion regarding actuator control will be made. Further, the waypoint guidance system as seen in Section 2.5.3 is placed in the guidance and optimization layer. As seen from Figure 3.1 the system also consists of a collision avoidance system and the online consequence analysis. The collision avoidance system was added in Figure 3.1 as it allows for discussion of the

OCA's placement in the control hierarchy. The collision avoidance system will typically be implemented as a contingency handling tool in the guidance and optimization layer. This corresponds well with the model for collision avoidance presented by Johansen et al. (2016), which take input from the vessel guidance system and outputs a modified desired heading to the autopilot controller, if a collision is inbound.

The online consequence analysis however will have a more natural placement in the mission planning layer, as it does not give direct feedback to the control layer, but to the guidance system and actuator system. One might argue that it would be natural to speak of the OCA as a part of the guidance and optimization layer, due to its direct feedback to the actuator system, but as its main function is to evaluate consequence and risk before making a decision based on that, its capabilities are better suited as a part of the mission planning layer.

Avoiding direct feedback from the online consequence analysis to the control layer also gives another benefit. By doing so, the collision avoidance system will always be able to override any commands given by the online consequence analysis. Based on some of the previously discussed challenges with the OCA, the system will benefit from a hierarchy as the one described above. If there are discrepancies in the simulated scenarios by the OCA, or for instance a moving obstacle did not move in a predicable way after the OCA has replanned the vessel path, the collision avoidance system would override this, thus making the entire system more robust against collision, which after all is the main purpose.

5.6 Decision-making Based on the OCA and Risk Indicator

The following section will briefly discuss the decision-making process based on the OCA results and risk indicator. The progress of making a decision as presented by the flowchart in Figure 3.5 shows one of many possible ways to ultimately make a decision to weather or not the mission strategy should be revised.

One question that occurred during the development process of the OCA, with regards to decision involving increased redundancy in the vessel's power/machinery system, was the question: how long should the increased redundancy last before it is reduced again (assuming that there is an increase in cost associated with the increased redundancy)? A possible way to answer this is to monitor the risk indicator after an increase in redundancy is decided, and if the total risk goes below a predefined threshold and stays there for a specified period of time, the increased redundancy may be ceased. If the probability of occurrence changes due to the increased redundancy, the decision to lower it must be based on what the total risk would be without the higher redundancy.

If a case such as Scenario 3 and 4 from Chapter 4 should occur, the decision-making algorithm must choose the option of increased redundancy, as replanning of the route is not applicable when inside a narrow channel.

5.7 OCA's Compliance With COLREGs

As briefly introduced in Section 2.3, the *International Regulations for Preventing Collisions at Sea (COLREGs)* regulates the vast majority of vessels in world, in order to prevent collisions at sea (IMO 1972). Some of the rules covered in COLREGs are discussed here, as the consequence analysis framework may contribute to achieving autonomous ships, which should follow these rules.

Rule 7: Risk of collision, states that all available means appropriate should be used to determine if there is a risk of collision with an object in proximity of the vessel. It also states that if there is any doubt, the risk should be deemed to exist. The rules developed in 1972 are not specified for autonomous vessels, thus some of the requirements will not be applicable. In this case, the risk should be solely calculated by the OCA, and not by deeming that on exists. Furthermore, the rule demands a use of radar equipment to give human operators an early indication to whether a risk of collision is inbound. As previously discussed during the thesis, this is a something the OCA is developed to assist a human operator with, and in the future, make the system independent of the operator. It is pointed out that none of the decisions should be made based on scanty information from the sensor system. This is emphasizes some of the elements discussed in Section 5.2, as the OCA would not function at all without good information from the sensors. Lastly Rule 7 concludes that a risk is to be deemed to exists if the bearing angle of an obstacle in the distance does not seem to change over time, which indicates that the vessel would be on direct collision course with the obstacle. If the OCA framework is to evaluate an obstacles bearing angle, it would have to be expanded to include moving obstacles.

Rule 9: Narrow channels, discusses how a vessel should behave when navigating through a narrow passage or channel. The first part of the rule explains that a vessel passing through a narrow passage shall keep a distance as near as possible to the channel on the vessel's starboard side. Scenario 3 and 4 in Chapter 4 illustrates this. A method for utilizing the OCA to determine how close to the channel wall it is safe to operate was proposed in Section 5.4, and will be necessary if an autonomous vessel shall be able to safely navigate through the channel. Lastly if a vessel is nearing a bend in the channel where the vessel's situation awareness may be obscured, it should operate with extreme caution. One way of solving this with the developed OCA could be to deliberately increase the total risk during similar situations, thus forcing an increase in redundancy.

The two rules discussed above is considered the most relevant based on the OCA framework developed in this thesis. It is advised that further investigation of how the OCA can comply with a broader aspect of COLREGs, should be conducted. The rules discussed above can be seen in Appendix D.

CHAPTER 6

Conclusions and Further Work

The research question of the thesis has been:

Is it possible to develop and utilize a continuously running online consequence analysis in order to increase the situation awareness of a vessel during transit, thus creating a better foundation for decision making with respect to management of power system redundancy, route planning and others? The system must be applicable both as a supervisor for manned vessels, but ultimately to take direct part in decision making for a highly autonomous vessel.

The following section concludes the thesis and gives suggestions for further work.

6.1 Concluding Remarks

A framework for an online consequence analysis has been presented. It was developed as a contribution to achieve highly autonomous marine vehicles, with a main focus on surface vessels during transit. The framework is relevant for the maritime industry as a pursue to achieve self-driving vessels independent of human operators, is taking place.

