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Tools and methods to manage risk in autonomous subsea inspection, maintenance and repair operations

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Thesis for the degree of Philosophiae Doctor

Trondheim, February 2018

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Preface

This thesis is submitted in partial fulfillment of the degree of Philosophiae Doctor at the Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Norway. The research work presented in this thesis was conducted during the period of August 2014 to October 2017. The Next Generation Inspection Maintenance and Repair (NextGenIMR) project funded the research period. The NextGenIMR project is associated with Project 9- Safety, risk and autonomy in subsea intervention at the Centre of Autonomous Marine Operations and Systems (AMOS) at NTNU. The Norwegian Research Council, Statoil, TechnipFMC, NTNU and SINTEF are the partners in the NextGenIMR project.

The target audience of this thesis is personnel working with development of autonomous remotely operated vehicles, subsea system developers, technical safety researchers and safety regulating bodies in the subsea oil and gas industry. The findings from the presented research may actively influence future regulation, design, and operation of autonomous subsea inspection, maintenance and repair (IMR) systems.

As the oil and gas industry looks to decrease the operational cost of subsea fields, the introduction of autonomy is regarded as one of the solutions. However, the impact of the introduction of autonomous principles to an existing system needs to be addressed. In addition, research literature focusing on risk management strategies for autonomous subsea interventions is limited and is in need of novel contributions. This thesis is, therefore, of significant value as it summarizes risk management aspects during planning and operation phases, which need to be addressed collectively by all stakeholders to develop safe autonomous subsea intervention systems.

Before starting on my Ph.D., I worked as a safety engineer in TechnipFMC where I amassed knowledge about the use of underwater vehicles in subsea interventions, the design of subsea infrastructure, design of safety instrumented systems and subsea intervention systems under development. My background in reliability and safety engineering has motivated me to understand, identify and model key risk influencing factors in future autonomous subsea interventions. With these experiences, I have tried to maintain objectivity in all research contributions during the Ph.D. period, and I believe, you as a reader will notice this.

Abstract

Autonomous subsea interventions are anticipated to decrease operational costs, reduce response time and optimally maintain the subsea infrastructure. However, the introduction of autonomy may lead to emerging risk factors in subsea intervention operations. Research on managing risk in future autonomous subsea interventions is scarce. At the same time, the industry and research communities are spearheading this technological change in subsea inspection, maintenance, and repair (IMR) operations by developing and demonstrating new concepts to realize autonomous subsea interventions. Techniques to identify, assess, and manage risk factors affecting autonomous subsea IMR operations are therefore required.

The purpose of this thesis is to develop novel tools and methods to manage risk in autonomous subsea IMR operations. Gaps in the industry standards, which lay requirements for current subsea interventions, have been mapped. The results show that technology and knowledge gaps exist in realizing autonomous subsea interventions and that the current standards are only partly applicable to future IMR systems. Risk influencing factors inherent in autonomous subsea interventions have been identified and analyzed. A Bayesian belief network is proposed to derive the probability of aborting an autonomous subsea IMR operation. Monitoring risk-influencing factors in terms of risk indicators can contribute to improved situational awareness and path planning. The proposed risk based indicators can highlight risk trends for the autonomous remotely operated vehicle.

Vehicle behavior under faults, failures and exposure to surrounding subsea obstacles has been explored in this thesis. A fuzzy inference system is proposed to derive a decision support basis for the autonomous remotely operated vehicle to make decisions to either continue or discontinue an IMR operation. It is observed that fuzzy logic can be used to suggest appropriate safe actions when component faults or failures occur. Concerning avoiding collision with surrounding obstacles, a novel underwater collision avoidance system is proposed consisting of safety envelopes around the autonomous remotely operated vehicle and subsea traffic rules. The subsea traffic rules are proposed for known static and dynamic obstacles in the vicinity of the autonomous remotely operated vehicle.

Overall, researchers, original equipment manufacturers, subsea system developers, and safety regulating bodies may benefit from the results of this thesis. The proposed tools and methods contribute to efficient identification, assessment and management of risks during autonomous subsea IMR operations.

Dedicated to my dear parents and brother.

Jagannath. M. Hegde

Jayalaxmi. J. Hegde

Jeevan Hegde

Acknowledgments

During the span of my Ph.D. project, I have been fortunate to have been coached by supervisors, such as Prof. Ingrid Bouwer Utne, Prof. Ingrid Schjølberg, and Mr. Brede Thorkildsen. I offer my sincere thanks to Prof. Utne, who as my main supervisor has introduced me to the nuances of how to perform structured research. I thank Prof. Schjølberg for giving me the opportunity to work in the NextGenIMR project and for her honest feedback on my Ph.D. work tasks.

I would also like to thank Mr. Brede Thorkildsen for continuously supporting and believing in my research ideas and for being a long-standing mentor in Norway. I am grateful for all the NextGenIMR project personnel from TechnipFMC, Statoil, and SINTEF for their honest and valuable feedback given during numerous NextGenIMR project meetings. I am also grateful to the funding received by the Norwegian Research Council that made my research possible.

I would like to thank my NextGenIMR project mates, Mr. Eirik Hexeberg Henriksen and Mr. Bård Nagy Stovner, for their support in successfully planning and executing the demonstrations in the Marine Cybernetics Lab. I thank Mr. Børge Rokseth for his kind assistance in debugging the software code. Mr. Christoph Thieme, my office mate, has been a great comrade in both happy and harsh times. I thank him for all the valuable official and personal discussions we had. Thanks to my co-authors, Dr. Mauro Candeloro, Dr. Anastasios M. Lekkas and Prof. Asgeir Johan Sørensen, for their valuable input to my work. I would like to thank the administration staff at the Department of Marine Technology for their help and support during this period. I would like to thank the committee members Prof. Faisal Khan, Dr. Siegfried Eisinger and Prof. Arne Ulrik Bindingsbø for their valuable feedback to an earlier version of this thesis.

I offer my sincere thanks to all my close friends in India and Norway who have always wished me well: Ashish, Anirban, Anirudh, Arindam, Ashutosh, Bhushan, Jitapriya, Kinga, Laxminarayan, Nathaniel, Pratima, Pavan, Suhas and Sulalit to name a few.

I would like to thank my family, who imbibed in me traits such as curiosity, resilience and humility. Their belief in my goals and in me is the only reason I am where I am today. Last but not the least; I thank Sharada, my wife, for her continued love and support.

I recall my first supervision meeting during which Prof. Utne quoted "Jeevith, a good Ph.D. is a finished Ph.D". With the delivery of this thesis, I believe I have managed to achieve just that.

Jeevith Hegde,
Trondheim, Norway

Contents

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Abbreviations

AI	Artificial intelligence
AIV	Autonomous inspection vehicle
AIS	Automatic identification system
AMOS	Centre for autonomous marine operations and systems
AROV	Autonomous remotely operated vehicle
AUV	Autonomous underwater vehicle
BBN	Bayesian belief network
CAS	Collision avoidance system
CPT	Conditional probability table
CPA	Closest point of approach
COLREGs	Collision regulations
FIS	Fuzzy inference system
IEC	International electrotechnical commission
IMR	Inspection, maintenance and repair
ISM	Interpretive structural modelling
LARS	Launch and recovery system
MIE	Mean impact energy
MTTC	Mean time to collision
NextGenIMR	Next generation inspection, maintenance and repair
OEM	Original equipment manufacturer
OOBN	Object oriented bayesian network
PAIV	Prototype autonomous inspection vehicle
RAUVIM	Reconfigurable autonomous underwater vehicles for intervention missions
RIF	Risk influencing factor
RMSE	Root mean square error
ROT	Remotely operated tools
ROV	Remotely operated vehicle
SAUVIM	Semi-autonomous underwater vehicle for intervention mission
SCM	Subsea control module
SPS	Subsea production system
SRV	Subsea resident vehicle
SSN	Space surveillance network
TCAS	Traffic collision avoidance system
TMS	Tether management system
TTC	Time to collision
UUV	Unmanned underwater vehicle

"All achievements, all earned riches,
have their beginning in an idea."

- Napoleon Hill

Part 1: Main Report

1 Introduction

1.1 Background and motivation

Globally, subsea oil and gas installations have increased rapidly in the last decade (Jossang et al., 2008; Zijderveld et al., 2012). Industry forecasts estimate continued growth in the subsea sector in the coming years (UTC, 2012). On the other hand, novel subsea infrastructure designs are being proposed to become more cost efficient and safe (Radicioni and Fontolan, 2016). In recent years, phrases such as All Subsea Operations and Subsea Factories are used to describe future subsea field concepts (Ramberg et al., 2013; Ruud et al., 2015). With a large number of existing subsea fields and the future development of subsea factories, there is a need to develop new technologies, which can optimize various phases of subsea operations to achieve cost efficiency and improved safety.

Currently, the subsea oil and gas industry in Norway is focusing on developing robust techniques to perform cost-effective subsea inspection, maintenance and repair (IMR) operations. IMR operations are fundamentally contingency activities, which are performed only when there is a need for preventive or corrective maintenance of the subsea infrastructure. The objective of an IMR operation is to ensure continued functional availability of subsea production systems (SPS). However, mobilizing resources in current/traditional IMR operations consists of resource-intensive tasks, such as planning logistics support, planning process shutdowns, determining marine vessel availability, spare part strategies, crew availability, and other operational resources (Chardard, Y and Copros, T, 2002). These resources are highly variable depending on factors such as location accessibility, operational weather windows and task complexity (Uyiomendo and Markeset, 2010). Improper planning of these resources can lead to an increase in the overall operating cost.

One novel solution to increase the efficiency of IMR operations is to utilize a fleet of autonomous systems, such as underwater vehicles that require limited operator control. The aim of the NextGenIMR project at the Centre for Autonomous Marine Operations and Systems (AMOS) is to investigate the application of underwater vehicles required to perform autonomous subsea IMR operations safely and economically. This project encompasses topics ranging from concept design of autonomous subsea systems, sensor fusion, path planning, and risk management aspects of underwater vehicles used in autonomous subsea IMR operations (Schjølberg et al., 2016; Schjølberg and Utne, 2015).

Challenges related to risk management during autonomous IMR operations could be mapped as shown in Figure 1. To achieve autonomous IMR capabilities, knowledge and

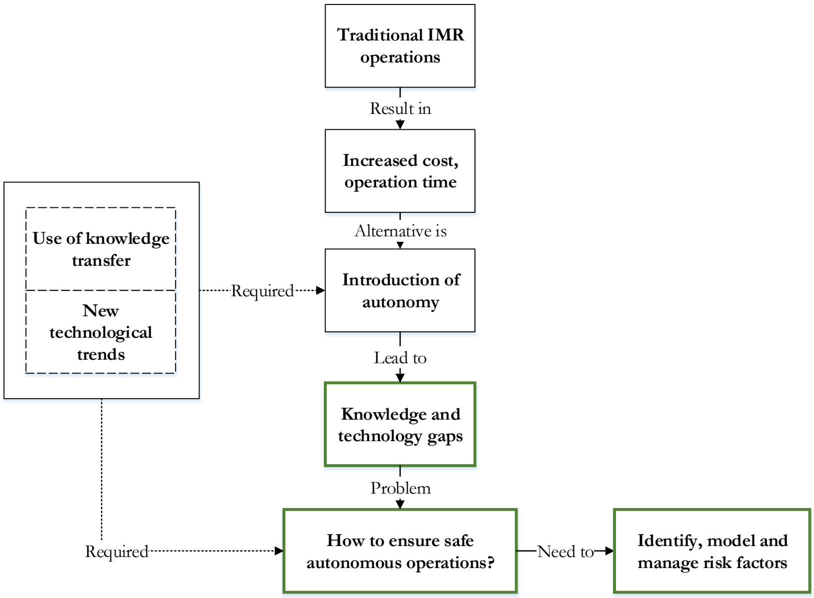

Figure 1.1: Risk management challenges in autonomous IMR operations

technology gaps need to be identified and addressed. These gaps can be filled through either technology transfer from other industries or new research and development initiatives. In both cases, the challenge is to ensure that the new IMR technologies not only consider improving future subsea operations, but are also able to function and service existing infrastructure. This is because the typical lifespan of the subsea infrastructure range from two to three decades, and new IMR technologies developed should be capable of catering to the requirements of both old and new subsea infrastructure until the end of their useful life.

In the presence of technology/knowledge gaps and emerging risks due to the introduction of autonomy, how can autonomous subsea IMR operations be safer? In such circumstances, focusing on risk management is vital as it provides a structured approach to identify, model, assess and manage risk factors involved in autonomous subsea IMR operations. With this as a premise, the next subsection describes the main research questions formulated to provide insight into the challenges mentioned.

1.2 Research objectives and questions

The aim of this Ph.D. study is to develop tools and methods to manage risk during autonomous subsea IMR operations. The risk management tools and methods proposed in this study may support human operators/supervisors of autonomous remotely operated vehicles (AROVs) and the AROVs themselves to make risk-informed decisions. AROVs can be defined as tethered or untethered underwater vehicles with autonomous functionality. The AROVs can independently control manipulator functions, permit shared control between the vehicle and the human operator, navigate autonomously, perform self-diagnostics, and be equipped with automatic remotely operated tool systems requiring limited operator control. AROVs do not currently exist commericially; however, they are in development, which is further discussed in Section 2.1.2

The proposed risk management tools and methods in this study focus on both the planning and the operational phases of autonomous subsea IMR operations. Regulating bodies in charge of safe operations of subsea oil and gas installations can utilize the results to propose requirements for risk management in future autonomous subsea IMR operations. The research study is streamlined by focusing on three main research questions and their sub-objectives elaborated herein.

Research Question 1: What do current standards specify about safe design and operation of underwater vehicles for subsea oil and gas applications, and are they suitable for autonomous subsea IMR operations?

Remotely operated vehicles (ROVs) are currently used in subsea IMR operations and various industry standards specify the requirements for such vehicles. However, with the introduction of autonomy in the subsea IMR processes, there is a need to identify existing technology and knowledge gaps. Also, future requirements for the design and operation of autonomous remotely operated vehicles need to be identified early in the development phase.

Objective 1: Identify current gaps in standards and guidelines concerning remotely operated vehicles.

Research Question 2: How can modeling of risk influencing factors (RIFs) provide decision support for autonomous subsea IMR operations?

ROVs are vehicles that are exposed to collision risk in the subsea environment. Land, air and water-based vehicles also consider collision risk as one of the main risks during planning and operation. Industries, such as aviation, marine, railways, and automotive have previously developed indicators or metrics to assess the risk of collisions, but there are no indicators developed specifically for underwater applications.

Objective 2: Develop risk-based indicators to plan safe waypoints in the vehicle path during autonomous subsea IMR operations.

The introduction of autonomy in subsea IMR operations can lead to numerous emerging RIFs. The state of these factors can affect the overall success of the IMR operation; therefore, it is vital to identify these risk factors and map their relation to each other. Since the types of risk range from technical, human and organizational, identification of risk factors is a challenging task.

Objective 3: Identify and model RIFs in autonomous subsea IMR operations.

Research Question 3: How can autonomous ROVs make or suggest safety critical decisions during autonomous subsea IMR operations?

During autonomous subsea IMR operations, the AROV needs to protect itself from colliding with obstacles in the subsea environment. This can be achieved by constructing a barrier in space and time between the AROV and the obstacle. The barrier here can refer to a safety envelope around the AROV. If the barrier is breached, the second line of defense is to model the behavior of the vehicle such that it avoids colliding with a known obstacle(s). Currently, a similar safety envelope and rule-based collision avoidance system (CAS) exists in industries such as aviation, marine, space, and land-based vehicles. Adaptation of CAS from other industries to the underwater vehicle applications may provide an intelligent behavior based underwater CAS.

Objective 4: Develop safety envelopes and subsea traffic rules to be used by autonomous ROVs.

Although human supervisors will need to continuously monitor the AROVs, in some situations AROVs will need to react on their own rather than waiting for an input from the supervisor, for example, deciding to discontinue the mission if a subsystem of the AROV fails. If a decision support basis is developed for AROVs, AROVs can use these guidelines to return to a safe condition with or without the input of human supervisors.

Objective 5: Developing decision support systems to aid vehicle behavior under component faults or failures.

1.3 Delimitations

The primary delimitation is linked to the nature of the system under study. AROVs do not currently exist in the market but are envisioned by the industry. There is limited publically available research literature focusing on risk management techniques for AROVs. Therefore, the research approach utilized in this study was a mixture of conceptual, applied, and quantitative research approaches, which are presented in Section 3.1. The conceptual IMR systems used as case studies in the articles are limited to two types of autonomous subsea IMR concepts a) An IMR system using AROVs that are launched from an intervention vessel, and b) An IMR system using resident AROVs that are launched from subsea garages.

Secondly, the industry partners in the NextGenIMR project represent companies manufacturing the SPS and the operator of oil fields; therefore, the goals set for autonomous subsea IMR operations reflect the perspective of the operator and the supplier company. These goals were used as a baseline when developing the proposed risk management tools and methods. Access to service contractors may have provided alternative perspectives on the topic, but this was not practically feasible within the scope of the project.

Although the tools and methods proposed in this study are related to risk management in autonomous subsea IMR operations, the proposed measures can be adapted and used in the application, such as subsea mining, aquaculture, offshore wind farms and other unmanned marine systems.

1.4 Overview of contributions

This section summarizes the key academic and industrial contributions made through the publications attached in this thesis. The contributions from all the co-authors are dually disclosed and satisfy the co-authorship requirements laid down by The Vancouver Group in 1985 (The Vancouver Convention, 2016).

1.4.1 Article 1 - Conference paper

Hegde J, Utne I, Schjølberg I. Applicability of current remotely operated vehicle standards and guidelines to autonomous subsea IMR operations. ASME. International Conference on Offshore Mechanics and Arctic Engineering, Volume 7: Ocean Engineering :V007T06A026. DOI:10.1115/OMAE2015-41620

- ✧ Contribution 1: Provides original equipment manufacturers (OEMs) of ROVs, service companies, regulators, and oil operators with an overview of current industry standards.
- ✧ Contribution 2: With the cooperation of partner companies in the NextGenIMR project, the Subsea Control Module (SCM) replacement IMR operation is described in a detail.
- ✧ Contribution 3: Demonstrates the lack of risk management requirements by organizations regulating the use of ROVs in the subsea industry, especially requirements for autonomous subsea IMR operations.

Contribution of authors

The candidate has reviewed current underwater vehicle standards and identified gaps. The candidate also drafted the article and presented the article at the International Conference on Offshore Mechanics and Arctic Engineering - OMAE 2015. The second author has contributed extensively in editing the article and proofreading. The third author has contributed in developing the case study for the article.

1.4.2 Article 2 - Journal article

Hegde, J., Utne, I.B., Schjølberg, I., 2016. Development of collision risk indicators for autonomous subsea inspection maintenance and repair, Journal of Loss Prevention in the Process Industries, Volume 44, 2016, Pages 440-452, ISSN 0950-4230, DOI:10.1016/j.jlp.2016.11.002

- ✧ Contribution 4: Presents a method for developing collision risk indicators for AROV applications.
- ✧ Contribution 5: Provides an overview of existing collision metrics from four vehicular industries.
- ✧ Contribution 6: Proposes three collision risk indicators, namely time to collision, mean time to collision and mean impact energy.

Contribution of authors

The candidate has developed the proposed risk indicators, drafted the article and corresponded with the Journal of Loss Prevention in the Process Industries. The second author has contributed extensively in framing the scope, refined the method, and proofreading the article. The third author has contributed in developing the case study and proofreading the article.

1.4.3 Article 3 - Journal article

Hegde, J., Utne, I.B., Schjølberg, I., Thorkildsen, B., 2017. A Bayesian approach to decision making applied to autonomous subsea IMR operations. Submitted to the Journal of Reliability Engineering and System Safety. Status - Resubmitted after first revision.

- ✧ Contribution 7: Proposes a thirty-eight node Bayesian Belief Network (BBN) to model the risk in autonomous subsea IMR operations. The proposed BBN is capable of calculating the probability of aborting the IMR operations for combinations of scenarios.

Contribution of authors

The candidate has developed the BBN model, drafted the article and corresponded with the Journal of Reliability Engineering and System Safety. The second author has contributed extensively in framing the scope, refined the method, and proofreading the article. The third author has contributed in developing the case study and proofreading the article. The fourth author arranged and assisted in performing expert elicitation workshop and proofread the article.

1.4.4 Article 4 - Conference paper

Hegde, J., Utne, I.B., Schjølberg, I., Thorkildsen, B., 2015. Application of fuzzy logic for safe autonomous subsea IMR operations. In Safety and Reliability of Complex Engineered Systems. CRC Press, pp. 415-422. DOI:10.1201/b19094-58

- ✧ Contribution 8: Proposes a fuzzy inference system to aid decision-making during component faults and failures in autonomous ROV subsystems.
- ✧ Contribution 9: Describes possible decisions autonomous ROVs can chose during component fault and failure scenarios.

Contribution of authors

The candidate has developed the proposed fuzzy inference system, drafted the article and presented the article at European Safety and Reliability Conference - ESREL 2015. The second author has contributed extensively in framing the scope, refined the method, and proofreading the article. The third author has contributed in developing the case study and proofreading the article. The fourth author made edits to the draft and proofread the paper.

1.4.5 Article 5 - Journal article

Hegde, J., Henriksen, E.H., Utne, I.B., Schjølberg, I., 2017. Development of safety envelopes and subsea traffic rules for autonomous remotely operated vehicles. Submitted to Journal of Safety, MDPI. Status - Under review.

- ✧ Contribution 10: Provides an overview of collision avoidance systems used in three vehicular-based industries.
- ✧ Contribution 11: Presents the process for developing safety envelopes and subsea traffic rules for autonomous underwater vehicles.

Contribution of authors

The candidate contributed to the development of the safety envelope and subsea traffic rules, and corresponded with the Journal of Safety. The second author has contributed extensively by testing the safety envelopes and safe traffic rules through simulation and laboratory tests. The third author has contributed to frame the scope and proofread the article. The fourth author has contributed in developing the case study and proofreading the article.

1.4.6 Article 6 - Conference paper

Candeloro, M., Lekkas, A., Hegde, J, Sørensen, Asgeir J., 2016. A 3D dynamic voronoi diagram-based path-planning system for UUVs. In OCEANS'16 MTS/IEEE Monterey. Monterey, US. DOI:10.1109/OCEANS.2016.7761427

- ✧ Contribution 12: Proposes safe subsea traffic rules to avoid collisions with known moving subsea obstacles.

Contribution of authors

The candidate developed the safe traffic rules in Section V. The first author contributed to the methods and performed the simulations. The second author contributed to the development of the path planning method. The last author proofread and provided active feedback.

1.4.7 Additional contributions

During the Ph.D. project, collaborative work with research colleagues has resulted in the following two articles. As these articles are in the draft stage, they are not included as a part of this thesis. These publications shall be completed and submitted to relevant conferences and journals in the future.

- ▷ Hegde, J., Henriksen, E.H., Utne, I.B., Schjølberg, I., 2018. Development of dynamic safety envelopes for autonomous remotely operated underwater vehicles. Full paper accepted for European Safety and Reliability Conference - ESREL 2018.
- ▷ Application of systems engineering to subsea autonomous IMR operations. To be submitted to a suitable journal.

1.5 Structure of the thesis

The thesis is divided into two parts, the main report and the collection of articles. The main report of the thesis is structured as follows:

- ▷ Section 1 describes the background, research questions, delimitations and research contributions of this thesis.
- ▷ Section 2 summarizes existing research results and presents the state of the art in the topics related to this thesis.
- ▷ Section 3 presents the approach used to structure and design the research.
- ▷ Section 4 documents the research results.