The online consequence analysis may function as a supervisor for manned surface vessels, or as a foundation for decision-making in a highly autonomous system. The analysis simulates a set of different failure dynamics online, based on the vessel's present state and prevailing weather conditions. Furthermore, it calculates a quantitative measure of the total risk for each conducted consequence analysis, which results in an online risk indicator for direct input in a decision-making process.

A simulation model was built in order to validate the functionality of the online consequence analysis. A case study investigated how the online consequence analysis performed with a selection of four different failure modes. The scenarios simulated in the case study covered straight line transit, simple maneuvering between static obstacles, and navigation through a narrow channel passage.

Through rigorous investigation of how different industries define taxonomies for autonomy, and a thorough investigation on what situation awareness means, and how it is defined, the framework for the online consequence analysis is concluded to have capabilities corresponding to LoA-3, management by exception. Achieving LoA-4, highly autonomous capabilities can not be concluded solely on the framework presented in this thesis, as such capabilities in a system depends on a broader set of factors than what this thesis scope covers.

In conclusion, the proposed online consequence analysis allows for increased situation awareness. It is also concluded that the framework complies with relevant sections of COLREGs.

6.2 Further Work

During the development process of the framework, several topics for further investigation have emerged.

The main proposals for further work are described in the list below.

1. Expansion of the framework to include moving obstacles will be necessary in order to be an efficient contributor for increased situation awareness.
2. A thorough investigation with regards to how often the online consequence analysis should be initialized is necessary. Possible parameters that could be used as a basis when deciding the initialization period may be: vessel speed, obstacle size, obstacle speed and current redundancy state.
3. It is advised to conduct a rigorous study on determination of consequence levels. Based on the static environment, moving obstacles, water depth, prevailing weather conditions, vessel speed, obstacle position uncertainties etc. the consequence levels should be dynamic to best suit the needs of the vessel in order to lower risk.
4. A sophisticated model including machinery dynamics should be implemented in order to better represent the failure mode dynamics of the system.
5. Probability analyses should be conducted in order to accurately calculate the probability of occurrence for each failure mode.
6. A thorough investigation regarding how the framework complies with COLREGs is advised.
7. A detailed model for the fluid flow dynamics around the rudder should be implemented, for better representation of the rudder freeze failure mode.

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APPENDIX A

Levels of Autonomy, Industry Definitions (Simplified Versions)

A.1 Automotive Industry

A.1.1 Society of Automotive Engineers, SAE.

Table A.1 shows SAE's LoA definition (SAE 2016).

Table A.1: SAE Definition, Levels of autonomy

SAE definition, Levels of autonomy
SAE 0: No automation. The driver performs all driving and navigation without any aids
SAE 1: Driver assistance: The car can keep a distance to other similar cars.
SAE 2: Partial automation: The car can perform simple tasks on its own, such as driving in the road system where it is located
SAE 3: Conditional automation: The car can drive on its own in specific situation (e.g. on motor-ways). The driver does not need to control the car actively or to keep a lookout, but must be able to intervene at short notice.
SAE 4: High automation: The car can drive on its own in specific surroundings, but the driver does not need to be ready to take over control.
SAE 5: Full automation: Driverless cars in all surroundings and in all potential situations

A.1.2 Germany Federal Highway Research Institute (BASt)

Table A.2 shows BASt's LoA definition (Gasser et al. 2013).

Table A.2: BASt Definition, Levels of autonomy

Nomenclature	Description of autonomation degree according to drivers' expectations	Exemplary systems
Driver Only	The driver continuously (throughout the complete trip) accomplishes longitudinal (accelerating/ braking) and lateral (steering) control.	No (driver assistance) system active that intervenes in longitudinal and lateral control.
Assisted	The driver continuously accomplishes either lateral or longitudinal control. The other/ remaining task is – within certain limits - performed by the system. • The driver must monitor the system permanently. • The driver must be prepared to take over complete control over the vehicle at any time.	Adaptive Cruise Control: • Longitudinal control with adaptive distance and speed control. Parking assistance system: • Lateral control is accomplished by the parking assistance (automatic steering into the parking space, the driver accomplishes longitudinal control).
Partial automation	The system takes over the lateral and longitudinal control (for a certain period of time and/ or in specific situations). • The driver must monitor the system permanently. • The driver must be prepared to take over the complete control of the vehicle at any time.	Motorway assistant: • Automatic longitudinal and lateral control • On motorways up to a certain top speed limit • Driver must monitor the actions constantly and respond immediately when prompted to take over
High automation	The system takes over lateral and longitudinal control for a certain period of time in specific situations. • Here, the driver need not monitor the system permanently. • If necessary, the driver will be prompted to take over control, allowing for a sufficient lead time. • All system limits are recognised by the system. The system is not capable of re-establishing the minimal risk condition from every initial state.	Motorway chauffeur: • Automatic longitudinal and lateral control • On motorways up to a certain top speed limit • Driver is not required to monitor the actions constantly. In case prompted to take over, the driver must respond within a certain lead time.
Full automation	The system takes over lateral and longitudinal control completely within the specification of the application. • The driver need not monitor the system • Before specified limits of the application are reached, the system prompts the driver to take over control, with sufficient lead time. • In absence of driver takeover, the system will return to the minimal risk condition. • All system limits are recognised by the system. The system is capable of returning to the minimal risk condition out of every situation.	Motorway pilot: • Automatic lateral control • On motorways up to a certain top speed limit • Driver is not required to monitor the actions • In case the driver does not respond to a takeover request, the vehicle will brake down to a standstill.

A.1.3 German Association of the Automotive Industry (VDA)

Table A.3 shows VDA's LoA definition (VDA 2015).

Table A.3: VDA Definition, Levels of autonomy

VDA definition, Level of autonomy	
Level 0: Driver only	Driver continuously performs the longitudinal and lateral dynamic driving task. No intervening vehicle system active.
Level 1: Assisted	Driver continuously performs the longitudinal or lateral dynamic driving task. The other driving task is performed by the system
Level 2: Partial automation	Driver must monitor the system at all times. System performs longitudinal and lateral driving task in a defined use case.
Level 3: Conditional automation	Driver does not need to monitor the system at all times. Driver must be capable of resuming dynamic driving task. System performs longitudinal and lateral driving task in a defined use case. Recognizes its limits and requests driver to resume the dynamic driving task with sufficient time margin.
Level 4: High automation	Driver is not required during defined use case. System performs lateral and longitudinal dynamic driving task in all situations in a defined use case.
Level 5: Full automation	No driver required during entire journey. System performs entire dynamic driving task on all road types, speed ranges and environmental conditions.

A.1.4 US National Highway Traffic Safety Administration (NHTSA)

Table A.4 shows NHTSA's LoA definition (NHTSA 2013).

Table A.4: NHTSA Definition, Levels of autonomy

NHTSA definition, Level of autonomy (Without examples)	
Level 0: No-Automation	The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls. Vehicles that have certain driver support/convenience systems but do not have control authority over steering, braking, or throttle would still be considered "level 0" vehicles.
Level 1: Function-specific Automation	Automation at this level involves one or more specific control functions; if multiple functions are automated, they operate independently from each other. The driver has overall control, and is solely responsible for safe operation, but cahhicle can automatically assume limited authority over a primary control (as in electronic stability control), or the automated system can provide added control to aid the driver in certain normal driving or crash-imminent situations (e.g., dynamic brake support in emergencies). The vehicle may have multiple capabilities combining individual driver support and crash avoidance technologies, but does not replace driver vigilance and does not assume driving responsibility from the driver. The vehicle's automated system may assist or augment the driver in operating one of the primary controls – either steering or braking/throttle controls (but not both).
Level 2: Combined Function Automation	This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Vehicles at this level of automation can utilize shared authority when the driver cedes active primary control in certain limited driving situations. The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times and on short notice. The system can relinquish control with no advance warning and the driver must be ready to control the vehicle safely.
Level 3: Limited Self-Driving Automation	Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The vehicle is designed to ensure safe operation during the automated driving mode.
Level 4: Full Self-Driving Automation	The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver1 will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles. By design, safe operation rests solely on the automated vehicle system.

A.2 Maritime Industry

A.2.1 Lloyd's Register

Table A.5 shows Lloyds Register's LoA definition (Lloyd's Register 2016).

Table A.5: Lloyd's Register Definition, Levels of autonomy

Lloyd's Register definition, Level of autonomy	
AL 0) Manual – no autonomous function	All action and decision making is performed manually – i.e. a human controls all actions at the ship level. Note: systems on board may have a level of autonomy, with 'human in/on the loop'; for example, pms and engine control. Straight readouts, for example, gauge readings, wind direction and sea current, are not considered to be decision support.
AL 1) On-ship decision support	All actions at the ship level are taken by a human operator, but a decision support tool can present options or otherwise influence the actions chosen, for example DP Capability plots and route planning.
AL 2) On and off-ship decision support	All actions at the ship level taken by human operator on board the vessel, but decision support tool can present options or otherwise influence the actions chosen. Data may be provided by systems on or off the ship, for example DP capability plots, OEM configuration recommendations, weather routing.
AL 3) 'Active' human in the loop	Decisions and actions at the ship level are performed autonomously with human supervision. High- impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them. Data may be provided by systems on or off the ship.
AL 4) Human on the loop – operator/supervisory	Decisions and actions are performed autonomously with human supervision. High impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them.
AL 5) Fully autonomous	Unsupervised or rarely supervised operation where decisions are made and actioned by the system, i.e. impact is at the total ship level.
AL 6) Fully autonomous	Unsupervised operation where decisions are made and actioned by the system, i.e. impact is at the total ship level.

A.2.2 Norwegian Forum for Autonomous Ships

Table A.6 shows NFAS's LoA definition (Rødseth & Nordahl 2017).

Table A.6: NFAS Definition, Levels of autonomy

NFAS definition, Levels of autonomy	
Decision Support	This corresponds to today's and tomorrow's advanced ship types with relatively advanced anti-collision radars (ARPA), electronic chart systems and common automation systems like autopilot or track pilots. The crew is still in direct command of ship operations and continuously supervises all operations. This level normally corresponds to ”no autonomy”.
Automatic	The ship has more advanced automation systems that can complete certain demanding operations without human interaction, e.g. dynamic positioning or automatic berthing. The operation follows a pre-programmed sequence and will request human intervention if any unexpected events occur or when the operation completes. The shore control centre (SCC) or the bridge crew is always available to intervene and initiate remote or direct control when needed.
Constrained autonomous	The ship can operate fully automatic in most situations and has a predefined selection of options for solving commonly encountered problems, e.g. collision avoidance. It has defined limits to the options it can use to solve problems, e.g. maximum deviation from planned track or arrival time. It will call on human operators to intervene if the problems cannot be solved within these constraints. The SCC or bridge personnel continuously supervises the operations and will take immediate control when requested to by the system. Otherwise, the system will be expected to operate safely by itself.
Fully autonomous	The ship handles all situations by itself. This implies that one will not have an SCC or any bridge personnel at all. This may be a realistic alternative for operations over short distances and in very controlled environments. However, and in a shorter time perspective, this is an unlikely scenario as it implies very high complexity in ship systems and correspondingly high risks for malfunctions and loss of system.