- ▷ Section 5 discusses the contributions made to the body of knowledge.
- ▷ Section 6 concludes the thesis and presents further work opportunities.

A collection of articles is enclosed in Part 2 of this thesis, consisting of six articles.

"Research is to see what everybody else has seen,
and to think what nobody else has thought."

- Albert Szent-Gyorgyi

2 State of the Art

As highlighted in Section 1, current subsea IMR operations face a variety of challenges during the planning and execution phase (Chardard, Y and Copros, T, 2002). This section presents an overview of risk management tools and methods used in other autonomous vehicle-based industries, which can be adapted to autonomous subsea IMR applications. Current challenges in introducing autonomy in subsea IMR operations are discussed in brief. The aim of this section is to demonstrate the novelty of this thesis when compared to historical results published in the literature. This section identifies relevant past contributions from other researchers, which can be adapted to solve the research questions of this thesis.

2.1 Subsea intervention

According to Bai and Bai (2010), subsea intervention encompases all activities performed subsea. It includes subsea activities performed in all stages of the subsea lifecycle ranging from field development to field abandonment. In particular, subsea intervention is vital during the operational stage of the subsea lifecycle as it ensures continuous production from the SPS by fixing faulty and repairing failed components of the SPS.

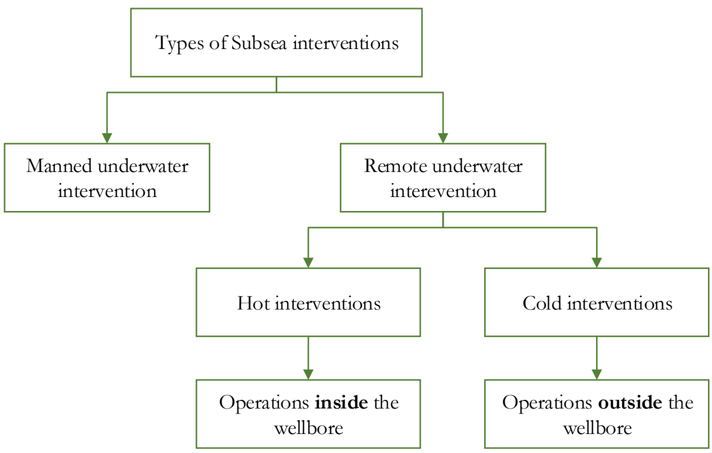

Figure 2.1: Classification of subsea interventions based on type of intervention

Subsea interventions are mainly categorized into two types, manned and remote underwater interventions as illustrated by Figure 2.1. Manned underwater interventions are where human divers perform the intervention operation; for example, underwater structure inspection and welding. Remote underwater interventions are when an unmanned technical system is used to carry out the intervention operation. Remote underwater intervention can further be classified into two types, hot and cold interventions.

Hot interventions are interventions in which the wellbore is actively intervened to perform IMR operations. Wireline, slickline, fishing, cleaning operations and other wellbore related IMR operations are also classified as hot interventions. On the other hand, cold interventions are intervention operations performed outside the wellbore and on the SPS and other subsea infrastructure. For example, an operation to open/close a subsea valve by use of an ROV can be classified as a cold intervention. The scope of this thesis is strictly limited to cold interventions. The next subsection describes how cold interventions are currently performed in the subsea industry.

2.1.1 ROV operations in the subsea industry

Currently, ROVs, along with remotely operated tools (ROTs), are key enablers in maintaining subsea infrastructure. Figure 2.2 illustrates how ROVs are currently used to perform subsea IMR operations. Subsea intervention starts when there is a need for preventive or corrective maintenance of the SPS, triggering the planning phase for the IMR operation. An intervention vessel consists of a minimum of one ROV. Once the intervention vessel has reached the target location, the vessel uses a dynamic positioning system to maintain the position. An ROV control room is situated in the intervention vessel. ROVs are dependent on human operators to fly, control and monitor them from the ROV control room. A tether management system (TMS) is attached to the ROV through an umbilical cable, which provides electric and hydraulic power to the ROV. The ROVs are launched from the launch and recovery system (LARS) situated in the intervention vessel. At a preplanned depth, the running (lowering) of the TMS is stopped. The ROV pilot detaches the ROV from the TMS, and a smaller umbilical roll present in the TMS provides the ROV with power and hydraulic supply (Christ and Wernli, 2014). Depending on the intervention operation, the ROV pilots perform the required operation using the ROT. The ROTs are either lowered using an ROV tool basket or attached to the TMS.

According to Chardard, Y and Copros, T (2002), there are four key drawbacks in traditional ROV interventions: 1) Traditional ROV interventions are costly due to the requirement of specialized intervention vessels, 2) Mobilizing for traditional ROV interventions is time-consuming and cannot cater to the urgent need for interventions, 3) The intervention operations are dependent on the weather window and environmental conditions, 4) The TMS and the umbilical are seen as weak points due to susceptibility to material failures in connectors and cables.

2.1.2 Underwater vehicles in subsea intervention operations

In recent years, the development and application of underwater vehicles have led to a new category of vehicles, as shown in Figure 2.3. Underwater vehicles, which are remotely operated by a human operator, are classified as Remotely Operated Vehicle (ROV). Underwater vehicles, which have autonomous flying capabilities, are termed as Autonomous Underwater Vehicle (AUV). Future requirements for autonomous subsea IMR focus on combining both of these functions into a single vehicle. These hybrid vehicles, or AROVs,

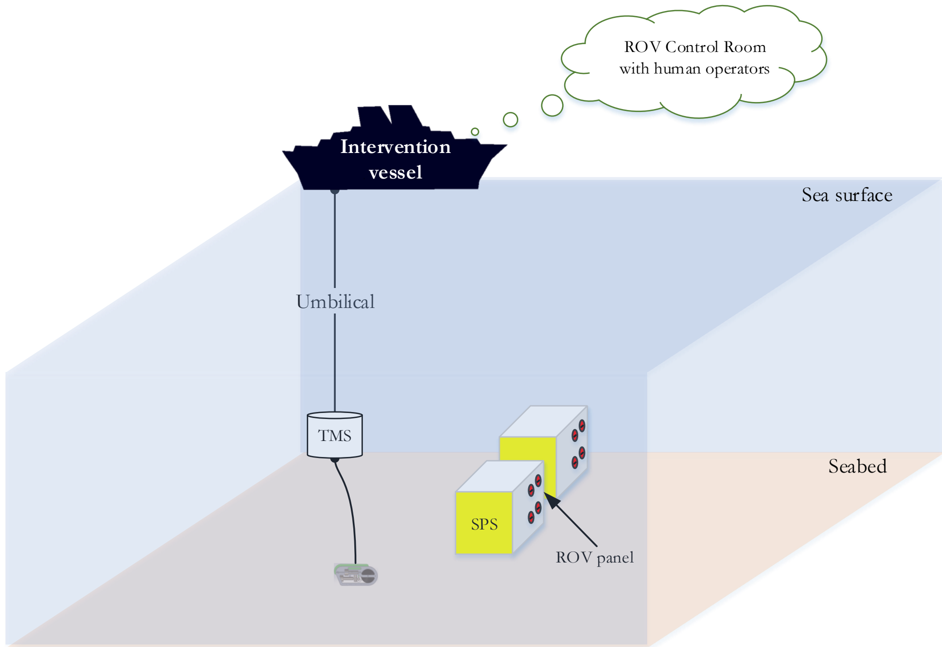

Figure 2.2: Intervention philosophy of traditional subsea IMR operations adapted from Bai and Bai (2010)

may retain the functions of both the ROVs and AUVs making them versatile during different IMR operations. The operators of these hybrid vehicles can choose to either carry out the operations through manual control, shared control or autonomous control.

Currently, autonomous IMR systems are still in the conceptual or testing stages of development. Some research projects have or are currently investigating development and implementation of autonomous functionalities and shared control in underwater vehicles. The research projects are trying to develop hybrid vehicles by two different approaches. The first approach is to modify ROVs to incorporate more autonomous functionality. The second approach is to modify AUVs to incorporate manipulation capabilities. A brief description of these projects is provided in the following subsections.

From ROVs to hybrid underwater vehicles

Chardard, Y and Copros, T (2002) proposed an innovative hybrid ROV/AUV concept called the SWIMMER. The SWIMMER vehicle was conceptualized to deploy an ROV on a deepwater field and avoid the need for umbilicals and intervention vessels. Saul and Tena (2007) presented British Petroleum's long-term goal to develop underwater vehicles capable of performing autonomous subsea interventions. The vehicle is named as Prototype Autonomous Inspection Vehicle (PAIV). BP, Chevron, Subsea 7 and SeByte are partners in this joint industry collaboration.

Jamieson et al. (2012) discussed the use of ROVs with autonomous capabilities, which can

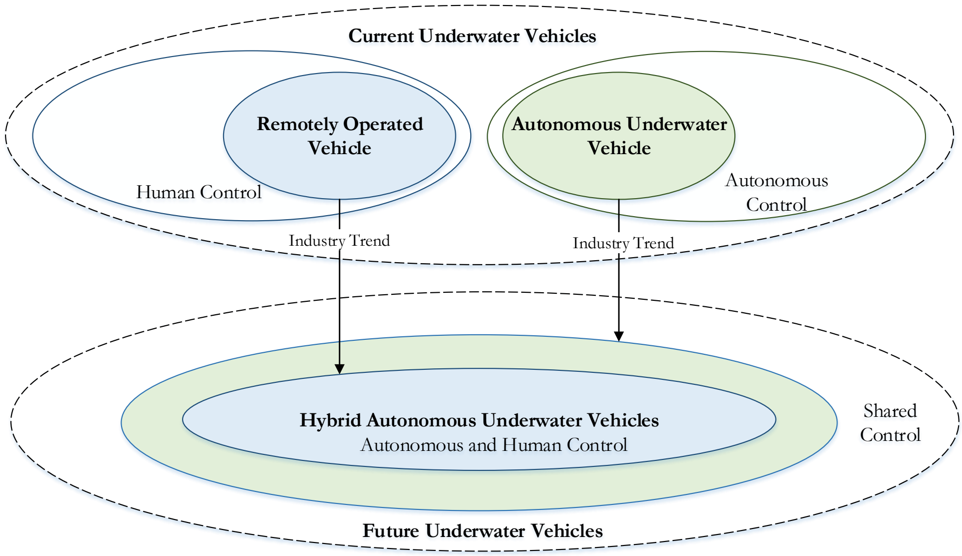

Figure 2.3: Development trend in underwater vehicles in IMR applications

navigate around the SPS and perform autonomous subsea interventions. In particular, the focus is on inspection and localization of the MK1 Autonomous Inspection Vehicle (AIV). The results from underwater trials show that the AIV errors during re-localization range from 2 to 5 meters. Furuholmen et al. (2013) described the need for subsea resident vehicles (SRVs) that are semi-autonomous, tetherless vehicles with hovering capabilities. Furuholmen et al. (2013) provided insight into three key drivers to use SRVs, namely i) general oil and gas demand, ii) increase in subsea fields located in deep and ultra-deep waters and iii) development in underwater robotics technology. System integrity, reliability, endurance, autonomy, underwater wireless communication, and underwater power charging are listed as critical challenges to realize IMR operations using SRVs.

Mai et al. (2016) claimed that AUVs have distinct advantages compared to ROVs when considering subsea IMR applications. AUVs are cheaper to deploy and recover, and also provide higher quality data, local high-level autonomy, limited battery capacity, and communication setups. Combining ROV functions with AUV functions is claimed to decrease inspection cost. Gancet et al. (2016) described the need for cost-effective and time-efficient ROV operations in the DexROV project. This project is proposing a solution for dexterous undersea interventions using a ROV as the primary underwater vehicle. Underwater perception and mapping, autonomous navigation and manipulation, deep water dexterous manipulator and effector, and remote control center and communication latencies mitigation are four objectives of the DexROV project. The project will demo the methods on a mock-up subsea infrastructure roughly 1300 meters deep in the mediterranean sea.

From AUVs to hybrid underwater vehicles

Marani et al. (2009) presented the results from the first trials of Semi-Autonomous Underwater Vehicle for Intervention Mission (SAUVIM). The SAUVIM is fitted with a MARIS 7080 underwater manipulator. According to Marani et al. (2009) , the key observation in the trials is the level of information transferred between the human supervisor and the SAUVIM. The task for the trial was to search and retrieve a target object and bring it to the surface. Prats et al. (2012) described the validation of the Reconfigurable Autonomous Underwater Vehicles for Intervention Missions (RAUVI) through a successful autonomous search and recovery task. The RAUVI software system consists of three layers, a physical layer, control layers, and an application layer. A flight data recorder is a target to be searched and retrieved to the surface. A vision based station keeping system is used to track the target and to maintain the position of the RAUVI.

McLeod (2010) highlighted three key aspects to focus on to make AUVs capable for intervention operations. The three aspects are increased autonomy, change in vehicle form factor, and a use of sensor fusion. McLeod and Jacobson (2011) showed the use of an AUV as an inspection tool in The Gulf of Mexico operated by only three people: vehicle operator, crane operator and deckhand. Lockheed Martin's Marlin autonomous underwater vehicle is also used in combination with LiDar sensors to generate subsea 3D maps that can be used to inspect the structural integrity of the subsea structures (McLeod et al., 2012). Albiez et al. (2015) focused on developing an inspection AUV capable of residing in subsea conditions and inspect subsea infrastructure on demand. FlatFish is a project collaboration between the British Gas group in Brazil and the Brazilian Institute of Robotics (Albiez et al., 2015).

As observed, the literature provides evidence that the development of hybrid underwater vehicles for subsea IMR applications is extensive as these types of vehicles are in high demand. In summary, future hybrid underwater vehicles may retain the functions of both the ROVs and AUVs, thereby making them versatile during IMR operations. Also, they can have capabilities to reside in subsea garages, which may decrease the IMR operation time. The operators of these hybrid vehicles can choose to either carry out the operations through manual control, shared control or autonomous control. However, it is not evident from the literature how autonomous subsea IMR operations will be different from traditional subsea interventions. For example, what kind of technology and knowledge expertise is needed to shift from traditional IMR operations to autonomous subsea IMR operations? Current standards focusing on the development of underwater vehicle technology may provide valuable insight. Objective 1 of this thesis addresses this challenge.

2.2 Risks in autonomous subsea IMR operations

"Risk" is a complex term, and the definition of risk has been debated in the literature, leading to no singular definition. Risk can be both subjective and objective. The definition of risk by one person may differ to that defined by another person or group. Rausand (2011) documented the different definitions of risk in the literature. Fundamentally, risk as per the context of this thesis depends on three questions: (1) What kind of accidental events can occur in a system?, (2) What is the likelihood of accidental event occurring?, and (3) What are the consequences of the accidental event?

According to IEC 60300-3-4 (2007), a system consists of hardware, software equipment and humans who operate and maintain such equipment by using predetermined procedures, and encompasses the surrounding environment. Current IMR systems and future autonomous IMR systems satisfy characteristics of socio-technical systems laid by Bad-

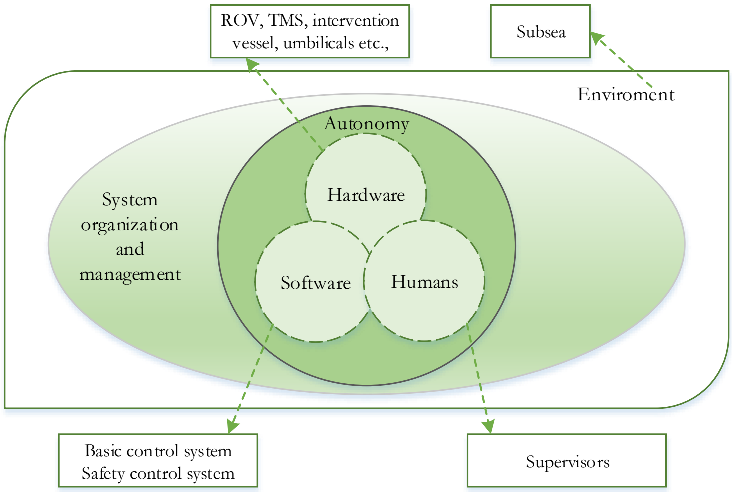

Figure 2.4: Elements of a socio-technical system adapted from IEC 60300-3-4 (2007)

ham et al. (2000). With the adoption of autonomy in subsea IMR operations, changes in operational philosophies are inevitable. The system, therefore, also has to include impacts of sharing autonomy within the hardware, software, human and environment as shown in Figure 2.4.

Hardware relates to the various equipment in the system; software relates to software and firmware required to operate the system; humans relate to the operators and maintenance personnel ensuring availability of the system; autonomy relates to the level of autonomous task allowed to perform by the hardware, software and the human; and environment relates to the immediate surroundings of the system. For an autonomous IMR system, AROVs, TMS, and the intervention vessel can be categorized as hardware. Software elements consists of the basic and safety control system, a human supervisor supervises the AROVs, and the operational environment is subsea.

Additional complexity introduced into the IMR system in the form of autonomy may result in emerging risk factors, for example, lack of situational awareness between the elements of the system, unclear human machine interfaces, unclear vehicle behaviour, unclear rules of engagement etc., It is, therefore, important to ensure that autonomous subsea IMR operations in the future are at minimum safer and more efficient than current subsea interventions. This notion is also reflected in an excerpt from Jamieson et al. (2012), which reads:

> *"Logic would lead us to think that automated systems by their nature are more reliable, repeatable and controllable. However, it is human nature to want to maintain some level of direct control even when it is acknowledged that the automatic system is well capable of performing the task."*

Griffiths et al. (2002) listed three categories of risks emerging from the adoption of AUV operations: technical, personnel and operational as illustrated in Figure 2.5. Some of the technical risks are the lack of knowledge of the AUV system, fault or failure in electromechanical systems, embedded software, sensor modules and the state of the subsea environment. According to Griffiths et al. (2002) the risk to personnel can be associated with procedural steps during the launch of the AUV when safety barriers are removed. Personnel working on AUVs can also be exposed to the AUVs' spent batteries. Operational risk can include procedural, liability and insurance risks.

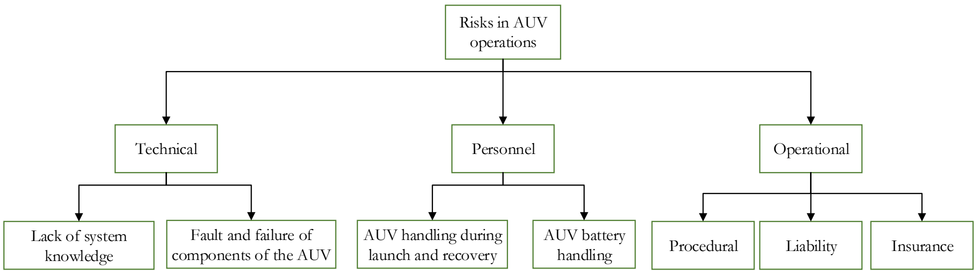

Figure 2.5: Risks emerging from AUV operations according to Griffiths et al., (2002)

Utne and Schjølberg (2014) identified and categorized risk related to AUV operations by considering different types of events. The four events are natural, technical, human behavior and malicious events. For each type of event, three levels of risk factors are identified and presented. Although many risk factors are documented in the literature for AUVs, the research studies have not considered emerging risk factors due to adoption of autonomy in subsea IMR operations. It is vital to identify and investigate how the interactions of these emerging risk factors take place and how to model them to develop a decision support system. This need is also reflected in Objective 2 and 3 of this thesis.

2.3 Risk modeling and monitoring methods

To ensure safe autonomous subsea IMR operations, technical, human and operational risk factors need to be modeled and managed. The literature provides sparse information on risk modeling of autonomous IMR system. Nevertheless, review of risk modeling and monitoring techniques from other applications can be advantageous in developing novel risk management tools and methods. This section presents the current literature on risk modeling and risk indicators.

2.3.1 Risk modeling

The term risk modeling is used in different contexts, and there is no singular definition of this term in the literature. Mohaghegh et al. (2008) described that a risk-modeling framework for socio-technical systems could be derived by a combination of modeling techniques. These modeling techniques could be formal probabilistic risk analysis techniques, such as event sequence diagrams, event trees, barrier block diagrams and fault trees. Process modeling techniques model the production process of organizations. Deterministic dynamic techniques can use existing "deterministic" relations to model the system. Regression based techniques calculates statistical causality or correlation between a set of a variables. In Bayesian belief networks, uncertain, soft, deterministic, probabilistic risk factors can be linked to each other to obtain a joint probability distribution.

Defense in depth, root cause determination, and barrier management are other techniques used in risk modeling (Vinnem, 2014). Risk modeling using defense in depth can be summarized as modeling numerous safeguards before or after the occurrence of an accident. Defense in depth is comparable to accident prevention strategies proposed by Haddon (1980), which describes multiple steps to avoid, reduce and contain the energy leading to accidents. In recent years, risk modeling is also performed by developing the barriers to avoid, contain and recover from high-risk accidents. The Petroleum Safety Authority in Norway has recommended the use of barrier management as a tool in risk modeling in the petroleum industry (Petroleum Safety Authority, 2013).

Bayesian belief networks

In recent years, Bayesian belief networks (BBNs) are combined with traditional risk modeling techniques, such a fault trees and event trees to develop risk models. The resulting risk models are aptly termed as hybrid risk models (Røed et al., 2009; Vinnem et al., 2012). Two key advantages of hybrid risk models are, 1) they allow incorporation of soft risk factors related to the organization and human operators, and 2) they can be extended from static systems to dynamic systems. However, BBNs are difficult to quantify. When the available evidence for a risk factor is non-definite, uncertain or partial, it can be categorized as a soft factor (Kjaerulff and Madsen, 2008; Mohaghegh, 2010). For example, human and organization risk factors can be categorized as soft risk factors. Renooij (2001); Renooij and Witteman (1999) highlighted challenges in determining conditional probability tables (CPTs) for BBNs when expert judgments are used. Hansson and Sjökvist (2013) and Mkrtchyan et al. (2016, 2015) discussed the current methods used to develop CPTs. Other researchers have proposed the use of fuzzy logic or object-oriented Bayesian networks (OOBN) to decrease the work load in CPT allocations (Luxhøj, 2015; McDonald et al., 2015). Since BBNs by design are exposed to expert's subjective judgment (both in structuring and in quantification), validating BBNs can also be challenging (Hodges and Dewar, 1992; Pitchforth and Mengersen, 2013; Pitchforth et al., 2014). Sajid et al. (2017) presented a solution to decrease structural uncertainties when constructing BBNs by using the interpretive structural modelling (ISM) technique.

Because of the flexibility of BBNs to incorporate probabilistic nodes, deterministic nodes, and expert subjectivity, they are currently being used to model the risk of autonomous underwater vehicle operations. Griffiths and Brito (2008) investigated the use of BBNs to estimate risk in missions under different sea ice conditions. Brito and Griffiths (2016) extended the Bayesian approach to analyze the risk of loss of AUVs during missions. Vehicle type, ice concentration, thickness, environmental constraints, etc. are highlighted to contribute to the loss of the AUVs. Expert elicitations are extensively used to quantify BBN models in both oil and gas and AUV applications (Brito and Griffiths, 2016; Gran et al., 2012; Griffiths and Brito, 2008; Vinnem et al., 2012). Involvement of experts in the development process aids in verifying the structure. The model proposed by Thieme et al. (2015) presented a BBN to assess the probability of monitoring success for an AUV mission focused on human supervisory actions. Thieme and Utne (2017) extended and quantified the Bayesian belief network to assess the performance of human–autonomy collaboration. In general, current risk modeling studies focus on risks related to human, technology and organizational structure.

Although some published research focuses on use of BBN for AUV applications, a holistic risk model has not been proposed that considers the complexity of the subsea IMR system. To obtain a holistic picture of risk influencing factors in autonomous subsea IMR operations, technical, human and organizational risk influencing factors need to be identified and modeled with due consideration to the scope of autonomy. The relationship between the factors needs to be mapped, and experts in current IMR operations need to provide their inputs to quantify the BBN. The quantification of the BBN is essential to demonstrate the use of the method for autonomous subsea IMR operations. To quantify the BBN, current methods proposed in the literature are promising (Mkrtchyan et al., 2016, 2015). Adoption of one of the quantification methods can be a realistic approach. Objective 3 of this thesis focuses on this challenge.

2.3.2 Risk indicators

Øien (2001) defined the risk-influencing factor (RIF) as an aspect of a system/activity. The measurable quantity of an RIF is termed a risk indicator. For example, consider a car in motion with a velocity of 30 km/s. One of the RIFs when a car is in motion is the velocity of the car. According to Øien (2001), if the "velocity" is an RIF, the value (magnitude) of the velocity is an indicator. When this indicator is used to assess the risk, it is called a risk indicator. Figure 2.6 illustrates the relationship between an RIF, a risk indicator and a risk model. The risk model is a form of a representation of the real world in a model; however, real world factors (RIFs) affect the change in risk. Øien (2001) proposed a generic eight-step method to developing risk indicators.

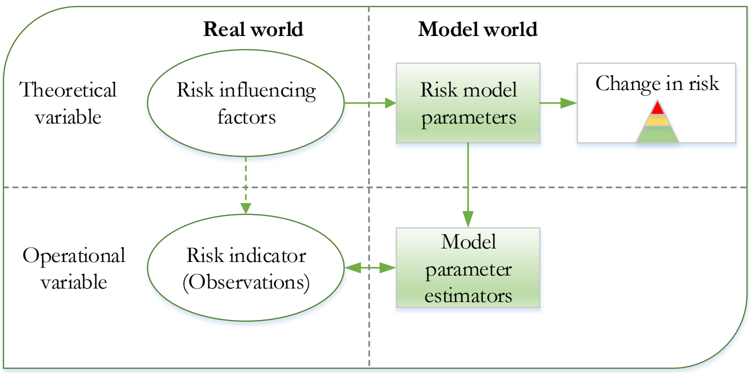

Figure 2.6: Relationship between RIF, risk indicator and risk model adapted from Øien (2001)

In the literature, the terms safety and risk indicators are used interchangeably as noted by Øien et al. (2011a). Risk indicators are used when considering risk models, while safety indicators are used to measure the level of safety either after an occurrence of an event or purely qualitatively before the event. Swuste et al. (2016) provided a comprehensive review of risk and safety indicators used in the process industries. The literature also provides various methods for developing and using risk based indicators: see, e.g., (Hassan and Khan, 2012; HSE, 2006; Jennings and Schulberg, 2009; Khan et al., 2009; Knegtering and Pasman, 2013; Øien, 2001; Øien et al., 2011a,b; Pasman and Rogers, 2014; Sonnemans et al., 2010).

Research focussing on the application of risk indicators in offshore oil and gas applications is well documented as described above. However, it can be observed that methods to develop and use risk indicators to plan safe autonomous subsea IMR operations are lacking. Future autonomous subsea IMR systems will need to incorporate these risk indicators to make risk informed decisions during the planning phase of the IMR operations. Objective 2 of this thesis tries to resolve this challenge.

2.4 Vehicle and human decision support

Decision support systems can aid human supervisors and the autonomous ROVs during autonomous subsea IMR operations to make risk informed decisions. If concepts such as resident vehicles are used, the risk of faulty or failed ROV can result in increased operating costs due to delays in intervention. To avoid costly re-planning and re-working, decision support tools need to be developed. The decision support system should allow a safe transition from a safety critical scenario to a pre-determined contingency. This section provides an overview of existing literature in the field of vehicle behavior under faults. Applications of decision support systems from other high-risk industries, such as aviation, space, marine, and automotive are presented.

2.4.1 Fuzzy logic in decision support

Fuzzy logic theory delivers precise outputs from imprecise inputs, similar to real-life scenarios, where an input parameter can vary within a given range of values. Figure 2.7 is adapted from Zadeh (2002, 1996), which describes the overall methodology of a fuzzy inference system (FIS). In an FIS, input and output variables contain 'n' number of fuzzy sets with shared memberships among other fuzzy sets. This process of converting the crisp input to range values is known as fuzzification. A fuzzy operator is used to connect the antecedent to a consequent through an if-then logic. Defuzzification is achieved by calculating the membership of input variable fuzzy sets against the output variable fuzzy sets. Defuzzification results in a crisp value that can further be used as input to make decisions.

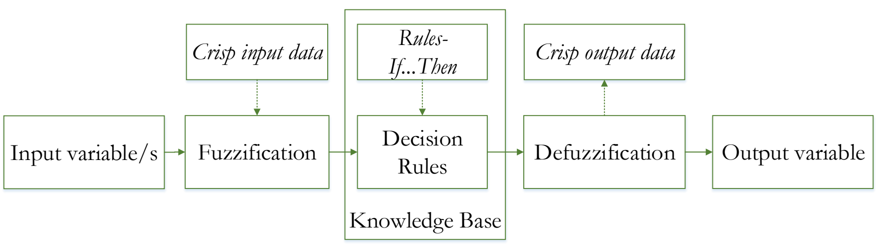

Figure 2.7: Elements of a fuzzy inference system

Ross (2009) highlighted the two main use cases for fuzzy inference systems: first, where the systems are highly complex and the system's behavior is vaguely understood; and second, where an approximate, but quicker solution is acceptable. However, two limitations of Fuzzy logic can be observed: first, fuzzy logic is a form of deductive reasoning i.e., to conclude on a specific truth by using generic inputs (Ross, 2009). An example for deductive reasoning is *"the ground is wet" (input)* therefore, *"it must be raining" (truth).* Second, the fuzzy rule set is developed with expert knowledge base and therefore the determination of fuzzy rule sets can be subjective in nature.

Xiang et al. (2017) presented a two-layered fault tolerant system comprised of a risk analysis and decision subsystem onboard an autonomous underwater vehicle. A fault tree model is developed to identify required data inputs to the fault detection module. The risk analysis module then uses data obtained from the detection module and fuzzifies the inputs to derive a final output decision. Zhu et al. (2015) presented a fault-tolerant strategy to aid decision making for autonomous, underwater vehicle integrated navigation. Anvar, A. P. and Dowling, T. and Putland, T. and Anvar, A. M. and Grainger. S. (2012) proposed a fuzzy logic based condition-monitoring system to perform prognoses and suggest remedial actions.

On the vehicular level, the AROVs need to have a set of behaviors to react to accidental scenarios; however, such decision basis does not exist in the current literature. Fuzzy Logic can be used to suggest decisions when one or more components of the AROV system are faulty or failed. Fault here is defined as an abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function (IEC 61508, 2009). Failure, on the other hand, is defined as the termination of the ability of a functional unit to provide a required function or operation of a functional unit in any way other than as required (IEC 61508, 2009). Essentially, a decision basis can provide an alternative/contingency to a component failure scenario. For example, if one of the sensors on the AROV fails, what should the AROV do? Should it continue the mission, return to the subsea garage, or wait for diagnostics? This challenge is addressed in Objective 5 of this thesis.

2.4.2 Vehicular safety envelopes and traffic rules

As future ROVs will need to operate more autonomously, they need to consider the risk of collision with the surrounding. Currently, in high-risk vehicle industries, an envelope based safety philosophy is used to derive safe traffic rules. Essentially, these envelopes provide a barrier to the vehicle in space and time allowing them to avoid collision scenarios.

Driving envelopes in autonomous road vehicles

Erlien et al. (2013) and Brown et al. (2017) defined a vehicular envelope as the maximum capabilities of the vehicle's tires. Within this envelope, operation of the vehicle can be safely controlled. Further, at every time step, the predicted area covered by the vehicle is input to an environment envelope in which the vehicle is collision free. When obstacles are detected in the envelope, the vehicle behavior changes accordingly to avoid a collision with the obstacle. Burns (2002) defined a safety envelope as a variable space surrounding the vehicle. The shape and the size of the envelope can be dynamically adjusted along its predetermined path and a predetermined set of rules (Burns, 2002).

Collision regulations for marine vessels

In the early 1970s, ships were claimed to be vulnerable to collisions due to increasing marine traffic. The need to safegaurd the ships was observed by the marine industry

(Fujii and Tanaka, 1971). The solution proposed was to utilize the safety philosophy used in the aviation industry and develop a safe area around the ship. The term "ship domain" is defined as "sea around the ship, which the navigator would like to keep free, with respect to other ships and fixed objects" (Goodwin, 1975). Figure 2.8 illustrates the ship domain as proposed by Goodwin (1975), where the safe area varies at different sections of the ship. Currently, numerous methods can be used to determine the effective shape and size covered by the ship domain (Davis et al., 1980; Lewison, 1978; Pietrzykowski and Uriasz, 2009; Tam et al., 2009).

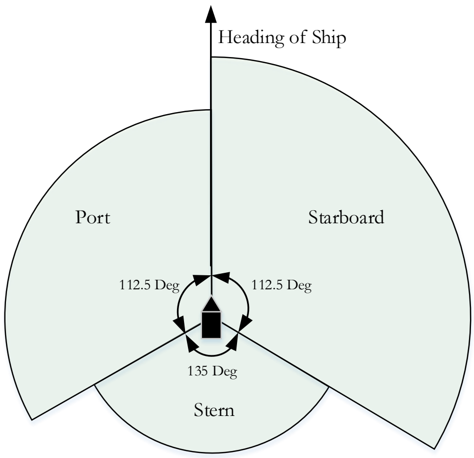

Figure 2.8: Examples of a ship domain as described by Goodwin (1975)

International Maritime Organization (2005) provides safe traffic rules to avoid collisions between powered/unpowered marine vessels at sea. Collision regulations (COLREGs) provide a broad set of rules that marine vessels needed to follow, especially when there is a risk of collision. Rules 7 and 8 describe the scenarios where the risk of collision must be considered and describes the required action to avoid a collision, respectively. Rules 13, 14, and 15 describe the maneuvering ships shall make during overtaking, head-on, and crossing scenarios. Rules 16 and 17 describe the actions that a give-way vessel and stand-on vessel need to take, respectively. Figure 2.9, Figure 2.10, and Figure 2.11 illustrate Rules 13-17, as described by the International Maritime Organization (International Maritime Organization, 2005). In the marine industry, the obstacle detection system is dependent on a functioning radar unit and the automatic identification system (AIS), which detects nearby vessels and their positions and velocities relative to the vessel. The fundamental aim of the COLREGs is to try to increase the horizontal separation distance between two marine vessels, which can be observed from Rules 13-17 of COLREGs.

Collision avoidance regulations in aviation

Due to the inherent nature of aviation operations and the potential risk to human lives, collision risk is addressed extensively in the aviation industry. Traffic collision avoidance systems (TCAS) can detect, assess, and recommend corresponding corrective actions to avoid midair aircraft collisions (Kuchar and Drumm, 2007; US Department of Transportation and FAA, 2011). The TCAS system is based on three fundamental modules, namely, the surveillance module, threat detection and display module, and threat resolution module. The surveillance module is tasked with detecting the intruding aircraft and obtaining

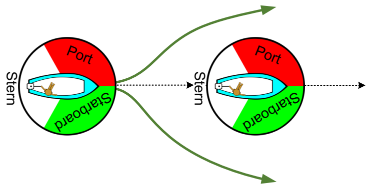

Figure 2.9: Rule 13 of COLREGS

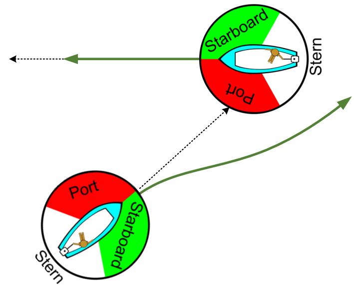

Figure 2.10: Rule 15, 16, and 17 of COLREGS

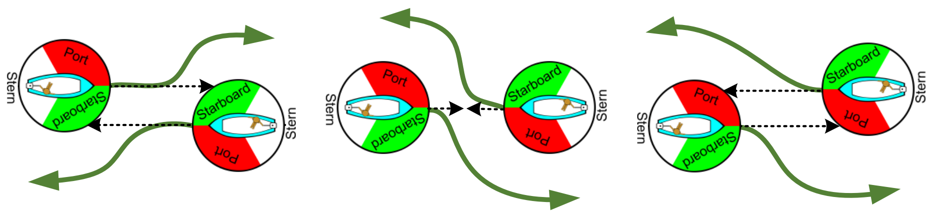

Figure 2.11: Rule 14 of COLREGs International Maritime Organization (2005)

its relative velocity, position, and heading. This is carried out by a set of surveillance sensors (transponders) on board the aircraft. When the intruding aircraft is assessed as a threat by the threat detection module, a traffic advisory alert is issued to the pilots. If the threat persists, an appropriate response is suggested by the threat resolution module of the TCAS in the form of a resolution advisory.

Figure 2.12 illustrates the TCAS envelopes, which consists of a caution envelope approximately 20 to 48 seconds away from the intruding aircraft. A secondary envelope is the warning area where the resolution advisory is suggested and is 15 to 35 seconds away from the intruding aircraft. The vertical separation is recommended to be approximately 850 feet both at the lower and upper regions of the aircraft for the caution area. The vertical distance covered by the warning area is 600 feet in both upper and lower directions.

The presence of TCAS in the intruding aircraft triggers a protocol to avoid the same threat response recommendation to both aircraft. The safety function of the TCAS system is to prevent midair collisions by monitoring vertical and horizontal separation between aircrafts. The human pilots execute the response suggested by the TCAS.

Collision avoidance in space

In the space industry, as the space shuttle orbits, the space control center scans for debris in space that could collide with the space shuttle. There are two envelopes of different

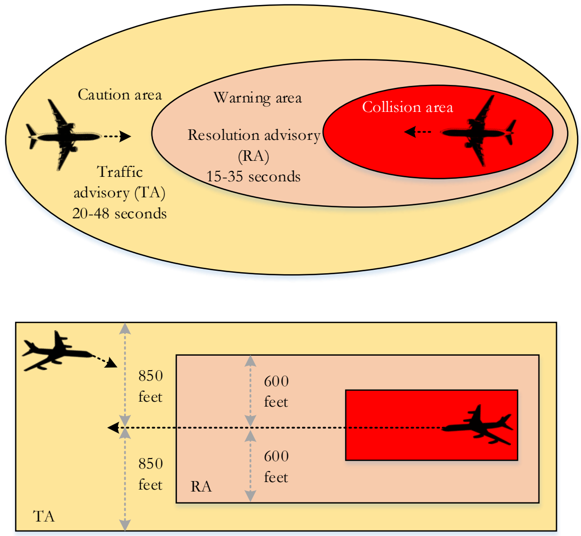

Figure 2.12: Safety envelopes in traffic collision avoidance systems (Kuchar and Drumm, 2007; US Department of Transportation and FAA, 2011)

sizes that are used to safeguard the space shuttle, as illustrated in Figure 2.13. The space surveillance network (SSN) calculates intruding objects within the area of 10 km x 50 km x 10 km, known as the alert box (shaded in yellow). If a threat is detected, the SSN estimates the possibility of the object intruding the maneuver box (orange box), which covers an area of 4 km x 10 km x 4 km around the space shuttle (National Research Council, 1997). If the risk of collision is greater than the operational effects of the maneuver, an avoidance maneuver as stated in the Debris Avoidance Criteria for Predicted Conjunctions shall be performed. The probability of collision in the yellow threshold area is set to 10^{-5} but less than 10^{-4}, and the probability of collision in the orange threshold is set to greater than 10^{-4} (NASA, 2002).

Unlike in marine, aviation, and automotive industries, safety envelopes and safe traffic

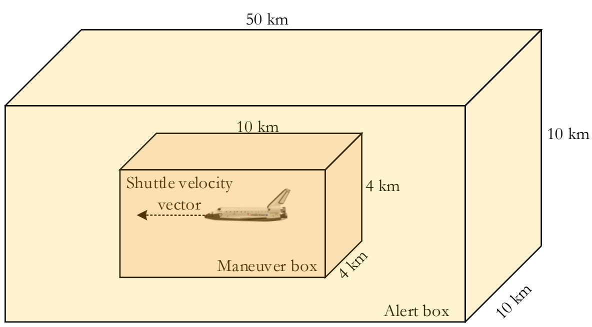

Figure 2.13: Shuttle alert and maneuver boxes adapted from National Research Council (1997)

rules for AROVs do not exist in the literature. Future AROVs could collide with subsea structures, the seabed or other underwater vehicles, which can pose a risk to safe autonomous IMR operations. To manage the risk of collision with underwater obstacles, safety envelopes and subsea traffic rules for AROVs need to be developed. Safety envelopes can create a barrier in space and time around the AROV, similar to the safety philosophy used in other vehicular industries. Objective 4 of this thesis addresses this challenge.

"Do what you can where you are with what you have."

- Theodore Roosevelt

3 Research Approach and Design

This section describes the types of research chosen to answer the objectives of the identified research questions. The aim of this section is to present the process/strategy used to generate original research contributions during the Ph.D. project.

3.1 Type of research

According to Kothari (2004), research can be defined as a scientific and systematic search for pertinent information on a specific topic. The topic can dictate the choice of the type of research needed to achieve the objectives.

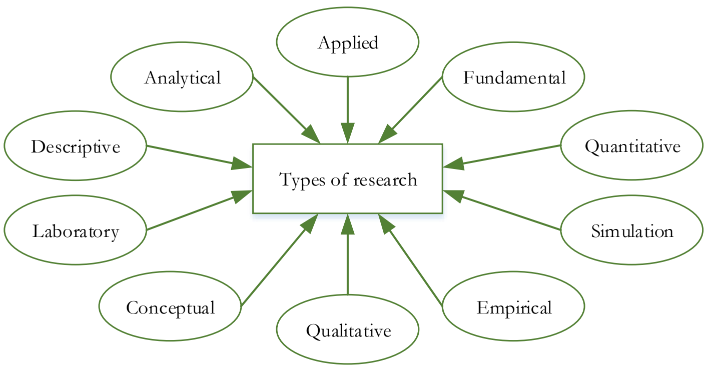

Figure 3.1: Types of research according to Kothari (2004)

Kothari (2004) described a wide variety of types of research, which is illustrated in Figure 3.1. Descriptive research can be categorized as research where a description of a particular topic is described without any opinions. In descriptive research, the researcher controls no variables and strictly reports his/her observations. On the contrary, analytical research requires researchers's to use existing facts and perform analyses to gain insight into the problem. Applied research aims at providing solutions to immediate problems of an organization or society; whereas, fundamental research concerns itself with generalizations and formulating a theory, adding to the existing body of scientific knowledge (Kothari, 2004). Qualitative research is concerned with the phenomena relating to quality or kind. In contrast, quantitative research is based on the measurement of quantity or amount. Conceptual research is performed when new concepts need to be developed in the form of abstract ideas or theory. Empirical research is dependent on prior experiences or observations with limited regard to the system and theory. The environment within which the research is performed can also influence the type of research, for example, simulation based research and laboratory based research.

To limit the choice of type of research to one of the above categories is not practical in risk and safety studies, where the socio-technical system under study is an amalgamation of humans, machines, and organizations. As summarized in Table 1, the type of research utilized in this thesis is a mixture of descriptive, analytical, applied, empirical, fundamental, qualitative, quantitative, conceptual, simulation and laboratory research.

Table 1: Overview of type of research employed in developing this thesis

Research Type	Article 1	Article 2	Article 3	Article 4	Article 5	Article 6
Descriptive	Yes	Yes	Yes	No	No	No
Analytical	No	Yes	Yes	Yes	Yes	Yes
Applied	Yes	Yes	Yes	Yes	Yes	Yes
Fundamental	No	No	No	No	No	No
Qualitative	Yes	No	No	No	No	No
Quantitative	No	Yes	Yes	Yes	Yes	Yes
Conceptual	Yes	Yes	Yes	Yes	Yes	Yes
Empirical	No	No	Yes	No	No	No
Simulation	No	Yes	Yes	Yes	Yes	Yes
Laboratory	No	No	No	No	Yes	No

3.2 Research design

Figure 3.2 illustrates the research design employed to answer the research questions. The study to identify current knowledge and technology gaps in any engineering application is a fundamental necessity. This premise is true in the case of this thesis, wherein a current social-technical system (IMR system) is envisioned to suit future autonomous operational requirements. Identifying gaps in the design and operation of a current IMR system to future requirements is a necessary step. Therefore, a literature study of current standards focusing on the use of underwater vehicles in subsea IMR was performed. This was also the basis for the Research Question 1 described in Section 1.2. According to Table 1, Article 1 employed descriptive, applied, qualitative and conceptual research methods to prove that there is a need to develop tools and methods to manage risks in future autonomous subsea IMR operations.

From the review of current standards governing IMR systems, it was clear that risk management requirements for autonomous subsea IMR operations were not extensively addressed in current standards. Logically, risk management tools and methods need to be used during either the planning or the operational phase of the IMR operation. For example, the tool developed in Article 5 can be used during the operational phase of IMR operations.

As explained in Section 2.1.2, new hybrid vehicles with their innate autonomous capabilities bring about challenges in identifying and managing risk factors. If an autonomous underwater vehicle needs to function in both autonomous and manual settings, it would need to master abilities to perceive dangerous scenarios. The path taken by the vehicle may be different during each operation. Article 2 focuses on providing solutions to Research Question 2 by developing risk indicators to identify risk prone paths. Article 2 describes a conceptual case study, prepares an analytical model for the risk indicator and uses simulations to collect required data. Therefore, according to Table 1, Article 2 is mix of descriptive, analytical, applied, quantitative, conceptual and simulation based research.