A.2.3 US Navy Office of Naval Research

Table A.7 shows the US Navy Office of Naval Research's LoA definition (NFA 2014).

Table A.7: US Navy Office of Naval Research, Levels of autonomy

US Navy Office of Naval Research, Levels of autonomy	
Level 1: Human Operated	All activity within the system is the direct result of human-initiated control inputs. The system has no autonomous control of its environment, although it may have information-only responses to sensed data.
Level 2: Human Assisted	The system can perform activity in parallel with human input, acting to augment the ability of the human to perform the desired activity, but has no ability to act without accompanying human input. An example is automobile automatic transmission and anti-skid brakes.
Level 3: Human Delegated	The system can perform limited control activity on a delegated basis. This level encompasses automatic flight controls, engine controls, and other low- level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.
Level 4: Human Supervised	The system can perform a wide variety of activities given top-level permissions or direction by a human. The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately redirected. The system does not have the capability to self-initiate behaviors that are not within the scope of its current directed task.
Level 5: Mixed Initiative	Both the human and the system can initiate behaviors based on sensed data. The system can coordinate its behavior with the human behaviors both explicitly and implicitly. The human can understand behaviors of the system in the same way that he understands his own behaviors. A variety of means are provided to regulate the authority of the system w.r.t. human operations.
Level 6: Fully Autonomous	The system requires no human intervention to perform any of its designated activities across all planned ranges of environmental conditions.

A.2.4 Taxonomy proposed by Ludvigsen and Sørensen, 2016

Table A.8 shows the LoA definition as seen in subsection 2.1.2 and Ludvigsen & Sørensen (2016).

Table A.8: Ludvigsen & Sørensen, Levels of autonomy

Ludvigsen and Sørensen, Levels of autonomy	
1. Automatic Operation (Remote Control)	Means that even though the system operates automatically, the human operator directs and controls all high-level mission-planning functions, often preprogrammed (human-in-the-loop/human operated).
2. Management by consent (Teleoperation)	Means that the system automatically makes recommendations for mission actions related to specific functions, and the system prompts the human operator at important points in time for information or decisions. At this level, the system may have limited communication bandwidth including time delay, due to i.e. distance. The system can perform many functions independently of human control when delegated to do so (human-delegated).
3. Semi-autonomous or Management by Exception	means that the system automatically executes mission-related functions when response times are too short for human intervention. The human may override or change parameters and cancel or redirect actions within defined time lines. The operator's attention is only brought to exceptions for certain decisions (human- supervisory control).
4. Highly autonomous	Means that the system automatically executes mission-related functions in an unstructured environment with ability to plan and re-plan the mission. The human may be informed about the progress. The system is independent

A.2.5 Aerospace- and Military Industry

A.2.6 The Air Force Research Laboratory

The definition presented in Table A.9 can be seen in (Clough 2002)

Table A.9: The Air Force Research Laboratory, Levels of Autonomy.

The Air Force Research Laboratory, Autonomous Control Level (ACL)					
Level	**Level Descriptor**	**Observe**	**Orient**	**Decide**	**Act**
10	**Fully Autonomous**	Cognizant of all within Battlespace	Coordinates as necessary	Capable of total indepenance	Requires little guidance to do job
9	**Battlespace Swarm Cognizance**	Battlespace inference - Intent of self and others (allies & foes). Complex/Intense environment - on-board tracking.	Strategic group goals assigned. Enemy strategy inferred.	Distributed tactical group planning. Individual determination of tactical goal. Individual task planning/execution. Choose tactical targets.	Group accomplishment of strategic goal with no supervisory assistance.
8	**Battlespace Cognizance**	Proximity inference - Intent of self and others (allies & foes). Reduced dependence upon off-board data	Strategic group goals assigned. Enemy tactics inferred. ATR.	Coordinated tactical group planning. Individual task planning/execution. Choose targets of opportunity.	Group accomplishment of strategic goal with minimal supervisory assistance.
7	**Battlespace Knowledge**	Short track awareness - History and predictive battlespace data in limited range, timeframe, and numbers. Limited inference supplemented by off-board data.	Tactical group goals assigned. Enemy trajectory estimated.	Individual task planning/execution to meet goals.	Group accomplishment of tactical goal with minimal supervisory assistance.
6	**Real Time Multi-Vehicle Cooperation**	Ranged awareness - on-board sensing for long range, supplemented by off-board data	Tactical group goals assigned. Enemy location sensed/estimated.	Coordinated trajectory planning and execution to meet goals - group optimization.	Group accomplishment of tactical goal with minimal supervisory assistance. Possible close air space separation (1-100 yds).
5	**Real Time Multi-Vehicle Coordination**	Sensed awareness - Local sensors to detect others, Fused with off-board data	Tactical group goals assigned. RT Health Diagnosis; Ability to compensate for most failures and flight conditions; Ability to predict onset of failures. Group diagnosis and resource management.	On-board trajectory replanning - optimizes for current and predictive conditions. Collision avoidance.	Group accomplishment of tactical plan as external ly assigned. Air collision avoidance. Possible close air space separation (1-100 yds) for AAR, formation in non-threat conditions.
4	**Fault/Event Adaptive Vehicle**	Deliberate awareness - allies communicate data	Tactical plan assigned. Assigned Rules of Engagement. RT Health Diagnosis; Ability to compensate for most failures and flight conditions - inner loop changes reflected in outer loop performance.	On-board trajectory replanning - event driven. Self resource management. Deconfliction.	Self accomplishment of tactical plan as externally assigned.
3	**Robust Response to Real Time Faults/Events**	Health/status history and models	Tactical plan assigned. RT Health Diag (What is the extent of the problems?). Ability to compensate for most control failures and flight conditions (i.e. adaptive inner-loop control).	Evaluate status vs required mission capabilities. Abort/RTB if insufficient.	Self accomplishment of tactical plan as externally assigned.
2	**Changeable Mission**	Health/status sensors	RT Health diagnosis (Do I have problems?). Off-board replan (as required).	Execute preprogrammed or uploaded plans in response to mission and health conditions	Self accomplishment of tactical plan as externally assigned.
1	**Execute Planned Mission**	Preloaded mission data. Flight Control and Navigation Sensing.	Pre/Post Flight BIT. Report status.	Preprogrammed mission and abort plans.	Wide airspace separation requirements (miles).
0	**Remotely Piloted Vehicle**	Flight Control (attitude, rates), sensing Nose camera	Telemetered data, Remote pilot commands	n/a	Control by remote pilot