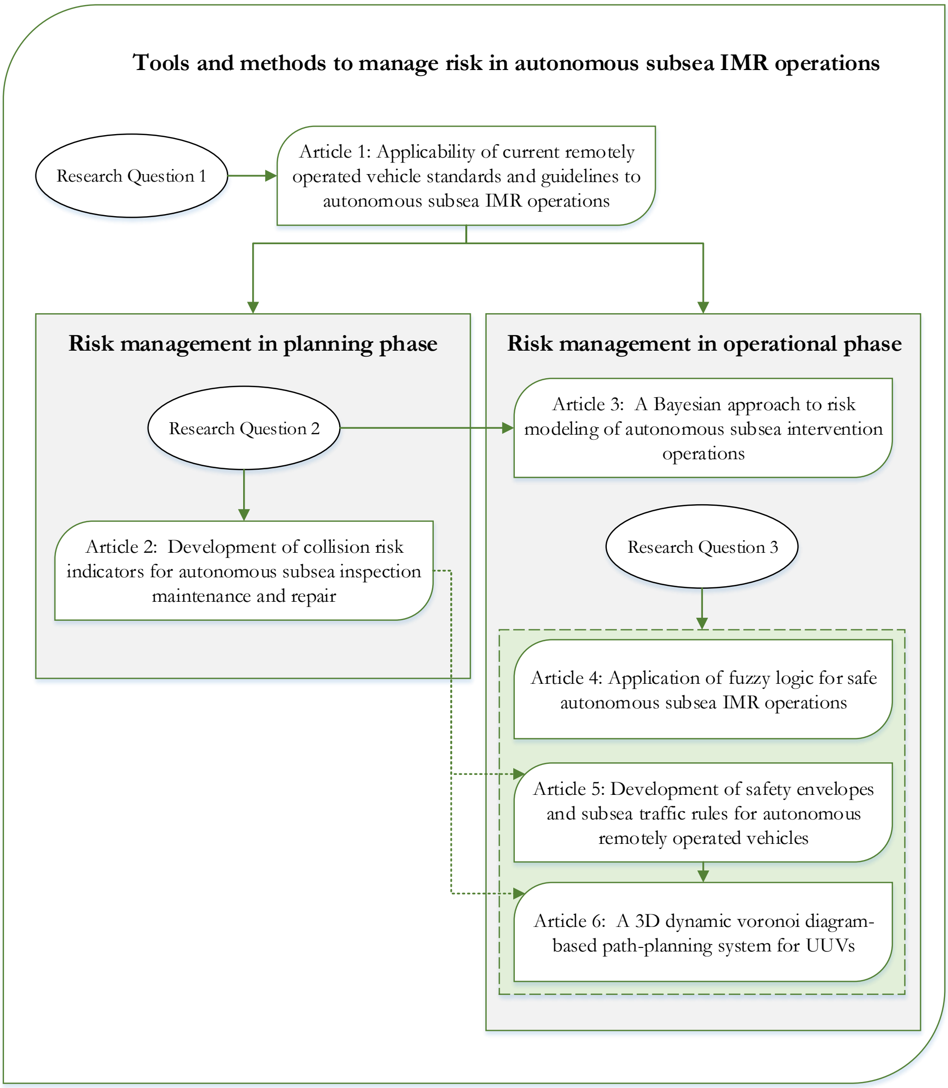

Figure 3.2: Research design for the Ph.D. project

Article 3 aims to structure and model RIFs in autonomous subsea IMR operations. It employs a descriptive method to identify the RIFs, uses analytical, empirical and quantitative methods to quantify the BBN, and simulates a given set of scenarios. Article 3, as mentioned in Table 1, employs descriptive, analytical, empirical, applied, quantitative, conceptual and simulation based research methods to obtain answers for Research Question 2.

Answers to Research Question 3 span across three articles, i.e., Article 4, 5, 6. In autonomous subsea IMR operations, it is essential that the decision process exists with both the human supervisors and the AROVs, as they both need to have situational awareness if some accidental/failure scenario is to occur. The focus in Articles 4, 5, and 6 is to develop operational tools the AROV and human supervisors could use when faced with accidental scenarios. All three articles use an analytical model with applied focus on subsea IMR operations. The three also employ quantitative, conceptual and simulation/laboratory based research methods to obtain answers to Research Question 3.

The research design described in this section is applied to produce original research contributions. The results from the articles enclosed with this thesis are further described in the next section.

"Once human beings realize something can be done,
they're not satisfied until they've done it."

- Frank Herbert

4 Summary of Results

This section summarizes the purpose, method used and results obtained of all the enclosed articles in this thesis. In Section 5, the impact of these results to the identified research questions is presented.

4.1 Article 1: Applicability of current remotely operated vehicle standards and guidelines to autonomous subsea IMR operations

Purpose and novelty

The purpose of this article is to investigate if current industry standards governing the design and operation of ROVs lack requirements for future autonomous subsea IMR operations. The novelty of this article is the identification of numerous knowledge and technology gaps, which are necessary to be filled before autonomous subsea IMR operations can be realized.

Method

There are two distinct parts in this article as illustrated in Figure 4.1. Part 1 utilizes a literature review. Seven current ROV design and operational standards and four recommended standards for design and operation of autonomous underwater vehicles are reviewed (American Petroleum Institute, 2013; ASTM, 2006, 2007a,b,c; European Committee for Standardization, 2000, 2006; IMCA, 2003, 2009, 2013; NORSOK, 2012). In collaboration with the project partners, Part 2 of the article describes the current Subsea Control Module (SCM) replacement case study. The described SCM replacement operation is subjected to a feasibility analysis while considering ROVs with and without umbilical. In each case, the knowledge and technology gaps are observed and discussed.

Results

From the feasibility analysis of SCM replacement operations using semi and fully autonomous ROVs, twenty-five technology/knowledge gaps are identified and listed in Table 2. The identified knowledge and technology gaps may hinder the development and adoption of autonomous subsea IMR operations. The symbol ✓ signifies existing gaps and the symbol ✕ signifies no gaps. It is observed that semi-autonomous ROVs (SAROVs) have fewer gaps compared to fully autonomous ROVs. This finding helps the ROV manufacturers to focus on the development of ROVs, which have collaborative capabilities, than focusing on developing fully autonomous ROVs. In short, the development work needed to achieve SAROV is less than for AROVs.

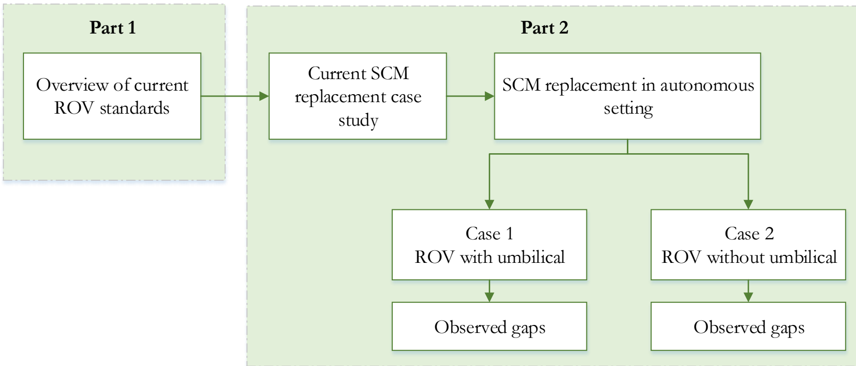

Figure 4.1: Main constituent parts of the article

4.2 Article 2: Development of collision risk indicators for autonomous subsea inspection maintenance and repair

Purpose and novelty

The purpose of this article is to investigate the application of risk indicators to manage collision risk of AROVs in the subsea environment. The novelty of this article is the proposed planning tool developed to identify risk prone paths by using the proposed collision risk indicators.

Method

As illustrated in Figure 4.2, the method used to develop collision risk indicators starts from describing the overall IMR system philosophy. In this article, it is assumed the AROV will be launched from an intervention vessel. In the second step, three possible collision accidental scenarios of the AROV during autonomous IMR operations are identified. The risk influencing factors contributing to the collision risk is identified in Step 3. The input to Step 3 is obtained by a literature study of collision risk metrics from other vehicular-based industries such as aviation, automotive, marine, and railway. Step 3 ends with the definition of the proposed risk indicators, such as time to collision (TTC), mean time to collision (MTTC) and mean impact energy (MIE). Data collection is carried out by using a simulation of the AROV's path to a subsea structure. For each identified risk indicator, Step 5 provides a safe threshold limit. In Step 6, the threshold limit is compared to the data collected in Step 4 to provide an overall picture of the risk of collision.

Results

The article results in developing and verifying the use of three proposed collision risk indicators, time to collision (TTC), mean time to collision (MTTC) and mean impact energy. The TTC indicator is an operational indicator that can be used by the AROV manufacturers or by AROV service providers to obtain an estimate of TTC during live or simulated missions. TTC is calculated by the following formulas: where x_1, y_1, z_1 are point coordinates on the AROV and x_2, y_2, z_2 are point coordinates on the target, V_x, V_y, V_z represent velocity vectors at x, y, and z directions, such that

Table 2: Gaps in autonomous subsea IMR operations

Aspects	Type 1 SAROV	Type 2 AROV
Autonomy	✓	✓
Navigation	✓	✓
Path-planning	✓	✓
Localization	✓	✓
Guidance	✓	✓
Qualification	✓	✓
Functional safety	✓	✓
Sensor fusion	✓	✓
Fault tolerance	✓	✓
Manipulator arms	✓	✓
Control and monitoring	✓	✓
Manual override and monitoring	✓	✓
Contingency planning	✓	✓
Resident properties	×	✓
Launch and recovery	×	✓
Lifting capacities	×	✓
Subsea facility design	×	✓
ROT systems	×	✓
Spare parts	×	✓
ROT control system (topside)	×	✓
ROT control system (self-contained)	×	✓
Subsea docking (for charging and parking)	×	✓
Environmental conditions	×	✓
Power	×	✓
Communication	×	✓

$$Distance_{(Target)} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{1}$$

$$Resultant\,velocity_{(AROV)} = \sqrt{(V_x)^2 + (V_y)^2 + (V_z)^2} \tag{2}$$

$$Time\,to\,collision\,(TTC) = \frac{Distance\,to\,target}{Resultant\,velocity\,of\,ROV} \tag{3}$$

The MTTC indicator can be defined as a pre operational (planning) collision risk indicator depending on the status of the mission completion in the AROV path. Where i is prior waypoint, i+1 is the next waypoint in the AROV path, and N is the total TTC data points between $Waypoint_1$ and $Waypoint_{i+1}$ gives,

$$Mean\,Time\,to\,Collision\,(MTTC) = \frac{\sum_{Waypoint_i}^{Waypoint_{i+1}} TTC}{N} \tag{4}$$

Mean impact energy is calculated between the chosen waypoints in the AROV path. N is the total number of impact energy data points between $Waypoint_i$ and $Waypoint_{i+1}$, giving

$$Mean\,Impact\,Energy = \frac{\sum_{Waypoint_i}^{Waypoint_{i+1}} Impact\,Energy}{N} \tag{5}$$

The proposed indicators are verified by simulating an AROV path consisting of four waypoints. During the transition of the AROV in between the waypoints as shown in Figure 4.3, the proposed indicators are continually calculated, and the data obtained from the simulation is used to calculate the overall risk priority number as listed in Table 3. Figure 4.4 provides a risk picture for the simulated AROV path by calculating the

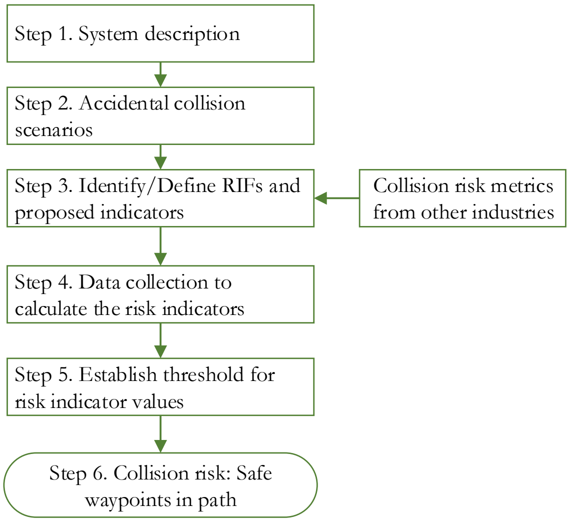

Figure 4.2: Risk indicator development and verification method, adapted from Øien (2001)

proposed risk indicators.

Table 3: Calculation of overall risk priority number

Waypoints	MTTC Structure	MTTC Seabed	MTTC 2nd AROV	Mean Impact Energy	Total Risk Priority Number
Waypoint 0 - 1	High	High	High	High	6/12
Waypoint 1 - 2	High	Intermediate	High	Low	5/12
Waypoint 2 - 3	Intermediate	Low	Low	High	11/12
Waypoint 3 - 4	Low	Low	Low	High	12/12

4.3 Article 3: A Bayesian approach to decision making applied to autonomous subsea IMR operations.

Purpose and novelty

Technical, operational and organizational risk factors exist in realizing autonomous subsea IMR operations. The purpose of this article is to model these risk-influencing factors to calculate the probability of aborting an autonomous subsea IMR operation. The novelty of this article is the proposed holistic BBN, which addresses the gap in the field of risk modelling of autonomous subsea IMR operations.

Method

Figure 4.5 describes the method developed in this article. A target node is a node where the joint probability distribution is calculated in a BBN model. Identification of a target node is, therefore, the first step in the BBN development process. In Step 2, all relevant nodes are identified by either studying the system interactions or through empirical data

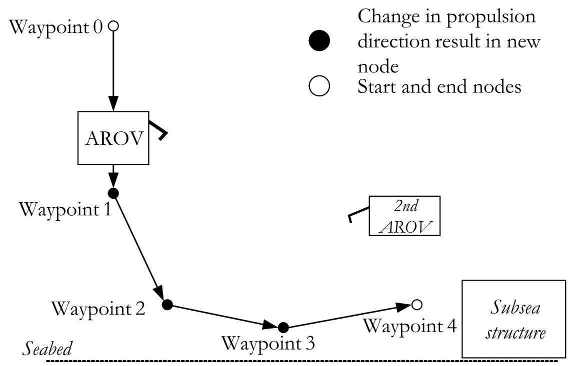

Figure 4.3: Simulated waypoints of the AROV path

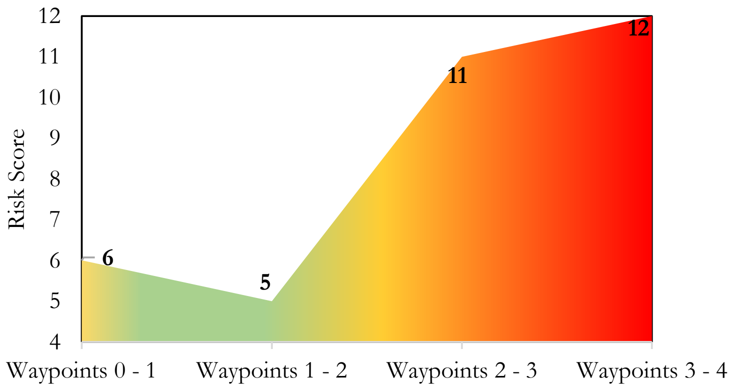

Figure 4.4: Risk picture for the simulated AROV path

in the literature. The nodes identified in Step 2 are investigated for causal relationships with other nodes. Arcs represent the causal relationships, connecting a parent node to a child node. In Step 3, the causal arcs are drawn from parent nodes to child nodes.

The outcome of this step is to ensure that the BBN model represents real-world causal relationships between the selected nodes. Each identified node contains different possible states, which can be determined in Step 4. Some nodes may have deterministic states while others may be probabilistic. For example, spare parts available in a warehouse are a known deterministic quantity. The model developed so far may have causal relations, which are not practically observable or quantifiable. Such relationships (arcs) are evaluated in Step 5. In Step 6 the BBN model can be quantified by many existing methods in the literature. In this article, the BBN quantification method suggested by Røed et al. (2009) is utilized. In Step 7, existing data or a scenario generation approach can be used to update the results of the states for each node in the BBN, resulting in an updated joint probability distribution. In Step 8, inferences can be made by assessing the joint probability distribution at the target node from Step 7.

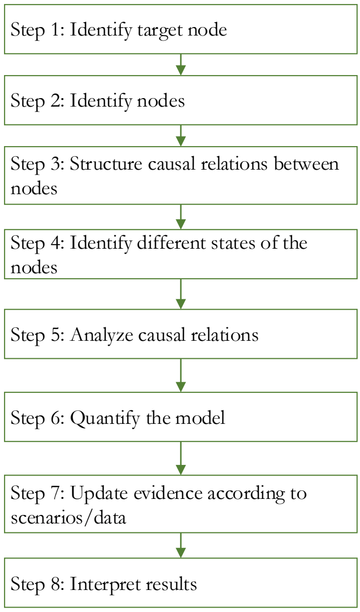

Figure 4.5: Generic BBN modeling method used in the article

Results

Reviewing existing literature, involving experts, and brainstorming risk factors led to the identification of thirty-eight risk-influencing factors (RIFs) that can influence the probability of mission abortion. Figure 4.7 illustrates the developed BBN consisting of technical, operational and organization categories of RIFs. Quantification of the BBN was performed by utilizing expert judgment through a workshop. The resulting joint probability distribution from the proposed BBN is illustrated in Figure 4.6.

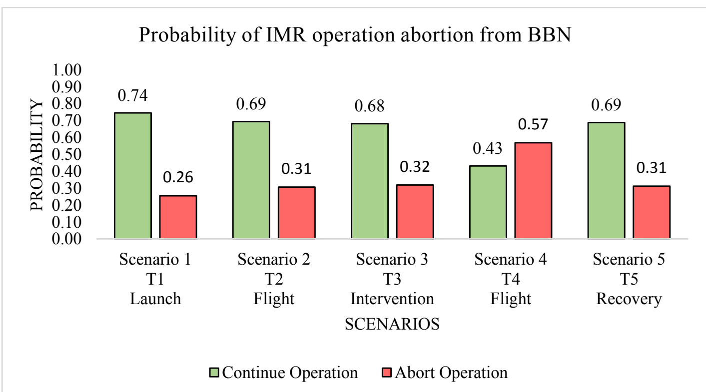

Figure 4.6: Results from BBN model with generated scenario evidence

The nodes in the BBN were updated with evidence for five unique scenarios. The resulting joint probability distribution is noted. Further, expert judgment to the same five scenarios are collected and subjected to a root mean square error (RMSE). The results also highlight that the proposed model has a root mean square error of 0.25 probability when compared with the expert estimation of aborting the IMR mission for the generated scenarios. This deviation between the BBN estimation and expert opinion can be due to three specific reasons. Firstly, uncertainties in the expert's judgment during the elicitation workshop could have introduced biased allocation of weights and R-index resulting in the model's estimation. Secondly, since the experts have a wide range of expertise within the subsea field, it may have resulted in an availability bias (value based on their recent experiences) while allocating abortion probabilities for the five scenarios. Thirdly, experts may perceive the scope of autonomy in a different manner resulting in different operational expectations.

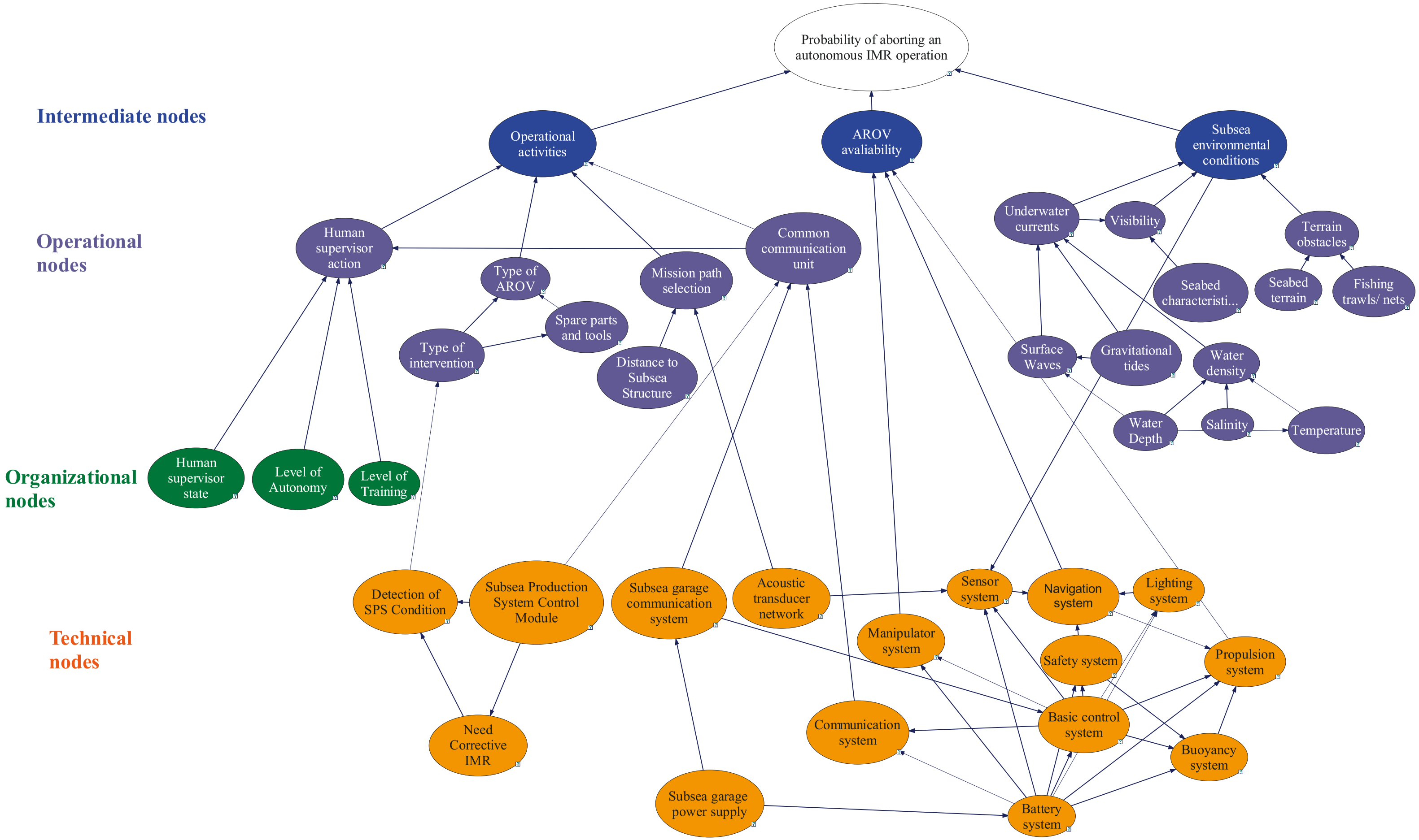

Figure 4.7: Proposed BBN model to provide decision-support. Node colors: orange-technical, green-organizational, light purple-operational, dark blue-intermediate, white-target

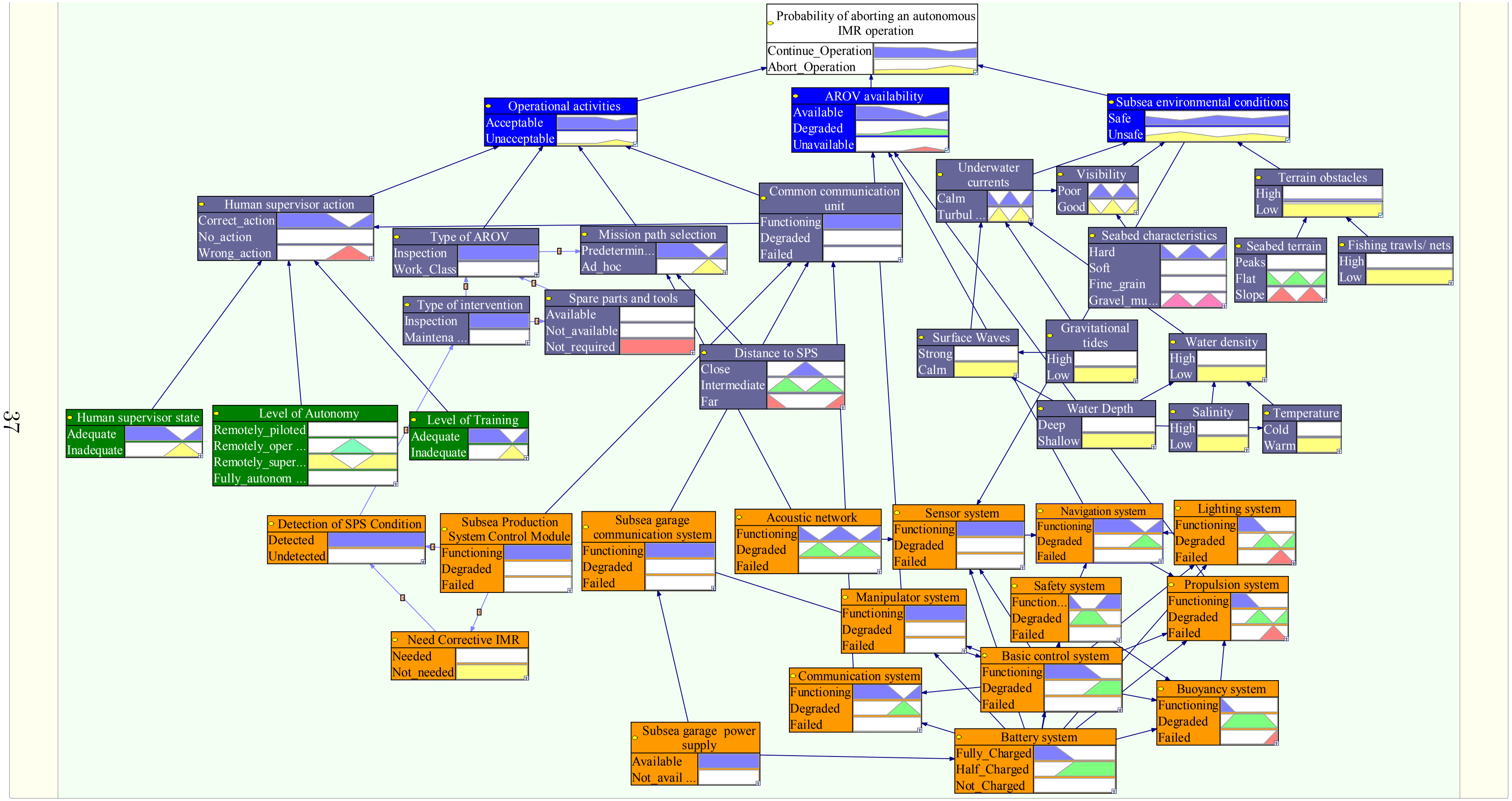

Figure 4.8: Resulting joint probability distribution with generated scenario

4.4 Article 4: Application of fuzzy logic for safe autonomous subsea IMR operations

Purpose and novelty

The purpose of this article is to investigate the feasibility of using fuzzy logic to develop an asset safety decision-support basis. The novelty of this article is the proposed FIS, which can be used by autonomous ROVs to operate safely in the presence of component faults and failures.

Method

Figure 4.9 illustrates the fuzzy inference system (FIS) developed in this study. Two fuzzy input variables are selected, namely ROV envelope and ROV sensor. The ROV envelope consists of three sizes of envelopes (red, yellow, green) and the ROV sensor with five membership states (ok, fault low, faulty high, failed low and failed high). Matlab Fuzzy Logic Toolbox is used to design the FIS. Range specifications of the subsea envelopes and sensor status of the underwater vehicle are established as part of the membership functions of the two input variables. Fuzzy rules are derived using the existing knowledge. A defuzzification method is used to covert the fuzzy rules to discrete values of the input variables. Finally, a decision is suggested by the FIS to either discontinue the mission, return to a reference, return to service base or continue the mission.

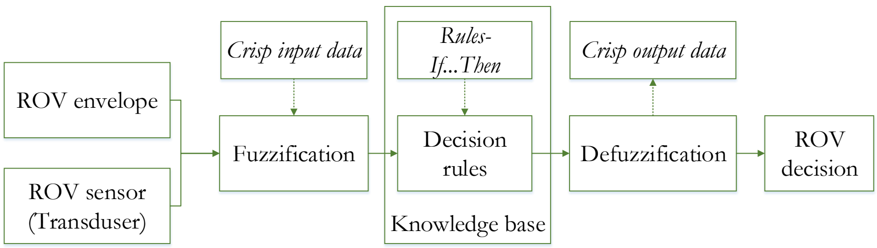

Figure 4.9: Overview of the proposed fuzzy inference system

Results

The FIS is simulated for each set of data points to suggest a suitable decision the ROV can take as shown in Figure 4.10. One of the green scatter points in Figure 4.11 corresponds to the input values, ROVenvelope = 15m and ROVsensor = 300 kHz, which results in a ROV decision output value of 0.837. The ROV decision, in this case, corresponds to "continue mission" according to the derived fuzzy rule set.

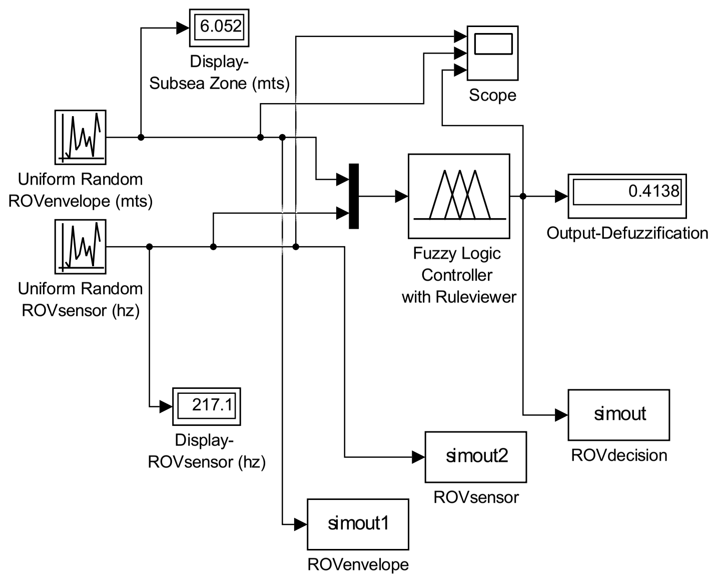

Figure 4.10: Simulink simulation model

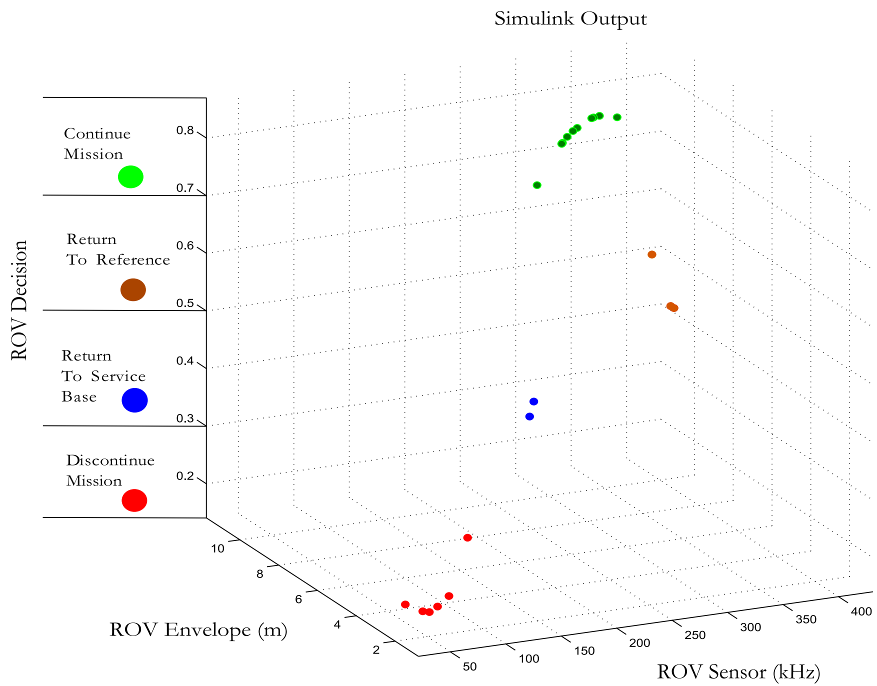

Figure 4.11: Output from the simulation

4.5 Article 5: Development of safety envelopes and subsea traffic rules for autonomous remotely operated vehicles

Purpose and novelty

The purpose of this article is to present an innovative method for developing safety envelopes and subsea traffic rules for autonomous remotely operated vehicles (AROVs) to be used in autonomous subsea IMR operations. Secondly, this article presents the results of tests performed in the simulator and laboratory to verify the feasibility of the proposed safety envelopes and subsea traffic rules. The novelty of this article is the implementation and testing of safety envelopes and subsea traffic rules for safe AROV operations.

Method

Review of existing collision avoidance systems (CAS) from other vehicular industries, such as marine, aviation, space, and autonomous underwater vehicles provides input to develop the overall method to develop safety envelopes and subsea traffic rules. Figure 4.12 illustrates the three parts of the method. In Part 1, various scenarios of possible collisions are assessed and based on CAS in other industries subsea traffic rules are developed. In Part 2, the properties of the safety envelope established. First, the size of the safety envelope is determined. Second, the safety envelope area is divided into smaller portions using an Octree method. Third, each of the octants is numbered. Finally, the traffic rules are linked to the octant numbers. In Part 3, the proposed safety envelopes and subsea traffic rules are verified by developing an obstacle detection process followed by a scoring module to recommend the appropriate subsea traffic rule. In short, Part 3 deals with the application of the safety envelope and subsea traffic rules.

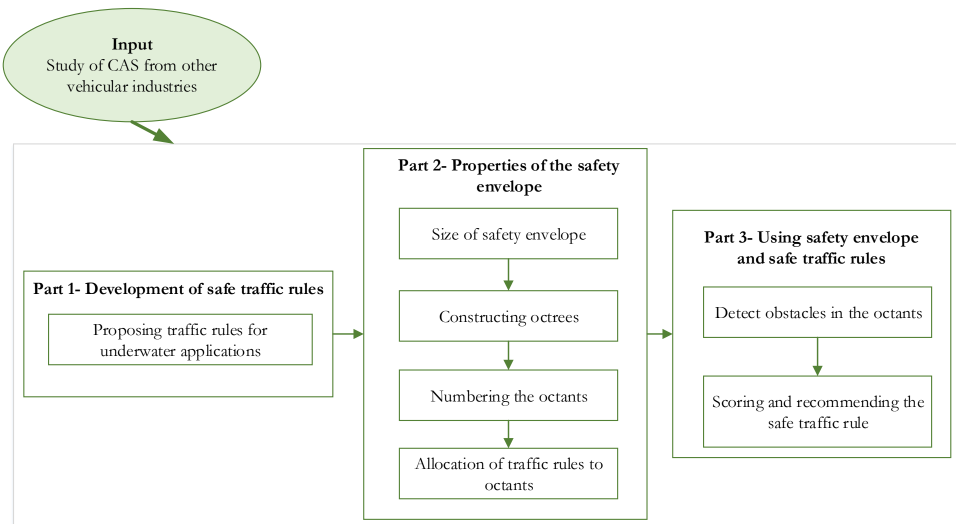

Figure 4.12: Method to develop safety envelopes and subsea traffic rules

Results

To get a visual representation of the collision detection module, several obstacles are modeled in the simulator. This representation is shown in Figure 4.13, which shows all octants in the envelope. When no collision is detected in an octant, the octant is represented with a green shade. When a collision is detected the octant color changes to red.

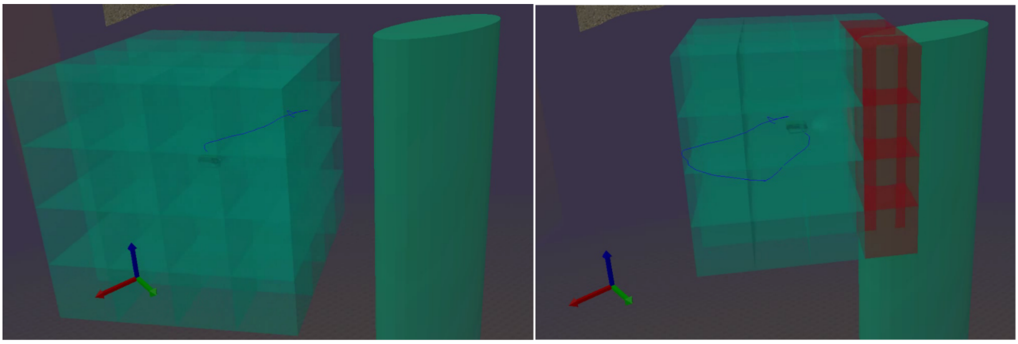

Figure 4.13: Underwater CAS in the underwater MORSE simulator

The user interfaces to demonstrate the proposed underwater CAS is as illustrated in Figure 4.14. When no obstacles are detected, the illustration to the left shows the AROV in the center of the screen with octants in green shaded boxes. In the figure to the right, the AROV moves toward the AROV panel, and the AROV panel is detected as an obstacle in Octant 61, which relates to the traffic rule "Stop-Collision alert." The level of autonomy in the shared control system is also highlighted in the display. When the human operator takes over control of the AROV, the control is displayed as a human control. The safety envelope and the AROV in the user interface mimic real-life orientation and rotational movement of the AROV during the laboratory test.

Data from the laboratory tests were used to verify the correctness of the proposed safe traffic rules. The colliding octants are linked to the octant numbers to derive the appropriate safe traffic rule. Table 4 lists the different data points collected during laboratory tests. The observations show that the traffic rules suggested by the underwater CAS during laboratory tests correspond to the proposed traffic rules.

Table 4: Verification of proposed traffic rules during laboratory tests

Datapoint	Collision Decteced in Octant	Proposed Traffic Rule	Traffic Rule suggested in Lab Tests
1	43	Stop-Collision Alert	Stop-Collision Alert
2	61	Stop-Collision Alert	Stop-Collision Alert
3	63	Turn left and climb	Turn left
4	43, 61	Stop-Collision Alert	Stop-Collision Alert
5	61, 63	Stop-Collision Alert	Stop-Collision Alert
6	27, 61, 63	Stop-Collision Alert	Stop-Collision Alert
7	25, 43, 61	Stop-Collision Alert	Stop-Collision Alert
8	7, 25, 43	Stop-Collision Alert	Stop-Collision Alert
9	43, 52, 61, 70	Stop-Collision Alert	Stop-Collision Alert
10	34, 70, 7, 43, 16, 52, 25, 61	Stop-Collision Alert	Stop-Collision Alert

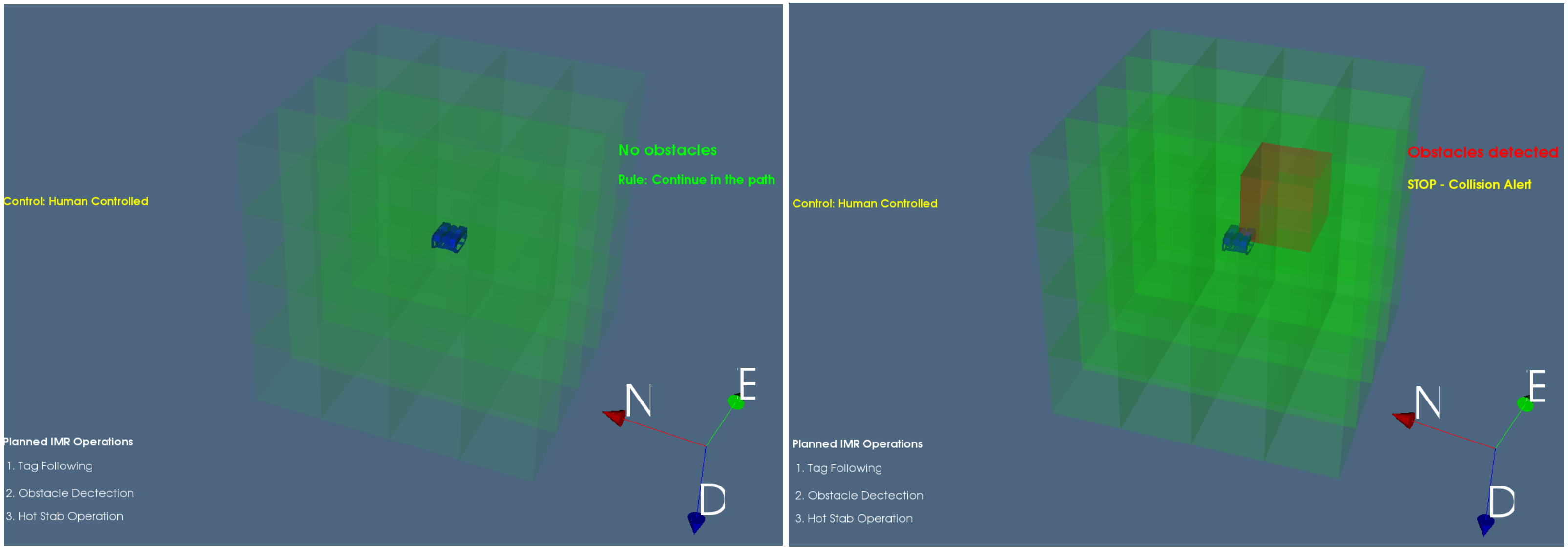

Figure 4.14: User display of the underwater CAS during laboratory tests

4.6 Article 6: A 3D dynamic voronoi diagram-based path-planning system for UUVs

Purpose and novelty

The purpose of this article is to propose a rapid path-planning and replanning system for Unmanned Underwater Vehicles (UUVs) that navigate in environments where subsea structures and other vehicles may be present. The novelty of this article is the extension and implementation of voronoi diagram to three-dimensional space and the proposed subsea traffic rules for underwater vehicles.

Method

The four steps of the method are as illustrated in Figure 4.15. The method starts with a system description of an autonomous subsea inspection by an unmanned underwater vehicle (UUV) and the subsea infrastructure. Scenarios and obstacles are modeled in Step 1. In Step 2, the path planning system is described. A 3D Voronoi diagram is generated using the available 3D model of the subsea infrastructure. The Voronoi diagram allows the path planning system to use a Dijkstra optimization algorithm to find the shortest possible path to reach the target location from the start location by considering minimum safe distances to the subsea infrastructure.

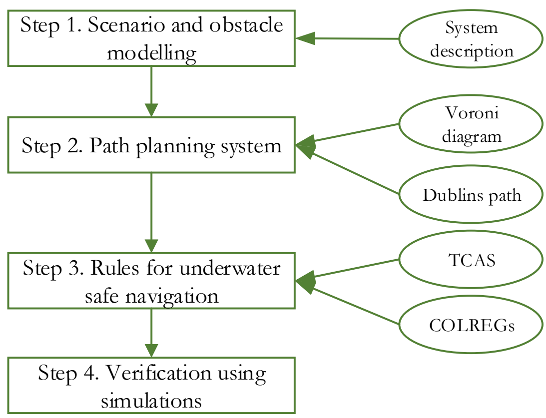

Figure 4.15: Main path-planning system's steps

Since the Voronoi diagram results in waypoints that end with vertices, the path is further shortened by using a 3D Dublins path by building a smooth path that respects the curvature constraints of a UUV. In Step 3, rules for underwater safe navigations are proposed, which are developed by using existing collision avoidance rules from aviation (TCAS) and marine (COLREGs) industries. Simulations to verify the proposed method are performed by simulating an obstacle in the UUVs path.

Results

During the UUV's navigation, a moving obstacle (an ROV that is returning to the docking station from the template B3) is detected in proximity of the B2 template. Since the

Closest Point of Approach (CPA) is too close to the UUV, the path is replanned as shown in Figure 4.16, applying the safe navigation rules. This produces the new starting and final points of the replanned segments (respectively $P_{r,s}$ and $P_{r,f}$) and the intermediate initial and refined points, shown in the same figure as empty or full red circles. The replanned path smoothly reconverges to the initial one (respectively the green and light red paths in Figure 4.16). The replanning is observed to consistently be slower than 2.5 seconds.

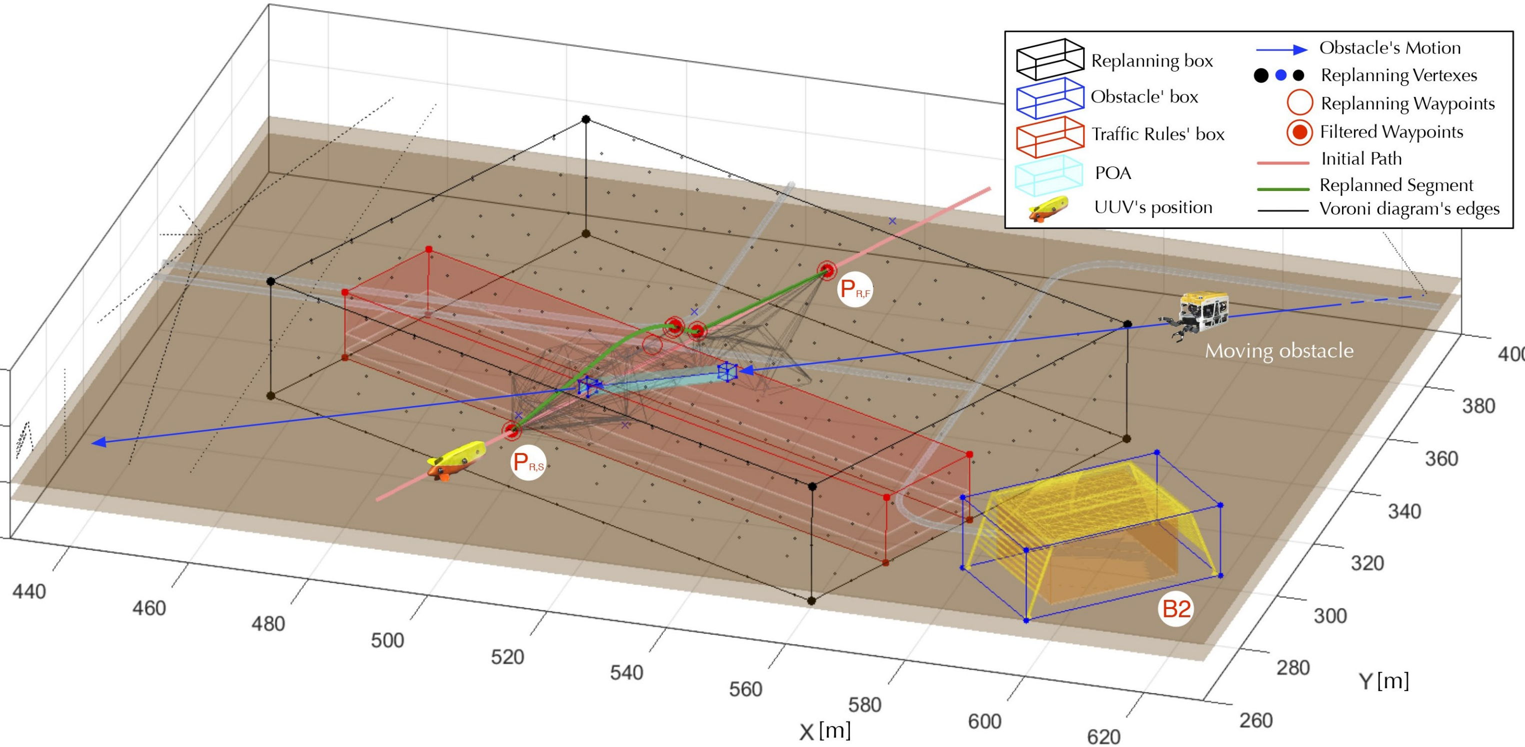

Figure 4.16: Simulation case of the replanning system

"What we find changes who we become."

- Peter Morville

5 Summary of Contributions

This section presents the overall contributions of this Ph.D. thesis by revisiting the identified research questions and objectives from Section 1.2. This section also discusses the impacts of obtained results to the future development of autonomous subsea IMR operations.

5.1 Addressing Research Question 1

In essence, Research Question 1 focuses on investigating the existence of technology and knowledge gaps in current underwater vehicle design and operational industry standards. This question was necessary to be answered, as it stands to impact future safe autonomous subsea IMR operations. Also, answers to Research Question 1 supported the hypothesis that functional safety is not prioritized in current standards. Answers to Research Question 1 were found through Article 1 where thirty-seven aspects concerning design and operation of underwater vehicles in the subsea industry were discovered. The reviewed standards focused on a particular set of requirements; however, an overview of these requirements did not exist in the literature. An overview of existing requirements on design and use of the underwater vehicle is important to OEMs, service companies and even regulating bodies as it highlights gaps in requirements in various standards. This is, therefore, the first contribution of this thesis, which is of both academical and industrial significance.