APPENDIX B

R/V Gunnerus, specifications

RV GUNNERUS - LNVZ

Multipurpose research vessel for Norwegian University of Science and Technology (NTNU)

Name	R/V GUNNERUS
Owner	Norwegian University of Science and Technology (NTNU) Faculty of Natural Sciences and Technology
Designed by	Polarkonsult AS, Norway
Built by	Larsnes Mekaniske Verksted, Norway
Delivery year	2006
Port of Registry	Trondheim, Norway
Classification Society	Norwegian Maritime Directorate

Main dimensions

Length over all	(Loa)	31.25 m
Length between pp	(Lpp)	28.90 m
Length in waterline	(Lwl)	29.90 m
Breadth middle	(Bm)	9.60 m
Breadth extreme	(B)	9.90 m
Depth mld. Main deck	(Dm)	4.20 m
Draught, mld	(dm)	2.70 m
Mast height / antenna		14.85 / 19.70 m
Dead weight		107 t

Class, Service Area

Range	Coastal areas out to 20 nautical miles from the coast (Liten Kystfart) Designed and built according to European trade.
Class Notation	DNV + 1A1 + Ice C + E0 + R2 Cargo ship

Deck equipment, scientific equipment and lab facilities

Trawl winches	2 x Mjosund 6 t, (wire D=14 mm, L=1000 m).
Net drum	Mjosund 5 m^3, D=2000mm, d=320mm
Main deck crane	Palfinger 14 m / 35 tm
CTD crane	HIAB/Mjosund, 5 m / 3.3 tm, Water sampler wire 5 mm/750m CTD wire 6,5 mm/750 m.
Stern mounted A-frame	6 t, hydraulic.
Hydraulic diving platform	500 Kg, 1,5m x 0,8m.
Hydraulic aggregate	Mjosund 110 kW
Capstan	Mjosund 8t/220bar, D=410, d=320, L=300
Anchor winch	Mjosund 2 drums, 20 m/min, 2 x 12,5m ø 22mm K2 chain/ 210m ø22mm. wire
Compressed air	Atlas copco compressor
Workdeck	75 m^2
Wet lab	13.9 m^2
Dry lab	11.8 m^2
Computer lab	11.2 m^2
Container attachment:	5, 10, 15 & 20 feet alongside or 20 feet abeam.
CTD	Saiv
CTD	Sealogger 25, Seabird electronics inc.

Watersampler system	Carousel water sampler, 12 x 2,5l bottles. Seabird electronics inc
Workboat	Polarcirkel 560 Work, Yamaha 80hp

<u>Capacities</u>

Crews cabins / berths	6 / 11
Daytime personnel capacity	25 incl. crew
Deadweight	107 t
Deck load	45 t
Fuel oil	44 m^3
Fresh water	11 m^3
Water ballast	62 m^3
Cargo hold	42 m^3
Galley	4,5 m^2
Mess, conference and dayroom	32 m^2 With 46” LCD monitor.

<u>Machinery: Diesel electric propulsion</u>

Main electric propulsion	1000 kW (Siemens 2 x 500 kW)
Main generators	3 x Nogva-Scania 450 kW
Bow tunnel thruster	1 x Brunvoll 200 kW
Speed at 100% MCR	12,6 kn
Cruising speed	9,4 kn
Gear	2 x Finnøy
Rudder	2 x Rolls-Royce, Ulstein Hinze Rudder FB-H 1200
Steering gear	2 x Rolls-Royce, Tenfjord SR562-FCPX2

The diesel electric system has been specially designed for low hydroacoustic noise levels. Diesel generators are mounted on a common double elastic frame and one of the generators are mounted in a noise dampening hood for special low noise mode.

<u>Navigation, communications and electronic equipment</u>

Dynamic Positioning system	Kongsberg SDP-11 / cPos
DP - Reference systems	GPS
	Kongsberg Seatex DPS 232
	HPR, Kongsberg transponders.
	Kongsberg Seatex RADius
Heading, Attitude and Positioning Sensor	Kongsberg Seapath 300
Acoustic positioning system	Kongsberg HiPAP 500
Motion reference unit (MRU)	Kongsberg Seatex
Autopilot	Simrad AP50
Compass, magnet	Nautisk service NS 150-A
Compass, gyro	Simrad GC80 / 85
Bearing repeater	Simrad DR76
Differential positioning sensor	Kongsberg DPS 232
Heading, attitude and positioning sensor	Kongsberg Seatex Seapath 300
GPS	Furuno Navigator GP-90
Radar	Furuno FAR 28x7 /FAR 21x7
Log	Furuno Doppler speed log DS-80
Echo sounder	Furuno FCV-1200L. 38, 50, 200 kHz – 2000m
Echo sounder, multibeam	Kongsberg EM 3002s
Catch monitoring system	Simrad PI54

Chartplotter 1	Telchart (AIS)
Chartplotter 2	Olex (Installed AIS, HT, SB, ITI, MBES)
Chartplotter 3	Olex LT (Office version)
AIS	Furuno FA-150
Navtex	JMC NT900
GMDSS console	
VHF fixed radio	Sailor
VHF handheld radios	Jotron
UHF handheld radios	Icom
Satellite phone	Sailor
Internet in sea	ICE & Telenor mobilt bredbånd
Internet at pier Trondheim	Wireless broadband NTNU.

Safety

MOB boat, inflateable craft	Narwhal 6 persons SOLAS aproved, Propulsion Mariner 20 Hp
Rescue boat davit	Ned Deck Marine
Life rafts	2 x 25 men each
Survival suits	25 Stearns model ISS-590i
Life jackets	Seamaster – 1983, SOLAS Approved
Work vests	25 Regatta
EPIRB	Jotron
SART	Jotron
Aircraft beacon	Jotron
Fire alarm system	Minerva Marine T1008
Fixed system	Engine room, CO2
Fire suit	Draeger
Search light	Tranberg
SAR	SECurus prototype, Apto maritime (Under construction)
Day and night vision	SECurus prototype, Apto maritime (Under construction)
Oil spill monitoring	SECurus prototype, Apto maritime (Under construction)