The details on how subsea IMR operations are performed is not well documented in the literature. The reason for this may be because details of IMR operations are not accessible without the participation of industry personnel. Fortunately, the NextGenIMR industry partners provided access to how an SCM is replaced using traditional ROVs. By describing the SCM replacement operation in detail, Article 1 has made the second contribution of this thesis. Other researchers can now use the described SCM replacement operation as a case study in their research, leading to the second contribution of academic significance.

The third contribution of this thesis answers the Research Question 1 by applying current requirements to future autonomous subsea IMR operations. It was found through Article 1 that many requirements necessary for safe operation of autonomous/semi-autonomous ROVs are not addressed in current standards. Even recent recommended standards for design and operation of autonomous underwater vehicles provide a disclaimer that reads "This guide does not address safety concerns, if any, associated with the use of the unmanned undersea vehicle system" (ASTM, 2006).

In summary, the answer to Research Question 1 is that both technology and knowledge gaps exist in current underwater standards when considering future autonomous subsea

IMR operations. They are only partly applicable and need to develop requirements to suit future autonomous subsea IMR operations.

5.2 Addressing Research Question 2

Literature reviewed in Subsection 2.2 shows that many factors can influence the performance of subsea IMR operations. Since autonomous IMR systems can be categorized as socio-technical systems, identifying the risk factors affecting their performance is vital. With the introduction of autonomy, these risk factors have been shown to increase as compared to traditional subsea IMR operations in Article 2. The interactions of these risk influencing factors and their effect on IMR operations are not explored in the literature. Therefore, Research Question 2 focused on investigating how modeling of risk influencing factors may assist in developing new decision support tools. To answer this research question, two different research objectives (Objective 2 and Objective 3) were strategized as presented in Section 1.2. In Article 2, a method was presented for developing collision risk indicators specifically targeting AROV applications. The proposed method is generic, and therefore other researchers can use this method to develop risk indicators for their applications. This is, the fourth contribution of this thesis. To propose collision risk indicators, Article 2 also investigated existing risk metrics used in other high-risk industries.

Using risk management techniques from other industries can help in reducing both knowledge and technology gaps when developing autonomous subsea IMR operations. It also aids adoption of system safeguards for safe operations. The fifth contribution of this thesis is, therefore, the overview of existing collision metrics from other vehicular industries, which are presented in Article 2. Three collision risk indicators are proposed that can be used to evaluate the collision risk for a given AROV path, which is the sixth contribution of this thesis. The proposed collision risk indicators can be used for either current ROVs or future AROVs as they consider the state of the vehicle for calculations. The main advantage of risk indicators is that they provide input to decision makers who can evaluate the acceptable level of risk and make changes to the operations. In other words, it promotes situational awareness between stakeholders by visualizing a risk picture before the commencement of the IMR operation.

The goal of Article 3 was to model risk influencing factors in such a way that the developed model was both visual and quantifiable. This approach promoted understanding the impact of risk factors influencing the probability of aborting an IMR operation. From the literature, it was evident that a BBN based risk model is well suited for this application as it is both visual and quantifiable. A risk model with thirty-eight nodes was constructed using BBN approach as part of Objective 3 of this thesis. The novel BBN risk model is the seventh contribution of this thesis. During expert elicitations to quantify the BBN risk model, it was observed that the visual nature of the model aided the experts to discuss freely and suggest changes where they seemed fit. A workshop with industry experts permitted quantification of the proposed BBN. By quantifying the BBN using the method proposed by Røed et al., (2009), Article 3 has successfully verified their method in full scale. The proposed BBN is capable of incorporating and calculating the probability of aborting an IMR operation for large combinations of scenarios. Unlike traditional risk models, a BBN risk model is advantageous because it can model multiple failure scenarios. The industry partners in the NextGenIMR project value the contribution of Article 3 and wish to adopt the proposed BBN model in their autonomous IMR concept verifications.

In summary, the two objectives set to answer the Research Question 2 were met through the combined contributions in Article 2 and 3. Article 2 developed a planning tool and Article 3 developed an operational tool to monitor and estimate risk during autonomous subsea IMR operations.

5.3 Addressing Research Question 3

Vehicle behavior is an interesting topic when considering autonomous vehicle applications on road, sea, air or underwater. If future autonomous subsea IMR operations are to be safe and successful, the AROVs need to have proactive and reactive abilities to return to a safe scenario before or after unwanted incidents occur. In essence, Research Question 3 of this thesis recognizes the importance of developing tools and methods to reduce the risk of loss of vehicular functions. Loss of AROV functions may cause delays and cost overruns and must be avoided in all cases. To answer the Research Question 3, two separate objectives (Objective 4 and Objective 5) were formalized, as presented in Section 1.2.

Perceiving safe and unsafe conditions by the AROV is a challenging and uncertain task. For example, how would an AROV perceive the failure of one of its sensors? What should an AROV do if the sensor readings are too high or too low? These questions fall into the realm of Objective 5 of this thesis. In such cases, suggestions for a safe action can be derived using fuzzy logic, which was explored in Article 4. A simulation of sensor readings and the size of the safety envelope were used as inputs to derive a decision support system when faults and failures occurred in the AROV subsystems. The eighth contribution of this thesis is the novel fuzzy inference system developed in Article 4. The advantage of fuzzy logic, unlike other artificial intelligence (AI) methods, is that it is an expert based methodology. In short, the outcome from the model is obtained by a process (fuzzy rules), which has been developed by the involvement of experts in subsea IMR. Therefore, the rule base/decisions the AROV can take are traceable by human supervisors unlike a black-box approach, which is used in other AI methods. A description of possible decisions the AROVs can make is presented in Article 4, which is the ninth contribution of this thesis. The AROV, under component faults and failures, can either continue the mission, return to a reference point, return to a subsea service base or discontinue the IMR mission. The four possible decisions AROVs can take during faults and failures reflect the need of the industry partners of the NextGenIMR project.

In industries, such as aviation, space, marine, and automotive, active safety envelopes are employed to protect vehicles from colliding with surrounding obstacles. In underwater vehicles, such safety envelopes or collision regulations do not exist. Article 5 describes current collision avoidance systems used in four vehicular-based industries, which is the tenth contribution of this thesis. This overview is useful because it displays the complexity of collision avoidance systems in these industries, which needs to be considered if they are to be adapted to underwater vehicles. The eleventh contribution of this thesis is the innovative method developed in Article 5 to build safety envelopes using Octree as a barrier in space and time against underwater obstacles. The proposed CAS can increase the distance of the vehicle from the obstacles both vertically and horizontally. This hybrid approach, along with the safety envelopes, can result in a robust underwater CAS. Article 6 extended the work performed in Article 5 to allow the CAS to avoid known moving obstacles in the subsea environment. The twelfth contribution of this thesis is the development of subsea traffic rules to avoid collisions with known moving obstacles. The proposed underwater CAS has been verified successfully in simulator tests and through live demonstrations.

In summary, Article 5 and Article 6 have answered the Research Question 3 of this thesis by developing and verifying the application of safety envelopes and subsea traffic rules for underwater vehicles.

"Progress in science depends on new techniques, new discoveries and new ideas, probably in that order."

- Sydney Brenner

6 Conculsions and further research

This section draws the overall conclusions from the thesis and the enclosed articles. Future research opportunities, which can continue the endeavor to manage risks in autonomous subsea IMR operations, are also described in this section.

6.1 Conclusions

Currently, both academic and industry research initiatives are continuing to investigate the use of autonomous remotely operated vehicles to perform subsea inspection, maintenance, and repair (IMR) operations autonomously. However, development of tools and methods to manage various risks in autonomous IMR operations are lagging. The goal of this thesis is to develop new tools and methods that can assist in managing the risks involved in autonomous subsea IMR operations. In particular, this thesis explores technology and knowledge gaps concerning risk management strategies in autonomous subsea IMR operations. The gaps in risk management strategies are divided into two types, i) managing risks during the planning phase and ii) managing risk during the operation phase of the autonomous subsea IMR operations.

Through a review of current underwater vehicle design and operational standards, this thesis has revealed that the current standards are only partly capable of providing risk management requirements for autonomous subsea IMR operations. The governmental bodies and organizations regulating subsea operations need to improve regulations to encompass design and operational requirements related to autonomous subsea IMR operations.

As AROVs are capable of autonomous operations, risk indicators are shown to promote situational awareness in different stakeholders of the system. Mean time to collision and mean impact energy are two proposed risk indicators. The proposed risk indicators can be utilized to determine safe areas in the AROV path during the planning phase. On the other hand, operators of autonomous remotely operated vehicles (AROVs) will have to consider not just technical systems, but also operational and organization risk factors. This thesis has demonstrated how technical, operational and organization risk influencing factors can be modeled using a Bayesian belief network to estimate the probability of aborting an autonomous subsea IMR mission. The proposed Bayesian belief network provides a tool to manage the risk of mission abortion in the operational phase of the IMR operations.

This thesis has demonstrated that autonomous remotely operated vehicles can be engineered to fail gracefully in the presence of component faults and failures. The proposed fuzzy inference system in this thesis can be used to derive a decision support system, which can suggest a safe behavior to the underwater vehicle or the human supervisor in case of component faults and failures. Such a tool is paramount for an autonomous system as it specifies the contingencies available to the AROV under component faults and failures. AROVs may also be resilient to collision risk if safety envelopes are implemented in combination with subsea traffic rules. The proposed safety envelopes and subsea traffic rules in this thesis may be able to provide AROVs and human supervisors with a set of safe maneuvers to avoid collisions with known subsea obstacles.

It must be noted that the contributions of this thesis are not limited to only the subsea oil and gas industry. The proposed tools and methods can be adapted to suit the offshore wind, aquaculture, and subsea mining industries, as well; therefore, the contributions made in this thesis are significant in the bigger picture of risk management in subsea operations.

6.2 Further research

From the results of this thesis, some interesting opportunities have emerged, which need further research efforts. Due to time limitations, these opportunities have not been explored in this thesis. This section lists four key opportunities identified to manage risks in autonomous subsea IMR operations.

▷ **Developing a dynamic Bayesian Belief Network**

The first opportunity is to extend the work from Article 3 and develop a dynamic Bayesian tool, which can utilize incoming data on the state of the nodes during operation. The state of the node can then be updated in real time to obtain the new probabilities for mission abortion. To automate this, classifiers need to be developed that can classify the incoming data for each node to a specific state. For example, for the battery system node, as the AROV discharges the battery, a classifying module can capture the change in the battery state, and an update to the dynamic Bayesian Belief Network can be made.

▷ **Bayesian Belief Network to develop dynamic vehicular envelopes**

The AROV safety envelope proposed in this thesis is static; however, if a BBN risk model is developed, it can be linked to the size variable of safety envelopes. When the risk of collision is high, the safety envelope increases in size, and when the risk of collision is acceptable, the safety envelope reduces in size. Dynamic vehicular envelopes may decrease the computation load on the detection module by optimizing the detection envelope area. However, these hypotheses need further investigation.

▷ **Vehicle behavior under component faults and failure**

Although this thesis has addressed the topic of vehicle behavior under faults and failure, it did so while only considering one particular subsystem (depth sensor) of the AROV in Article 4. A socio-technical system, such as the Autonomous ROV system, has many more failure modes than ones found in traditional ROVs. To identify these emerging failure modes, development of an overall decision basis is vital if autonomous ROVs are to be used in subsea IMR applications. Emerging machine learning algorithms may be used to detect operational anomalies and generate vehicle behavior under fault and failure scenarios.

▷ Investigate human-machine interaction during shared-control IMR operations

The increase in autonomy and shared-control philosophies bring with them risks during human interaction with the vehicle. Two levels of decision processes can confuse both the human and the machine. To increase situational awareness, both the human and the machine need to interact smoothly. During a laboratory demonstration of research results from the NextGenIMR project, an observation was made regarding the rate at which the normal operation or function of the AROV deviates to a collision scenario. Even in the presence of a well-versed human operator, accidents may occur. A human supervisor had a split second to take control of the AROV before the AROV deviated from normal operation. The opportunity, therefore, is to investigate the minimum reaction time and program the behavior of the vehicle in such a way that, if and when the vehicle deviates from the normal operation, it does it in a manner that can be identified and controlled by the human supervisor.

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Part 2: Collection of Articles

Article 1

Applicability of current remotely operated vehicle standards and guidelines to autonomous subsea IMR operations

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APPLICABILITY OF CURRENT REMOTELY OPERATED VEHICLE STANDARDS AND GUIDELINES TO AUTONOMOUS SUBSEA IMR OPERATIONS

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ABSTRACT

This paper employs a combination of literature review and case study methodology to assess the gap between current remotely operated vehicle (ROV) standards and future autonomous IMR operation requirements. With advent of autonomous subsea and underwater vehicle systems, current ROV standards and guidelines may not offer the same benefit in designing and setting guidelines for safe autonomous operations. The reasons for this claim are two-fold. Firstly, the literature review shows that existing requirements in the ROV standards lack specifications related to autonomous subsea interventions. Secondly, the results from the case study demonstrates existence of knowledge and technology gaps, which pose challenges in development of future autonomous IMR operations.

INTRODUCTION

In recent years, the amount of subsea oil and gas installations have increased rapidly. Industry estimates state existence of over 4000 functional subsea oil and gas installations worldwide [1]. Maintaining production from these installation is the key goal of subsea operators around the world. However, similar to other man-made systems, subsea systems are susceptible to failure during their useful-life. Failures in such systems can result in production losses, which add on to field operating costs. The way to restore a faulty or failed susbea system is by intervening i.e. through subsea intervention. With the increase in number of subsea installations, demand for subsea interventions are also estimated to increase [1]. Subsea intervention, maintenance, and repair (IMR) operations can potentially provide cost benefits if carried out safely and efficiently.

Remotely operated vehicles (ROVs) are key enablers to install, operate, and maintain oil and gas, fisheries, and marine infrastructures. In the subsea oil and gas industry, applications of ROVs range from simple observational diving assistance

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to complicated heavy subsea interventions. With advances in technology, operational capabilities of different ROV classes have increased in the last decade [2]. Standards and guidelines such as EN ISO 13628-part 8, ISO 13628-part 9, API 17H, NORSOK U-102, IMCA R 004, IMCA R 005, and IMCA R 018 have spearheaded application of safe design and operational principles of ROVs for subsea interventions [3–9].

The Norwegian oil and gas industry continues to focus on optimizing subsea IMR activities. The industry together with the scientific community currently envision a prospective solution of developing underwater vehicles capable of autonomous operations with limited or no operator control. Subsea factories in the future will also create need for autonomous IMR operations. Intervention systems operating in subsea factories need capabilities to maintain and repair subsea systems autonomously thereby maintaining production uptime and reducing cost of intervention.

Demonstrations of underwater vehicles capable of performing autonomous IMR operations are steadily increasing with added functionalities [10–18]. Research projects are experimenting with manipulator arms installed on AUVs to perform IMR operations and have been successful in their early trials [19, 20]. *DeepStar project* is a joint industry project in Houston, which is currently working on standardizing AUV interfaces [21]. [22] highlights that hazards associated with use of autonomous systems vary depending on different environmental scenarios. Similarly, functional requirements differ when autonomy is introduced into existing technical systems, as suggested by [23]. It is vital to get an overview of current standards specifying functional and operational requirements of ROVs to determine to which extent autonomous functionality already is covered. This will contribute to highlighting any knowledge gap that may hinder the development and adoption of autonomous IMR operations in the industry.

The main objective of this paper is to provide an overview of existing ROV standards and perform a gap analysis related to autonomous IMR operation capability. A subsea intervention operation is used as a case study to demonstrate the gaps.

This paper is organized as follows: the next section provides a review of international ROV standards/codes and standards describing autonomy in underwater vehicles. A subsea intervention case study is presented in the succeeding section. A discussion on the observations from the review and case study is followed by conclusion and scope for future work.

ROV STANDARDS

Fig. 1 illustrates the collection of international ROV standards reviewed in this paper. Tab. 1 provides overview of the requirements in current international standards. Symbol ✓ signifies the requirements are specified in the respective standard/code while, symbol ✕ signifies absence of corresponding requirements.

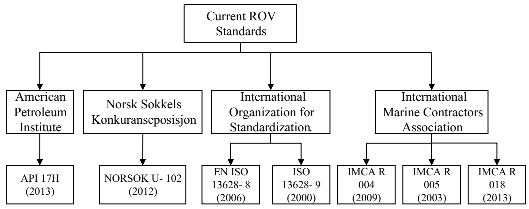

FIGURE 1. OVERVIEW OF CURRENT ROV STANDARDS

EN ISO 13628-8: 2002 (E)

The International Organization for Standardization (ISO) is the author of ROV specific standard ISO 13628- part 8. The European Committee for Standardization (CEN) adopted the standard in 2006 and designated EN ISO 13628-8 as a national standard. Currently, the standard is applicable in twenty-nine countries within Europe [3].

Guidelines on intervention philosophy and functional requirements for ROV application in the petroleum industry are described in the standard. Five standard ROV intervention configurations are explained; ROV intervention with manipulators, a manipulator arm, tool deployment unit, dual down line method, and tool skids or frames. For each configuration, the standard highlights general design and operational considerations. The standard provides guidelines towards subsea facility design in relation to fail-safe design, damage potential of subsea structures, load reaction of subsea structure, interface minimization between the ROV and subsea structures, position control of the ROV, and ROV access requirements.

The ROV access requirements are further divided into externally located interfaces, external boundary penetration, and internally located interfaces. The internally located ROV interfaces on subsea structures are required to consider width of access, height of access, and vertical access limits. Conceptual design considerations address assessment of requirements, failure mode identification, method of intervention, frequency of intervention, and use of standard tools. Loading forces exerted on the subsea system and the ROV are also required to be considered namely, the design for loading, forces exerted by tools, sea water currents, and collision with unprotected subsea facilities.

ROV design involves developing desired features related to visual aids on the ROV, recommendations on color codes on structures, requirements on anti-fouling, parking locations of the ROV, use of guide cones and guideposts, orientation of the subsea structure, and protection of valve steps against excessive torquing. In contrast, snagging of umbilicals with subsea struc-

TABLE 1. OVERVIEW OF ASPECTS IN INDUSTRY ROV STANDARDS

Aspects	ISO 13628-8	ISO 13628-9	API 17H	NORSOK U-102	IMCA R 004	IMCA R 005	IMCA R 018
Design	✓	✓	✓	✓	×	×	×
Materials	✓	✓	✓	×	×	×	×
ROV classification	×	×	×	✓	✓	×	✓
Type of vessel	×	✓	✓	×	✓	×	✓
Life cycle cost	×	✓	✓	×	×	×	×
Type of intervention	✓	×	✓	×	✓	×	×
Launch and recovery system (LARS)	×	✓	✓	✓	✓	×	✓
Tether management system	×	✓	×	✓	✓	×	✓
ROV parking	✓	×	×	✓	✓	×	✓
ROV control room	×	×	×	✓	✓	×	✓
Subsea interfaces	✓	✓	✓	✓	×	×	×
Subsea equipment marking	✓	×	✓	×	×	×	×
Operations	✓	✓	✓	✓	✓	✓	×
ROV access	✓	×	✓	×	×	×	×
ROV docking (for stabilization)	✓	×	✓	×	×	×	×
Power (electric and hydraulic)	×	✓	✓	✓	×	×	✓
Handling systems	×	✓	✓	✓	✓	×	✓
Human machine interface	✓	×	×	✓	✓	×	×
Intervention crew	×	×	×	✓	✓	✓	×
Personnel communication	×	×	×	✓	✓	×	✓
Crew training	×	×	×	✓	✓	✓	×
Organization responsibilities	×	×	×	✓	✓	✓	×
ROV tooling	✓	✓	✓	×	✓	×	×
Risk assessment	✓	✓	×	✓	✓	✓	✓
Emergency recovery	×	×	×	×	×	×	✓
Environment	×	✓	✓	×	✓	×	✓
Working temperatures	×	✓	×	×	✓	×	×
Seabed characteristics	✓	✓	×	×	✓	×	×
Documentation	✓	✓	✓	✓	✓	×	×
Navigation	×	×	×	×	✓	×	×
Communication (ICT)	×	×	×	×	×	×	✓
Umbilicals	×	×	×	✓	✓	×	×
Certification	×	✓	×	✓	✓	×	×
Testing	×	✓	✓	✓	✓	✓	×
Condition monitoring	×	×	×	✓	×	×	×
Maintenance	×	×	×	✓	✓	✓	×
Spare part strategy	×	×	×	✓	✓	×	×

tures, size of the subsea valve, orientation of levers, hidden indicators from ROV point of view and low operating heights are undesirable ROV design features. To ensure safe ROV interfaces with the subsea systems, EN ISO 13628-8 provides a comprehensive checklist on ROV interface requirements for the subsea structures. Design of structures, such as subsea trees, manifolds, subsea valves and chokes, control modules, multiphase meters, high integrity pressure protection systems (HIPPS), and umbilical jumpers should satisfy the requirements. Operational limitations, such as access requirements for certain operations need consideration. The human machine interface provides visual cues to the ROV operator. Requirements to design indicator systems, which help the operator to easily process the information, are provided in the standard.

Material selection of the subsea interface is specified in relation to the yield stress, ultimate tensile strength, fatigue, internal wear and tear due to frequent use, corrosion of interface, and marine fouling of the material. Documentation requirements on equipment design, testing and information feedback in design, testing and installation phases are recommended to be maintained. The standard concludes with set of ROV interfaces, as shown in Tab. 2.

ISO 13628-9: 2000 (E)

Part 9 of the ISO 13628 standard describes functional requirements and recommendations for remotely operated tool (ROT) systems interfacing with subsea structures. This standard is limited to ROT systems and does not cover ROV intervention systems, such as manned intervention systems, replacement of subsea modules and internal wellbore tools. [4] defines ROT system as *dedicated, unmanned, subsea tools used for remote installation or module replacement tasks that require lift capacity beyond that of free swimming ROV systems*. The ROT systems consists of systems dedicated to certain intervention tasks, deck handling systems, intervention control system, deployment or landing equipment, and ROV spread interfaced with ROT systems. Examples of ROT systems are component change-out tool (CCO), equipment running tools, connection actuation tool (CAT).

ROT systems are utilized in all phases of a subsea field and are required to consider intervention operations performed in all phases. The link between ROT intervention systems and the Life-Cycle-Cost (LCC) of the field is highlighted in the standard. Improper planning of ROT systems can increase the LCC of the whole subsea field. Deck handling equipment, such as skid systems, winches, vessel cranes, mobile A-frames and heave-compensated systems, influence the choice of intervention vessel. Since some ROT systems are controlled from topside facilities, requirements on control and monitoring of ROT during topside function test, running of tool during and in between interventions are specified. Possible deployment and landing of tools through guideposts, funnels and connectors, side entry, variable buoyancy of ROT and haul-down require consideration during ROT design and operations.

Tools for primary intervention during tie-in operations need to specify sealine, type of intervention vessel, and environmental attributes (e.g., water depth, sea current), and production system layout. While tools for primary intervention during module replacement need to specify operational issues, environmental attributes, access to subsea facility, frequency of intervention, and physical limits of the module to be replaced (e.g., mass, dimensions). Functional requirements and recommendations with respect to deployment and landing, surface equipment, control system, tie-in operations, and module replacement are extensively listed [4][page 8-18].