Details are believed to be correct but not guaranteed

APPENDIX C

Online Consequence Analysis, MATLAB Source Code

Table of Contents

Vessel Dynamics

```
function [eta,nu,t,stop] =
 simplifiedVesselModelSim1(eta0,nu0,tau0,v_c_n0,MRB,MA,Bv,Dp,G,rho_w,Ax,lpp,T,B,WP
 fm_start, fm_duration, rudderLoss, powerLoss, powerFrac, totalLoss)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Nonlinear Unified Seakeeping and Maneuvering Model
% without Fluid Memory,based on Perez & Fossen 2017.
%
% The function also includes a PID autopilot controller.
%
% Author: Markus Fossdal 2018.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Simulation parameters
 Ts_sim = 0.1;
 Tlength = 60;
 Tsim = Tlength/Ts_sim;

% Parameters
M = MRB + MA; %Rigid-body mass + added mass matrix
M_inv = inv(M);


L = [0  0  0  0  0  0; %Selection matrix
     0  0  0  0  0  1;
     0  0  0  0  -1  0;
     0  0  0  0  0  0;
     0  0  0  0  0  0;
     0  0  0  0  0  0];

R_zc = Rzyx(eta0(4),eta0(5),eta0(6));
nu_c0 = [R_zc'*v_c_n0; 0 ; 0 ; 0]; %Body current

nCs = 20; %Number of vessel cross sections

%Controller
i_term_N = 0; %integral term initial value

% Memory allocation
nu = zeros(6,Tsim);
nu_c = zeros(6,Tsim);
nu_r = zeros(6,Tsim);
```

```
eta = zeros(6,Tsim);
t = zeros(1,Tsim);
tau_N_temp = zeros(1,Tsim);

% Initial conditions
eta(:,1) = eta0;
nu(:,1) = nu0;
nu_c(:,1) = nu_c0;
t(1) = 0;
WPk = WPk0;
% Computations
%Solves combined forward and backward Euler integration (Fossen 2011,
 appendix B)
for k = 1:Tsim-1

    %Current rotation from NED to Body
    R_zc = Rzyx(eta(4,k),eta(5,k),eta(6,k));
    nu_c(:,k) = [R_zc'*v_c_n0; 0 ; 0 ; 0]; %Body current

    %Relative velocity
    nu_r(:,k) = nu(:,k) - nu_c(:,k); %relative nu
    U_r = nu_r(1,k); %relative surge velocity

    %Coriolis matrices rigid-body and added mass.
    CRB = U_r * MRB * L;
    CA = U_r * MA * L;

    %Quadratic surge resistance
    Cx = 1;
    qsr_x = -0.5*rho_w*Cx*abs(nu_r(1,k))*nu_r(1,k)*Ax;
    tau_qsr = [qsr_x 0 0 0 0 0]';

    %Cross-flow drag
    cs = -(lpp/2):(lpp/(nCs-1)):(lpp/2);
    dx = lpp/(nCs-1);
    Y_cf = 0;
    N_cf = 0;
    for i=1:nCs
        Y_cf = Y_cf + (-0.5*rho_w *
 T*Hoerner(B,T)*abs( nu_r(2,k)+cs(i)*nu(6) ) *
 ( nu_r(2,k)+cs(i)*nu(6,k) ) )*dx;
        N_cf = N_cf + (-0.5*rho_w *
 T*Hoerner(B,T)*cs(i)*abs( nu_r(2,k)+cs(i)*nu(6,k) ) *
 ( nu_r(2,k)+cs(i)*nu(6,k) ) )*dx;
    end
    tau_cf = [0 Y_cf 0 0 0 N_cf]'; %Cross-flow drag, Y and N

    %Waypoint Guidance
    [chi_d,WPk1] = guidance([eta(1,k);eta(2,k)], WP, lpp,WPk);
    WPk = WPk1;

    %Sideslip compensation
    [psi_d] = sideSlipComp(chi_d,nu(:,k));
```

```
%Input calculation (tau)
psi = eta(6,k); %heading
r = nu(6,k); %yaw-rate

Kp_N = 0.8*MRB(6,6); %Proportional gain
Ki_N = 0; %Integral gain
Kd_N = 0.6*MRB(6,6)*10; %Derivative gain

e_N = rad2pipi(psi_d-psi); %PID Error

p_term_N = Kp_N * e_N; %PID proportional contribution
i_term_N = i_term_N + Ki_N * e_N; %PID integral contribution
d_term_N = -Kd_N * r; %PID derivative contribution

tau_N = p_term_N + i_term_N + d_term_N; %PID Control

%Failure mode logic
if rudderLoss && powerLoss
    stop = true;
    error('Rudder- and Power loss cannot be activated at the same
time.');
else
    stop = false;
end

if rudderLoss
    %Rudder loss logic
    if t(k)== fm_start
        tau_N_temp(k:k+((20+45)/Ts_sim)) = tau_N;
    end

    if t(k) > fm_start && t(k) <= (fm_start+fm_duration)
        tau_N_used = tau_N_temp(k);
    else
        tau_N_used = tau_N;
    end

    tau = [1*tau0(1,1) 0 0 0 0 tau_N_used]';

elseif powerLoss
    %Power loss logic
    if t(k) > fm_start && t(k) <= (fm_start+fm_duration)
        tau = [powerFrac*tau0(1,1) 0 0 0 0 tau_N]';
    else
        tau = [tau0(1,1) 0 0 0 0 tau_N]';
    end
elseif totalLoss
    %Lose both rudder and power
    if t(k) > fm_start && t(k) <= (fm_start+fm_duration)
        tau = [0 0 0 0 0 0]';
    else
        tau = [tau0(1,1) 0 0 0 0 tau_N]';
    end
```

```
    else
        tau = [tau0(1,1) 0 0 0 0 tau_N]';
    end


    %Equations of motion
    nu(:,k+1) = nu(:,k) + Ts_sim*M_inv*(tau - CRB*nu(:,k) -
CA*nu_r(:,k) - (Bv+Dp)*nu_r(:,k) - G*eta(:,k) + tau_qsr + tau_cf);
    [J,~,~] = eulerang(eta(4,k),eta(5,k),eta(6,k));
    eta(:,k+1) = eta(:,k) + Ts_sim*J*nu(:,k+1);
    t(k+1) = t(k) + Ts_sim;

end %simulation

end
```

Not enough input arguments.

Error in deliveryFiles (line 18)
M = MRB + MA; %Rigid-body mass + added mass matrix

Guidance Law

```
function [chi_d,k1] = guidance(pos, wayPoints, L_ship,k)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Lookahead-based steering law, taken from Fossen (2011).
%
% Author: Markus Fossdal 2018.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Design lengths for guidance system
R_accept = L_ship*2;
R_los = L_ship*3;

% Loading the waypoints
xPos = wayPoints(1,:);
yPos = wayPoints(2,:);

% Correcting the first waypoint if zero
if xPos(1) == 0
    xPos(1) = -0.00001;
end
if yPos(1) == 0
    yPos(1) = -0.00001;
end

% If still not reached the first waypoint
if k == 0
    xk = 0;
    yk = 0;
else
    xk = xPos(k);
```

```
    yk = yPos(k);
end

% The next waypoint
xk1 = xPos(k+1);
yk1 = yPos(k+1);

% Finding the path-tangential angle
chiP = atan2(yk1-yk,xk1-xk);

% Finding the cross-track error
e = -(pos(1)-xk)*sin(chiP) + (pos(2)-yk)*cos(chiP);

% Correcting e if larger than R_los
if abs(e) > R_los
    e = R_los-1;
end

% Using a constant lookahead distance if not reached the first
 waypoint
if k == 0
    delta = L_ship;
else
    delta = sqrt(R_los^2 - e^2);
end

% Caluclating the desired course
chi_d = rad2pipi(chiP + atan(-e/delta));

% Switch to next waypoint if within circle of acceptance
if (xk1-pos(1))^2 + (yk1-pos(2))^2 < R_accept^2
    if k < length(xPos)-1
        k1 = k+1;
    else
        k1 = k;
    end
else
    k1 = k;
end
end
```

Sideslip Compensation

```
function [psi_d] = sideSlipComp(chi_d,nu)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sideslip compensation algorithm, from Fossen (2011).
%
% Author: Markus Fossdal 2018.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
U = sqrt(nu(1)*nu(1)+nu(2)*nu(2)); %Vessel speed

if U == 0
    U = 0.001;
```

```
end

beta = asin(nu(2)/U); %Sideslip angle
psi_d = chi_d-beta; %Corrected heading input
end
```

Consequence Level Evaluation

```
function [level,vioLvl] = levelCheck(eta,t,obstacles,obstLevels,
 noObst)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Consequence level evaluation, from Fossdal (2018).
%
% Author: Markus Fossdal 2018.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Initialize level at zero
level = 0;
maxLevel = 0;

%Declare empty distance vector
dist2obj = zeros(1,size(eta,2));

%Declare empty minimum distance vector
minDist = zeros(1,size(obstacles,2));


%1) For loop through obstacles and save the smallest distance to the
 different
%objects
for i = 1:size(obstacles,2)
    for j = 1:size(eta,2)
        %Calculate scalar distance from vessel to obstacles
        dist2obj(j) = sqrt((obstacles(2,i)-eta(2,j))^2 +
 (obstacles(1,i)-eta(1,j))^2);
    end
   %Vector containing the closest distance during a simulation to the
 obstacles
   minDist(i) = min(dist2obj);
end

%2) Check if these distances violate the largest level zone.
%Declare relevant index values
relIdx = zeros(1,size(obstacles,2));

%Index to closest obstacle
if size(obstacles,2) > 1
    for i=1:size(obstacles,2)
        if minDist(i) < obstLevels(1,1)
            relIdx(i) = 1;
        else
            relIdx(i) = 0;
        end
    end
```

```
else
    relIdx = 1;
end

% 3) Investigate which levels that are violated. Output highest level
 to
% online system.

%Declare violation level vector
vioLvl = zeros(size(t,2),size(obstacles,2));

for i=1:size(obstacles,2)
    if relIdx(i)
        for j = 1:size(eta,2)
            dist2obj(j) = sqrt((obstacles(2,i)-eta(2,j))^2 +
 (obstacles(1,i)-eta(1,j))^2);
            for k = 1:noObst
               if dist2obj(j) < obstLevels(k)
                  vioLvl(j,i)=k;
               end
            end
        end
    end
end

maxLevel = max(max(vioLvl));


%Output max level violated in simulation.
if maxLevel > 0
    level = maxLevel;
elseif maxLevel == 0
    level = -1;
else
    level = 0;
end


end
```

Risk evaluation function

```
function [riskIn,riskInMax,fmIdx] = riskAnalysis(prob,CL1,CL2,CL3,CL4)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Total risk level evaluation, from Fossdal (2018).
%
% Author: Markus Fossdal 2018.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Put CL in vector
CL = [CL1,CL2,CL3,CL4];

%CL mapped
```

```
CL_m = zeros(1,size(CL,2));

%Map consequence levels
for i=1:size(CL,2)
    if CL(1,i) == -1
        CL_m(1,i) = 0;
    elseif CL(1,i) == 1
        CL_m(1,i) = 0.33333;
    elseif CL(1,i) == 2
        CL_m(1,i) = 0.66667;
    elseif CL(1,i) == 3
        CL_m(1,i) = 1;
    end
end

%Calculate risk levels
r = zeros(1,size(CL,2));
for i=1:size(r,2)
    r(i) = prob(i)*CL_m(i);
end

%Calculate max risk
r_max = 1*sum(prob);

%Aquire risk indicator and fm with the largest risk.
fmIdx = 0;
[riskInMax,fmIdx] = max(r);
riskIn = sum(r)/r_max;

if max(r) == 0
    fmIdx = 0;
end

end
```

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APPENDIX D

Selection of COLREGs Rules

This appendix presents a selection of rules from COLREGs, discussed in Chapter 5.

D.1 Rule 7: Risk of Collision

(a) Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. If there is any doubt such risk shall be deemed to exist.

(b) Proper use shall be made of radar equipment if fitted and operational, including long-range scanning to obtain early warning of risk of collision and radar plotting or equivalent systematic observation of detected objects.

(c) Assumptions shall not be made on the basis of scanty information, especially scanty radar information.

(d) In determining if risk of collision exists the following considerations shall be among those taken into account:

   (1) such risk shall be deemed to exist if the compass bearing of an approaching vessel does not appreciably change.

   (2) such risk may sometimes exist even when an appreciable bearing change is evident, particularly when approaching a very large vessel or a tow or when approaching a vessel at close range.

D.2 Rule 9: Narrow channels

(a) A vessel proceeding along the course of a narrow channel or fairway shall keep as near to the outer limit of the channel or fairway which lies on her starboard side as is safe and practicable.

(b) A vessel of less than 20 metres in length or a sailing vessel shall not impede the passage of a vessel which can safely navigate only within a narrow channel or fairway.

(c) A vessel engaged in fishing shall not impede the passage of any other vessel navigating within a narrow channel or fairway.

   (1) In a narrow channel or fairway when overtaking can take place only if the vessel to be overtaken has to take action to permit safe passing, the vessel intending to overtake shall indicate her intention by sounding the appropriate signal prescribed in Rule 34(c)(i). The vessel to be overtaken shall, if in agreement, sound the appropriate signal prescribed in Rule 34(c)(ii) and take steps to permit safe passing. If in doubt she may sound the signals prescribed in Rule 34(d).

   (2) This Rule does not relieve the overtaking vessel of her obligation under Rule 13.

(d) A vessel nearing a bend or an area of a narrow channel or fairway where other vessels may be obscured by an intervening obstruction shall navigate with particular alertness and caution and shall sound the appropriate signal prescribed in Rule 34(e).

(e) Any vessel shall, if the circumstances of the case admit, avoid anchoring in a narrow channel.