Testing requirements consist of re-qualification due to change in fit form and function, evaluation for qualification and wet testing, verification of contingency functions, surface testing prior to deployment, verification of entry access angles, verification of electrical and hydraulic interfaces, verification of masses and dimensions, verification of ROT torque output, calibration of sensors, switches etc., and verification of ROV access for monitoring inspection of ROT systems. The standard concludes with a set of internal and external interface requirements on the vessel/rig, subsea structures and the ROV systems.

API 17H

The latest version of API 17H (2013) standard is drafted by the American Petroleum Institute (API). However, the current API 17H standard is a combination of EN ISO 13628-8 and ISO 13628-9 standards. Tab. 2 shows the difference in requirements for ROV tooling interfaces in EN ISO 13628-9 and API 17H.

In addition to the contents of ISO 13628- part 8 and part 9, API 17H describes component and module intervention by illustrating two different types of ROT system philosophies: ROT with self-contained control system and ROV supplied hydraulic/electric power ROT systems. The major difference in the ISO 13628-8, 9 and API 17H is that API 17H is a recommended practice guideline, whereas ISO 13628-8 and 9 are normative standards in design of ROV and ROT systems. This is evident in the language used while drafting requirements. The API 17H describes requirements in *should* (recommendation), whereas ISO standards uses *shall* (mandatory) while specifying requirements. Since the API 17H standard is a combination of ISO 13628- part 8 and part 9 and to avoid duplication of content, further detail of requirements in API 17H are not described here (refer to two previous subsections).

NORSOK U-102

The NORSOK U-102 standard is developed by the Norwegian petroleum industry to ensure safe and efficient ROV operations. The standard is published with support of Norwegian Oil Industry Association (OLF), Federation of Norwegian Industry, Norwegian Shipowners' Association and the Petroleum Safety Authority of Norway (PSA) [6].

NORSOK U-102 classifies ROVs into three major classes; Class I-Pure observational class, Class II- Observation with payload options, and Class III- work class vehicles. Class II ROVs are further classified into Class II A-Observation class with payload and Class II B-Observation class vehicles with light intervention, survey and construction capabilities. Class III ROVs are further classified into Class III A- work class vehicles $<$ 100 kW and Class III B- work class vehicles $>$ 100 kW. NORSOK U-102 is one of the standards in this review, which is also applicable to autonomous underwater vehicles (AUVs).

The standard specifies set of administrative requirements, such as documentation of quality management systems, contractors responsibilities, maintenance systems and reporting. Personnel qualification requirements with respect to manning level, crew qualification, ROV pilot requirement are extensively listed. Requirements related to interface between the ROV and intervention vessel, such as deck loads, sufficient electric power, noise levels, installation outlets, safe access between control and launch sites, launch positions, vessel motion characteristics, protected area for maintenance, hoses and cable routings, and safe launch distances from the vessel are described in the standard.

Technical requirements for all three classes of ROVs are extensively specified in [6][page 15]. These technical requirements are specified for operational depth of the ROV, buoyancy, maneuverability, choice of cameras and lights, type of instrumentation, automatic functions (depth and heading readings) and choice of transponders/responders on the ROV. For Class II and Class III vehicles, additional requirements on type of sonars (obstacle avoidance and measuring sonars), plug in connection points, manipulator arms (outreach, lift capacity, grip capacity) and hydraulic power packs are specified.

Operational requirements are addressed in relation to risk assessment, operational management, mobilization plan, function testing of equipment, work procedures, personnel familiarization and experience transfer. Requirements to comply with safe working loads and length of the tether management system (TMS) are specified and are subject to the scope of the work. While, umbilical and tether are required to be designed as to limit mechanical damage during normal operations. Requirements on handling system, such as safe working load, launching criteria and umbilical winch speed are specified. The standard concludes with set of requirements on ROV control room facil-

TABLE 2. TOOLING INTERFACES ISO 13628-9 VS. API 17H

ROV Tooling Interfaces	ISO 13628-8, 9	API 17H
Stabilization	✓	✓
Handles for use with manipulators	✓	✓
Handles for use with tool deployment unit	✓	×
Rotary docking	✓	✓
Rotary interface low torque	✓	✓
Rotary interface high torque	✓	×
Linear interface type A and C	✓	✓
Linear interface type B	✓	✓
Hot Stab connection A	✓	✓
Hot Stab connection B	✓	✓
Hot Stab connection C & D	×	✓
Rotary fluid coupling	✓	✓
Component Change Out interface	✓	✓
Lifting mandrels	✓	✓
Electrical and hydraulic jumpers	✓	✓

ities. The ROV control room shall be designed to reduce noise level, maintain ergonomic working conditions with video feeds and provide communication channels with the bridge and launch areas while, operator stations shall be designed to reduce physical stress. Condition monitoring capabilities shall be provided in the ROV control room to monitor ROV status.

IMCA R 004

IMCA R 004 ROV (Rev.3 2009) code of practice is authored by International Marine Contractors Association (IMCA). Previous versions of this code of practice date to the year 1997 and 2003. The earliest version of this code dates to the year 1988 [24].

The code classifies ROVs into five categories, such as observation, observation with payload, work-class, towed and bottom crawlers and prototype vehicles. The classification is followed by brief description of ROV tasks, such as observation, survey, inspection, construction, intervention, burial and trenching. ROV tools used during ROV operations, such as video cameras, non-destructive testing (NDT) sensors, acoustic and tracking sensors, cleaning devices, vehicle station keeping devices, and work tools are briefly explained. However, no detail requirements or recommendations are provided on operating these ROV tools.

Requirements on environmental considerations, ROV operations, equipment certification and maintenance, and personnel are addressed extensively in IMCA R 004. Environmental conditions, which influence safe ROV operations are divided into weather, sea state and swell, sea currents, water depth, seabed characteristics, and pilot experience of unfavorable conditions. Weather characteristics, such as wind speed, rain and fog, combinations of wind, rain and snow, hot and humid weather effect on ROV electronics are recommended to be considered during ROV operations. Sea state due to rough seas, and their effects on handling systems, and personnel on board is described and use of heave-compensated deployment systems is recommended. Hazards due to varied sea current are highlighted, and simulations of sea current is recommended to obtain better sea current predictions. Factors affecting ROV maneuverability underwater, such as length of umbilical, propulsion system, flying depth and orientation, vehicle hydrodynamics, non-uniform current profiles, and umbilical spinning in deep water are explained. Consideration of working depth with respect to umbilical length and drag, transit time, visibility, temperature, salinity, pollutants, and water movements are described. Seabed characteristics, such as rocky outcrops and soft seabed bottom need consideration during ROV operations phase.

The code recommends performing a risk assessment to identify and mitigate site-specific hazards before every ROV operation. Description and measure to mitigate physical hazards within handling systems, water intakes and discharge, ROVs near diving operations (operations along with human divers), electricity, and high-pressure water jetting operations are mentioned. The ROV contractors are recommended to maintain documentation of operations manual, HSE management system, technical manuals for equipment, daily logs/reports, planned maintenance schedules, maintenance and spare parts records, and pre/post-dive checklists. ROV location and integrity on the intervention vessel with respect to factors, such as vessel size, handling systems, mobilization plans, permit-to-work system, hazardous areas, and ships center of gravity are discussed.

[7] provides requirements on equipment certification and maintenance. The certification requirements encompass vehicle, electronic control, vehicle power-on checks, ancillary tools, and handling systems certifications. The maintenance requirements encompass equipment register, planned maintenance schedules, and spare part planning. Handling systems consisting of ROV lifting cables, sheaves, rings, shackles and pins are required to be examined and certified every six months. The code concludes with requirements on personnel (crew) and associated responsibilities of the different stakeholders during ROV operations. Support functions, safe working practice, minimum crewing levels, and tooling setup dictate the team size required for every operation. Maximum working period of 12 hours for personnel is recommended to limit exhaustion and safety incidents due to low concentration levels. Personnel training requirements consist of survival, first aid, fire fighting, and hazard awareness.

IMCA R 005

IMCA R 005 is a guidance document developed to ensure electrical safety while handling high voltage equipment (voltage exceeding 1kV) such as ROVs [8]. The document describes responsibilities of ROV crew towards familiarization of electrical hazards at work-site and recommends a syllabus for training personnel designated to work in high voltage and electrical hazardous areas. IMCA R 005 recommends maintaining work safety systems such as safety procedures by contractors, presence of at least two personnel while handling high voltage equipment, control of permit to work system, mechanical isolation of work-sites, familiarization with the equipment, and risk assessment before start of operations.

Procedures to area isolation and access for maintenance include safe isolation of work-site and certified proved dead (no voltage) areas by voltage tester. The code also provides checklists to prepare for maintenance work and fire extinguishing activities. The code concludes with testing requirements on instruments, testing equipment and proving dead areas [8].

IMCA R 018

IMCA R 018 is not normative, but provides general outline requirements for installation of ROV systems on offshore vessels and platforms [9]. Sub-systems of ROV are ROV, LARS, TMS, control cabin, umbilical winches and workshop cabin. The documents classifies ROVs into five classes as classified by [7]. Two generally used ROV deployment methods are explained, i.e., over the side and moonpool deployment. Over the side deployment is mostly used in offshore vessels while, the moonpool deployment is used on fixed or floating platforms. Platform inlets or outlets and simultaneous operations are recommended to be considered prior to installation of LARS. Working area near or directly behind the handling systems and the umbilical winch need to be cleared before launch and recovery to ensure minimum restrictions in umbilical movement. [9] provides guidance checklists for installation of A-frames, hydraulic power units (HPUs), ROV control room, ROV workshop area, deck space (for ROV parking and handling), head room (overhead clearance), skid handling systems, oil reclamation and water drainage system, control stations of handling systems, access and exit paths and emergency recovery of ROV (e.g., isolation of vessel thrusters, capable and available crane coverage and prior risk assessments).

Furthermore, the document describes in detail the electrical power requirements for both support vessel main supply and the ROV. Two-way communication between ROV control room and positioning sensors on the ROV along with continuous video-links (camera feeds) are recommended to be established. Fresh water availability for washing ROV after recovery, fire alarm integration to all outdoor sections of the vessel, close circuit camera television (CCTV) and survey sensor requirements are recommended. The document concludes with operational requirements concerning sea state, total load path of the ROV (load of ROV, winch, umbilical and handling system), deck loading and relevant regulations are recommended to be followed.

STANDARDS ADDRESSING AUTONOMY

In addition to the traditional industry ROV standards, the American Society for Testing and Materials (ASTM) is the author of four standards applicable to autonomous unmanned undersea vehicles (UUVs). Fig. 2 provides an overview of these standards [25–28]. These standards provide general guideline to develop autonomous UUVs by addressing requirements for each sub-system making the UUV. The four standards address aspects related to general autonomy and control, payloads and interfaces, recommendations for communication networks, and collection and processing of sensor data by autonomous UUVs. However, these four standards do not provide detailed requirements on functional safety aspects of UUVs. Tab. 3 provides an overview of the high level aspects mentioned in these standards.

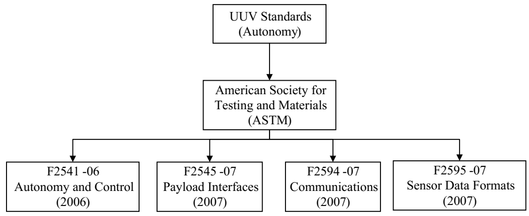

FIGURE 2. STANDARDS CONSIDERING UUV AUTONOMY

F2541- 06

This standard addresses requirements, which can enable UUV systems to operate autonomously for extended period of time without human intervention [25]. The standard defines terminologies used in describing autonomy and control of UUVs extensively. The standard describes UUV functional susbsystems and interfaces namely, vehicle control, payload control, autonomous control, on-board safety systems, and communications. An extensive list of UUV capabilities is listed in the standard, for example, levels of situational awareness of the UUVs are categorized. Levels of autonomy, system capabilities, system architecture and design, operator interaction, sensor input, application of autonomy levels, system performance, and collaboration requirements are specified.

F2545- 07

This standard addresses key interface aspects for autonomous UUV systems interfacing with dedicated mission payloads. Requirements related to the physical payload, such as physical characteristics (size, buoyancy and trim, hull, mechanical/electrical connections and vent plugs), functional characteristics, and signal interface are addressed in the standard [26]. Quantitative requirements for each of the above mentioned high level requirements are addressed in the standard. For example, size requirements of the physical payload are divided into sub-requirements of acceptable payload volume (5 cubic ft), payload diameter (20.940 inches), and payload weight (400 pounds) .

TABLE 3. OVERVIEW OF ASTM UUV AUTONOMY STANDARDS

Aspects	F2541- 06	F2545- 07	F2594- 07	F2595- 07
Design	✓	✓	✓	✓
Autonomy	✓	✓	✓	✓
Physical payload	✓	✓	×	×
UUV classification	✓	×	×	×
Functional safety	✓	×	×	×
External/Internal interfaces	✓	✓	×	✓
Electrical power	×	✓	×	×
Sensor integration	✓	×	×	✓
Communication (ICT)	×	×	×	✓
Navigation	✓	×	×	×
Environmental data	✓	×	×	×
Situation awareness	✓	×	×	×

F2594- 07

This standard addresses communication requirements for autonomous UUV systems. The document is categorized as an informative guideline and not a normative standard [27]. The guideline adopts the nomenclature used by the telecommunications industry of Seven Layer Open System Interconnection (OSI) and specifies requirements for each of the seven layers, i.e., physical, data link, network, transport, session, presentation, and application layer. Optical communication requirements with respect to laser communications is specified. Underwater acoustic communication constraints, such as information exchange rates, adverse transmission channel, asynchronous networking, efficiency and endurance of underwater batteries, and information transfer, are discussed. Radio frequency (RF) communications requirements for light of sight, tactical common data link (TCDL), and beyond line of sight techniques are specified. UUV network and communication security requirements are also described. Challenges in communication related to seven layers of OSI are discussed in the document.

F2595- 07

This standard describes various methods and techniques to setup and integrate sensor networks to enable UUV operations [28]. The main requirements addressed in this standard are derived from U.S. Navy's Mission Reconfigurable UUV systems. The main requirements for sensor data formats are described in 11 sub sections namely, general water column and ocean bottom guidelines, low volume data versus high volume data, governing U.S. Military specifications, specific water column guidelines, specific ocean bottom guidelines, imagery data, unified sonar image procession system (UNISIPS), side looking sonar (SLS), ambient noise, other geophysical data, and above-waterline sensor data. Specification of mission data formats are described, i.e., mission timing, vehicle mission data, external interface data formats, joint architecture for unmanned systems (JAUS), and security. The standard data storage media and metadata format requirements are followed by recommendations of sensor formats for UUVs.

CASE STUDY

To demonstrate the gap in current requirements for ROV design and operation, a case study method is hereby employed. Replacement of a subsea control module (SCM) is chosen as the subsea intervention operation, which will be evaluated against two ROV system scenarios. SCM is a metal canister, which houses redundant subsea electronic modules (SEM) providing two-way communication between topside and subsea facilities. The SCM also houses hydraulic directional control valves (DCVs) used to operate subsea valves either autonomously or by emergency push-buttons installed topside. The choice of this particular intervention operation is based on inputs from the partners in the NextGenIMR project at AMOS centre.

This paper provides a high level definition of autonomous ROVs in-line with the definition of autonomous underwater vehicles (AUV) is described in [6] and associated intervention philosophy. *Autonomous ROV is equipment used in water with an ability to position itself and operate ROT systems on subsea systems without interference from surface (i.e, without cables to surface)*. The autonomous ROVs can be classified into two distinctive subsea intervention philosophies:
Type 1 semi-autonomous ROVs (SAROV) can operate with existing offshore infrastructure, launch and recovery systems, subsea systems, subsea interfaces and umbilical systems, but are able to fly, control the manipulator arms, and perform subsea IMR operations with limited operator control.
Type 2 autonomous ROVs (AROV) are able to function autonomously and reside in designated subsea docking areas, are able to independently control manipulator functions, can navigate autonomously, perform self diagnostics, and are equipped with automatic ROT systems. The case study considers both *Type 1* and *Type 2* ROVs as work-class vehicles, as defined by [6].

Based on the set of autonomous functions required in the future, the intervention operation of replacement of SCM will be evaluated against existing requirements in the following subsections. A brief operational sequence of the intervention is listed in Tab.4.

Replacement of SCM- current scenario

Definition of task is replacement of subsea control module. Specification for this task consists of technical information on the subsea system and ROV contractors. Intervention philosophy is use of IMR vessel with combination with ROT and ROV systems to replace the SCM. Subsea and ROV interfaces are defined to develop the torque tool, manipulator arms, jumper parking zones with reference to standards [4, 5]. ROV access requirements are also referred from [3, 5]. The subsea equipment is designed to interface smoothly with the ROT systems. ROT systems such as

TABLE 4. SEQUENCE OF SCM REPLACEMENT

Step	Description of SCM replacement operation
Step 1	The ROV is launched through the LARS from an IMR vessel.
Step 2	The ROV is flown by two human ROV operators (one controlling the flight path and other controlling the manipulator arms) to the vicinity of the X-mass tree.
Step 3	The ROV manipulator arms remove the electrical and hydraulic jumpers connected from the X-mas tree to the SCM connector ports (electric/hydraulic/optical connectors).
Step 4	The ROV parks the jumpers in the slot provided in the X-mas tree.
Step 5	The ROV is flown above the SCM and the SCM protection cap is removed.
Step 6	The SCM lock down mode is disengaged by the ROV manipulator arms.
Step 7	The torque tool is lowered down in an ROV tool basket.
Step 8	The torque tool is picked up by the ROV and placed in the slot provided on top of the SCM. (with correct orientation)
Step 9	The torque tool is engaged and is turned to a predetermined revolution.
Step 10	The SCM running tool is run subsea from a different location of the IMR vessel.
Step 11	The ROV steers the SCM running tool and guides it to the SCM slot on the X-mas tree.
Step 12	The SCM running tool is mechanically locked in position by use of a lock mechanism by the ROV manipulator arms.
Step 13	The SCM is connected to the running tool and the topside winch lifts the SCM while the ROV guides the operation subsea.
Step 14	The spare SCM is lowered on the SCM running tool and the *sequence is reversed to replace the SCM*.

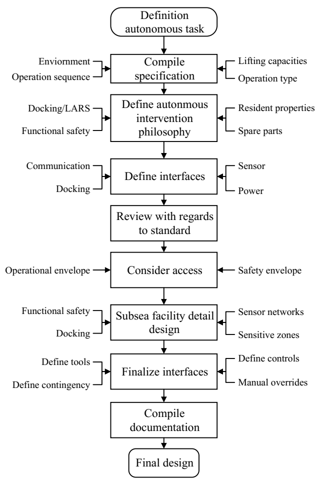

FIGURE 3. DESIGN PROCESS FOR ROV/ROT ADAPTED FROM [3]

SCM running tool, manipulator arms, torque tool, SCM protection cap and parking leads are defined, finalized, and document before final design. Sequence of operations is as described in Tab. 4.

Requirements for semi-autonomous ROV (SAROV) systems

ASROV systems will be able to carry out predefined autonomous functions. Since such systems can utilize current offshore infrastructures, adoption of these systems by the petroleum industry will be earlier than the fully autonomous ROV systems (*Type 2 ROV systems*).
For this case study, the following assumptions have been made: a) SAROV can operate with existing LARS, ROT, subsea interfaces and umbilicals. b) SAROVs can fly along their planned flight path and operate manipulator arms without human intervention. c) Autonomous functions of SAROVs can be overridden by human interference from ROV control room. The SAROV operational sequence is suggested as follows- Step 1, and step 3 to step 14 are identical to SCM replacement in current scenario as described in Tab. 4. Step 2 will require monitoring from the ROV operators topside.

Gap in requirements With reference to Tab. 4, SAROV systems can perform steps 1, 7, 9, 10, 13, and 14 using existing offshore/subsea infrastructure. However, steps 2, 3, 4, 5, 6, 8, 11, 12, and 13 require further development in functional requirements related to navigation, localization and guidance. In addition, sensor fusion requirements are necessary for the SAROVs perception of the surroundings. Functional safety requirements related to asset and subsea equipment safety are also key requirements, which need development. Requirements concerning manipulator arms capabilities (e.g., lifting capacities, reach), fault tolerance capability (e.g., accuracy levels with sensor degradation), control and monitoring from topside (e.g., personnel requirement and competence), manual overrides (e.g., scenarios triggering manual override), and contingency plans (emergency SAROV recovery) are other key areas for development.

Tab. 5 indicates the gap in requirements for *Type 1* ROVs (SAROVs). Symbol ✓ signifies existence of gap in current requirements while symbol ✕ signifies relevant requirements are currently existing in standards/codes.

Requirements for autonomous ROV (AROV) systems

AROV systems are aimed at performing functions with full operational autonomy. Previous studies with similar intervention philosophy using AUVs have been demonstrated by [17,19,20]. The intervention philosophy of the systems in these studies is derived from AUVs with manipulator capabilities. Nevertheless, the philosophy in this case study as compared to [17,19,20] is the same, i.e., subsea intervention by use of underwater vehicles and manipulators. In this paper underwater vehicle refers to ROVs.

Gap in requirements If the requirements for AROV systems were derived from current ROV standards, AROVs would not be able to perform any steps described in Tab. 4. The reason for this claim is- autonomous operations are not defined in the current ROV design or operational standards/codes. Furthermore, previous studies [17, 19, 20], do not cite to any standards including [25–28], meaning that the functional requirement of AUV demonstrated in past studies were developed on a case-by-case basis.

In addition to the requirements mentioned in Tab.3, Tab.5 identifies additional requirements, such as safe state of the AROV, fault tolerance, maximum sensor degradation, and functional safety. These requirements are critical to safe autonomous operations, but need further development.

TABLE 5. GAPS IN AUTONOMOUS IMR OPERATIONS

Aspects	Type 1 SAROV	Type 2 AROV
Autonomy	✓	✓
Subsea facility design	×	✓
Navigation	✓	✓
Path-planning	✓	✓
Localization	✓	✓
Guidance	✓	✓
Functional safety	✓	✓
Sensor fusion	✓	✓
Fault tolerance	✓	✓
Resident properties	×	✓
Launch and recovery	×	✓
Manipulator arms	✓	✓
Lifting capacities	×	✓
Qualification	✓	✓
ROT systems	×	✓
Spare parts	×	✓
ROT control system (topside)	×	✓
ROT control system (self-contained)	×	✓
Subsea docking (for charging and parking)	×	✓
Environmental conditions	×	✓
Power	×	✓
Communication	×	✓
Control and monitoring	✓	✓
Manual override and monitoring	✓	✓
Contingency planning	✓	✓

DISCUSSION

The case study approach shows that autonomous IMR operations using ROV systems need to consider a variety of technical requirements in addition to the requirements specified in existing ROV standards. The sequence of operations mentioned in the case study highlights key challenges and gaps in realizing autonomous subsea IMR operations. Studying IMR operations, such as installation of pig-loop, installation of subsea connectors etc. may reveal more gaps, which the SCM replacement case study did not uncover.

The terminology and classification of types of underwater vehicle systems vary in the standards. Standards have introduced many nomenclatures for underwater vehicles for example, ROVs, AUVs, UUVs, which post challenges in defining assumptions for the case studies. Some gaps identified from this study are applicable to AUVs. For example, aspects, such as sensor fusion, manipulator arms, manual override and monitoring, resident properties, subsea docking, navigation, localization etc. are applicable to underwater vehicles other than the ROVs.

The existing ROV tooling design process described in EN ISO 13628-8 is a robust process, which can be adapted to develop autonomous ROV/ROT systems as illustrated in Fig. 3. The figure illustrates the additional inputs required to design ROV/ROT systems for autonomous IMR operations as identified in Tab. 5.

SAROVs defined in this paper can utilize existing infrastructure and can potentially decrease the duration of intervention activities. They also require less development work when compared to the development work scope of fully autonomous ROV systems.

CONCLUSION AND FURTHER WORK

This paper provides an overview and a detailed review of existing ROV standards and standards considering underwater vehicle autonomy. The study shows that a combination of current ROV standards provides a basis for further development of requirements for both autonomous IMR operations, and associated ROV systems. However, with introduction of autonomous functions, the paper demonstrates that there is a need for additional requirements at various sub-system levels, for example, functional safety, sensor fusion, subsea facility design etc.

This paper describes the SCM running and retrieval sequence carried out during SCM replacement subsea intervention. The study highlights the importance of a semi-autonomous systems, which can operate on existing infrastructure. Due to technology and knowledge gaps, the study concludes that current ROV standards are only partly applicable to future subsea autonomous IMR operations. However, the ASTM standards reviewed in this paper provide a starting point for developing detailed functional requirements.

Measures to fill the gaps highlighted in this study require further research by multi-disciplinary research teams. For example, developing functional safety requirements for AROV systems and defining safe states of AROVs need combination of control theory and reliability analysis. Investigation of reliability assessment of safety critical systems of autonomous ROVs and development of safety functions is one of the key future work prospects. Replicating the method used in this paper to study other subsea intervention operations can lead to identification of additional technology and knowledge gaps.

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Article 2

Development of collision risk indicators for autonomous subsea inspection maintenance and repair

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Development of collision risk indicators for autonomous subsea inspection maintenance and repair

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ABSTRACT

The objective of this article is to present a method for developing collision risk indicators applicable for autonomous remotely operated vehicles (AROVs), which are essential for promoting situation awareness in decisions support systems. Three suitable risk based collision indicators are suggested for AROVs namely, time to collision, mean time to collision and mean impact energy. The proposed indicators are classified into different thresholds; low, intermediate and high. An AROV flight path is simulated to gather input data to calculate the proposed indicators and three collision targets are established, i.e., subsea structure, seabed and a cooperating AROV. The proposed indicator development method together with the case study show a proof-of-concept that the combination of mean time to collision and mean impact energy indicators can identify risk prone waypoints in the AROV path. The method results in an overall risk picture for a given AROV path. The results may provide useful input in replanning of mission paths and for implementation of risk reducing measures. Even though the method focuses on collision risk, it can be used for other accident scenarios for AROVs.

1. Introduction

Technology development initiatives in the oil and gas industry are necessary to realize the vision of subsea factories (Ramberg et al., 2013). Operational availability of these future *subsea factories* depend on safe operation of the subsea infrastructure and related intervention systems. In the oil and gas industry, Remotely Operated Vehicles (ROVs) are used to install, operate, and maintain subsea production systems. Currently, the need for subsea intervention systems, such as ROVs, are increasing across the world due to the increased number of subsea production wells. A subsea intervention system is also termed as an inspection, maintenance and repair system (IMR system), where *inspection* refers to visual inspection of subsea production system (SPS), *maintenance* refers to preventive maintenance and *repair* refers to corrective maintenance. The cost of subsea intervention is one of the key factors affecting future subsea maintenance. One alternative to reduce the cost of maintenance of future subsea fields is to introduce autonomy in the subsystems of both SPS and IMR systems (Schjølberg and Utne, 2015). However, increased autonomy in subsea intervention operations introduce technology and knowledge gaps (Hegde et al., 2015).

When autonomous functionalities are implemented into a ROV, in the following denoted AROV, a system safety perspective is necessary to ensure safe functioning of the AROV during IMR operations. Future IMR operations may partly be remotely operated and partly be performed autonomously. The subsea equipment manufacturers and operators predict use of autonomous IMR systems in the next 5–10 years (Ramberg et al., 2013). In such a scenario, monitoring the AROV condition becomes paramount to ensure operational uptime and avoid costly incidents.

The development trend towards AROVs can be observed in recent literature, in terms of a combination of ROVs and autonomous underwater vehicles (AUV) (Chardard and Copros, 2002; Saul and Tena, 2007; Marani et al., 2009; McLeod, 2010; Johansson et al., 2010; McLeod and Jacobson, 2011; McLeod et al., 2012; Jamieson et al., 2012; Simetti et al., 2014; Albiez et al., 2015). Therefore, research results and recommendations contributing to safe AUV operations should also be considered during the development of AROVs. Collision risk is also highlighted as one of technical and operational risks in AUV operations (Griffiths et al., 2002; Utne and Schjølberg, 2014).

Introduction of autonomy in subsea IMR operations may also increase the probability of AROV collision with the SPS. The SPS contains sensitive instruments, which aid in maintaining optimal production rates. An example is the multi-phase meter, which is a sensitive instrument used to calculate the amount of oil, gas, and

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water flowing downstream through the SPS. External damage to such a sensitive instrument can result in shutdown, production loss or accidental leak of hydrocarbons. Relying only on failure information of the IMR subsystems is not a valid monitoring philosophy in an autonomous setting. In traditional ROV operations, the operator has a vital role in collision detection/avoidance. The operator is aided by advanced sensor systems, such as cameras, sonars and depth control. Even with autonomous capabilities, the AROV should allow for monitoring and control by human operators from an intervention vessel, or a remote onshore location. If a potential collision is about to occur, reliable collision risk indicators can promote situation awareness for both the autonomous control system and for the human operator. Therefore, early collision detection and avoidance ability of the AROV is vital in an autonomous setting to ensure safe IMR operations.

An excerpt from the underwater vehicle standard Germanischer Lloyd Aktiengesellschaft (2009) reads; *systems for locating of obstacles, like rocks, wrecks, pipeline, offshore structures, etc., are to be provided to avoid collision safely*. Implementation of recommended requirements on AROVs requires an overall new operational philosophy, which uses the locational information from existing/future subsea infrastructure to map potential obstacles and mission target locations for IMR operations. By considering the existing obstacles and the IMR mission parameters of AROVs, such as velocity, position etc., collision risk indicators can contribute to improved planning and safety through simulations of the subsea IMR operations.

Swuste et al. (2016) provide a comprehensive review of indicators used in the process industries. The literature also provides various methods for developing and using both safety and risk based indicators (see, e.g., Øien, 2001; HSE, 2006; Khan et al., 2009; Sonnemans et al., 2010; Øien et al., 2011a, 2011b; Hassan and Khan, 2012; Knegtering and Pasman, 2013; Pasman and Rogers, 2014; Jennings and Schulberg, 2009). However, current research into collision risk indicators for subsea IMR operations is very limited. The terms safety and risk indicators are used interchangeably from one application field to another. According to Øien et al., 2011a, 2011b, risk indicators are parameters that are estimated based on a risk model by using available data. Risk influencing factors (RIFs) are an aspect of a system or an activity that affects the risk level of this system/activity (Øien, 2001).

The objective of this article is to present a method for identifying and quantifying collision risk indicators for AROV operations. A review of collision indicators/systems from other high risk sectors, i.e., the aviation, automotive, marine, and railway industries, is presented, providing input to development of collision indicators for subsea IMR operations. Such indicators can be utilized mainly in two different situations; i) by subsea IMR contractors to assess the collision risk associated with a given AROV path during the planning phase of an IMR operation; and (ii) as an aid for operators to assess collision risk online during IMR operations. A case study is performed focusing on application area (i), i.e., planning of an intervention mission.

The main contribution of this work is a novel methodology for developing an overall risk picture for a given AROV path. The article focuses on collision risk, but the method can also be applied to other accident scenarios. No such methodology exists today. Early collision detection and avoidance is vital in autonomous operations to ensure safe IMR operations.

This paper is organized as follows: Section 2 highlights related work on collision risk systems/metrics from other vehicular-based industries. This is followed by the general presentation of the proposed indicator development method in Section 3. Section 4 presents the case study with detailed step-by-step application of the proposed method. Section 5 discusses the findings and evaluates the properties of the proposed indicators followed by conclusions in Section 6.

1.1. Definitions

Autonomous Remotely Operated Vehicle (AROV): ROVs that can perform select IMR operations autonomously (in presence of human supervisors) and reside in designated subsea docking areas. They shall be able to independently control manipulator functions, can navigate autonomously, perform self-diagnostics, and are supervised by human supervisors (Hegde et al., 2015).

IMR system: Consists of equipment and personnel necessary to perform inspection, maintenance, and repair operations on the SPS. IMR system consists of subsystems such as ROV, tether management system, control room, umbilical, ROV tools and launch and recovery system (Bai and Bai, 2010).

Waypoint: Waypoints in this study refer to points in the AROV path where the AROV velocity and acceleration vector change in x, y, or z directions (Authors' definition).

Risk indicator: A risk indicator is a measurable/operational definition of a Risk Influencing Factor (Øien et al., 2011a).

Subsea intervention: Subsea intervention are all activities performed subsea (Bai and Bai, 2010).

Response time: The total time required by the AROV to successfully execute the predefined safety protocol for a given accidental scenario (Authors' definition).

2. Collision risk in other vehicular industries

This section provides an overview of existing metrics to quantify collision risk in four vehicular industries. The aim of this section is to summarize and understand how collision risk metrics are used in other industries.

Table 1 provides overview of existing collision detection/avoidance systems and metrics in four vehicular industries, further discussed below. Some of the selected literature do not use the term *risk indicator* specifically in their contributions (Arumugam and Jermaine, 2006; Dai et al., 2013; Garcia et al., 2007; Kuchar and Drumm, 2007; Lehner et al., 2008; Pereira et al., 2013, 2011; Zarèa et al., 2013). However, the measures suggested in these papers, can be interpreted as risk indicators, because they are dependent on operational variables of risk influencing factors (RIF) in their respective application contexts. Therefore, according to the definition of RIFs and risk indicators, the collision metrics are classified as risk indicators in this article.

In the aviation industry, due to the inherent nature of operations, collision risk is addressed extensively. Collision risk is monitored by a Traffic Collision Avoidance System (TCAS), which can detect, assess, and recommend corresponding corrective actions to avoid mid-air aircraft collision. The main goal of the TCAS system is to avoid loss of life and aircrafts by monitoring vertical and horizontal separation between two or more aircrafts in flight. The suggested corrective response is carried out by manual control by human pilots. Methods for collision risk assessments for autonomous air vehicles using kinematic equations by solving the collision in horizontal and vertical spaces also exist in the literature. In applications of Unmanned Aerial Vehicles (UAVs), indicators, such as probability of detection of pipeline leak and probability of false alarm are proposed to provide indication of leaks and spurious detections.

In the automotive industry, collision indicators are explained in detail with different theoretical and experimental methods. Two indicators, namely time to collision (TTC) and headway are widely discussed. TTC indicates the time between two automobiles, which do not take evasive action to prevent collision. Headway is defined as the time difference between two vehicles passing the same target location. Extensions of TTC and headway indicators are also described in the literature, namely time exposed time to collision (TET) and time integrated time to collision (TIT). The TET indicator

Table 1
Overview of collision detection/avoidance systems and metrics used in different vehicular industries.

Vehicular industries	Collision systems/metrics	Parameters measured	Reference publication
Aviation	Traffic Collision Avoidance System (TCAS)	Intruding aircraft detection and distance between aircrafts. Travel advisory (TCAS1). Resolution advisory (TCAS II and III)	(Belkhouche, 2013; Billingsley et al., 2012; Kuchar and Drumm, 2007; Morrel, 1957)
	Probability of detection	True positives, total targets	(Zarèa et al., 2013)
	Probability of false alarm	False positives, total targets	(Zarèa et al., 2013)
Automotive	Time to collision (TTC)	Time to collision with the vehicle in front.	(Minderhoud and Bovy, 2001; Vogel, 2003)
	Headway	Distance between two vehicles moving in the same direction.	(Vogel, 2003)
	Time Exposed Time to collision (TET)	Threshold value of TTC	(Minderhoud and Bovy, 2001)
	Time Integrated Time to collision (TIT)	Integral of threshold value of TTC	(Minderhoud and Bovy, 2001)
	TTC societal risk	TTC exposed to society (other road users)	(Qu et al., 2014)
	TTC individual risk	TTC exposed to individual (motorists)	(Qu et al., 2014)
Marine	Closest Point of Approach (CPA)	Separation distance between two ships	(Arumugam and Jermaine, 2006)
	Time to Closest Point of Approach (TCPA)	Minimum time to approach	(Arumugam and Jermaine, 2006)
	Minimum risk path	Risk between path waypoints of an underwater vehicle	(Pereira et al., 2013, 2011) (Lefebvre et al., 2016)
Railway	Railway Collision Avoidance System (RCAS)	Distance between trains. Braking command. Traffic alert.	(Garcia et al., 2007; Lehner et al., 2008)

is expressed in seconds and is an extension of TTC. When a threshold value of TTC is reached within time *t*, the time exposed in this state is measured. The TIT indicator is expressed as the integral of the TTC profile. Other extensions of the TTC indicator are TTC societal risk and TTC individual risk. The total number of TTC conflicts observed on a segment of a road in 1 h represents TTC societal risk. The individual (road user or motorist) risk is exposure to TTC conflicts in the journey time. The TTC indicator has also been used to detect potential collisions between motor vehicles and cyclists through video analysis of TTC indicator.

In the marine industry, the minimum risk path for underwater glider missions can be calculated by using Automatic Identification System (AIS) data of ship positions. A glider resurfacing in the same position as that of a ship is defined as an accidental event. The minimum risk path is calculated by using a heuristic cost function, which is set to minimum risk along N number of resurfacing way points of the glider. The closest point of approach (CPA) and Time to closest point of approach (TCPA) are two metrics used in managing collision risk in the maritime industry. CPA is the position at which two dynamically moving objects attain their closest possible distance. TCPA is the minimum time to approach the closest possible distance between two dynamically moving objects.

In the railway industry, studies are performed to investigate different communication protocols used in collision avoidance systems in aviation, maritime and automotive industries, which are then modified to railway applications. Specifically, collision surveillance methods used in the TCAS system are modified to the railway applications (Railway collision avoidance system - RCAS) and formulas to quantify the distance between trains, braking command and traffic alert messages have been proposed.

3. Method for developing collision risk indicators

The method presented in this article for developing collision risk indicators is illustrated in Fig. 1, consisting of six steps. Collision risk metrics from other industries described in Section 2 are used as inputs to Step 3 as shown in Fig. 1.

Table 2 describes the six steps of the proposed method. The steps involved in the proposed method is applied to a case study in Section 4.

The proposed risk indicator method is adapted from Øien (2001), but modified to suit all types of underwater vehicles, including AROVs. The modifications are:

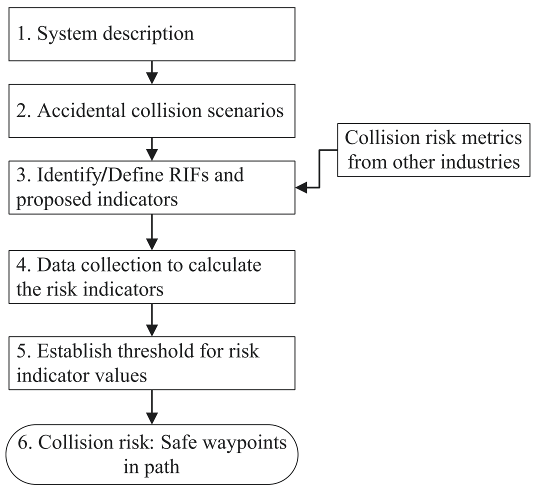

Fig. 1. Proposed indicator development and verification method, adapted from Øien (2001).

(i) A systems description step is added to define the boundaries and operational philosophies of the system.
(ii) Collision risk metrics from other vehicular industries provide input for identifying RIFs and risk indicators.
(iii) Threshold values for indicators are established to compare the results from simulation during planning. Such values are also useful for decision support during the planning phase of IMR operation.

4. Case study – collision risk indicators for subsea IMR operations

In the following, the method presented in Section 3 is applied to develop collision risk indicators, which are useful in the planning of IMR operations with AROV. The case study is structured according to the six steps as described in Section 3 and is elaborated in the following subsections.

Table 2
Steps involved in the proposed indicator development and verification method.

Step 1 System description	The outcomes from the system description step are identification of system boundary, identification of subsystems making the vehicle system, types of operation modes (system interaction with external surroundings) and type of operational/control philosophies (human machine interface). The system description shall provide relevant background information of the system to perform the following steps in the method.
Step 2 Accidental collision scenarios	By understanding the systems' boundary, limitations and interaction with the surroundings, accidental collision scenarios shall be identified in Step 2. Modes of operation of a vehicle can support identification of vehicle interaction with the surrounding. For example, an underwater vehicle is exposed to the seabed during the IMR mission, therefore; one of the accidental scenarios is collision with the seabed.
Step 3 Identify/define RIFs and proposed indicators	The factors influencing the accidental scenarios, shall be listed, for example, the time required by a vehicle to collide with an obstacle, velocity of the vehicle etc., Step 3 shall result in identification of indicators and RIFs applicable to the concerned systems. In this step, modification of existing risk indicators from other vehicular industries should be explored and their applicability to the system under study needs to be evaluated.
Step 4 Data collection to calculate the risk indicators	Input data (RIF data) is needed to calculate the proposed indicators. RIF data can either be collected from operational logs or systems, or an alternative is to obtain simulated results. This step can be challenging for novel vehicles due to absence of historical data. If such, simulation approach can be one of the alternative to collect required RIF data.
Step 5 Establish threshold for risk indicator values	The threshold values are established for the proposed indicators values. The threshold values are necessary to classify the risk indicator values as either risk prone or risk averse. These threshold values can be derived from either acceptance criteria or requirements from industry standards. In case there are no existing criteria or requirements, assumptions can be made by expert judgment.
Step 6 Collision risk: Safe waypoints in path	Since, the method is based on a risk model, simulations can be used to generate an overall risk picture, which can highlight unsafe waypoints in a given vehicle path. Risk priority numbers are allotted to the classification of the risk indicator thresholds (for example; low, intermediate, high). Depending on the number of collision scenarios, the summation of risk priority numbers can highlight the collision risk in different waypoints of the vehicle path and for different collision targets.

In order to verify the proposed indicator development method, an autonomous subsea IMR case study approach is established. Fig. 2 illustrates the IMR case study used in this article. In Fig. 2, the AROV is launched from an intervention vessel and is capable of flying to the target SPS structure by utilizing a 3D acoustic network for navigation. The human supervisors either from the intervention vessel or from an onshore facility predetermine the AROV path. During the intervention mission, an AROV can come across another AROV (2nd AROV) as illustrated in Fig. 2.

The following assumptions are made in the case study:

- A subsea acoustic communication network can provide relatively accurate positioning of the AROV and the targets
- The AROV does not require running of an umbilical chord or a tether from the intervention vessel. Nevertheless, the proposed indicators can also be used for traditional ROVs operating with a tether.
- Human supervisors predetermine the AROV path during planning and the IMR mission.
- External factors, such as human interaction and sea currents, are assumed to be in ideal/safe conditions during the IMR operation and are therefore not considered in this case study.
- The AROV is assumed to be in full working condition and technical faults or failure in the AROV subsystem, such as the navigation system, are absent during the mission.
- Three collision scenarios are considered: (i) collision with subsea structure, (ii) collision with seabed, and (ii) collision with other underwater vehicles (2nd AROV).
- The point of collision contact is the outermost plane of the AROV in the heading direction and the exposed plane of the AROV panel on the subsea structure. The second AROV is parallel to the AROV heading direction as illustrated in Fig. 3. For collision with seabed, the AROV plane in the heave direction (the lower horizontal plane of the AROV) is considered.

4.1. System description - step 1

In this section, the AROV system, different modes of operation, and the architecture for human machine interface (HMI) are described for the chosen case study.

4.1.1. The AROV system

The AROV system consists of various subsystems, such as, battery, navigation, control, buoyancy, safety, manipulator,

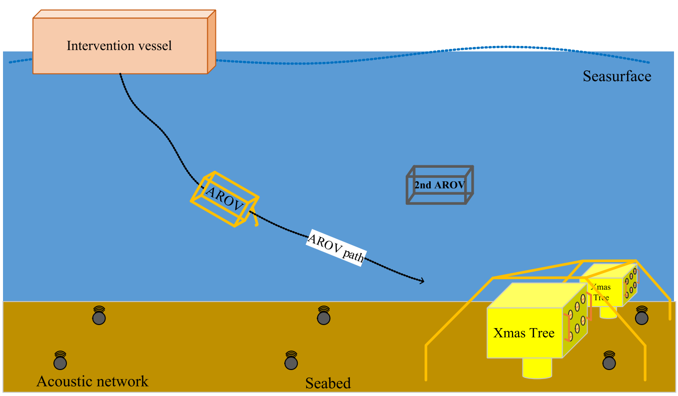

Fig. 2. The autonomous IMR case study.

communication, propulsion, lighting and sensor subsystems. In reference to Fig. 2, the AROV sensor inputs provide the vehicle control system with data, such as AROV acceleration, relative position, and AROV velocity. These vehicle data can be used by the safety surveillance system of the AROV to calculate risk based indicators, as described in following subsections. The AROV also uploads the vehicle data to the HMI of the human supervisor.

4.1.2. Modes of operation of AROVs

Current ROV operational modes during subsea interventions can be categorized into five modes of operation i) launch, ii) approach to SPS structure, iii) intervention, iv) return to base, and v) recovery. The base mode for traditional ROVs is an intervention vessel. An acoustic (e.g., Long Baseline) positioning system empowers the ROV system with navigation capabilities (Christ and Wernli, 2013). Each mode of operation demands different behavior from the IMR system. Currently, this need for change in system behavior is achieved by ensuring that all modes of operations are actively controlled and supervised by human operators usually located on an intervention or support vessel.

The modes of operation for AROV systems will be similar to current ROV systems, as illustrated in Fig. 4. Fig. 4 shows how an AROV can be launched either from an intervention vessel or a subsea garage (on the seabed), as shown in Mode 1. In Mode 2, the AROV approaches the SPS structure (AROV flight) in subsea environments where the acoustic network is present. In Mode 3, the AROV performs the intended intervention operation on the SPS. In Mode 4, the AROV returns to the flying mode through the subsea environment. In Mode 5, the AROV can be recovered by the intervention vessel or reside inside a subsea garage. The 3D acoustic positioning encompasses acoustic transducers installed on the seabed of the field and Ultra-short Baseline (USBL) acoustic systems from an intervention vessel. In areas where the acoustic signals are weak, the sensor system on the AROV assist in safe navigation to target.

4.1.3. Human machine interface

There is a need for common situation awareness between the AROV control system and the human operators supervising the AROV. Similarly, decision making needs to be shared across both the AROV and the SPS.

Fig. 5 illustrates that perceived operational hazards by any one of the two decision support systems (DSS) (subsea local DSS and human supervisor DSS) need to be assessed and communicated to both the human supervisor and the AROV. The AROV and the SPS also communicate and make decisions among each other. Operation-specific decisions, such as time to approach, approach velocity, orientation of the vehicle in relation to the SPS, faulty state of the SPS and AROV can be communicated between the two systems to enhance local situation awareness and take appropriate corrective actions. For example, if the AROV is approaching towards

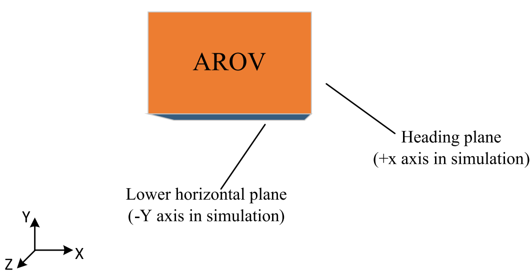

Fig. 3. Assumed collision planes of the AROV in the case study.

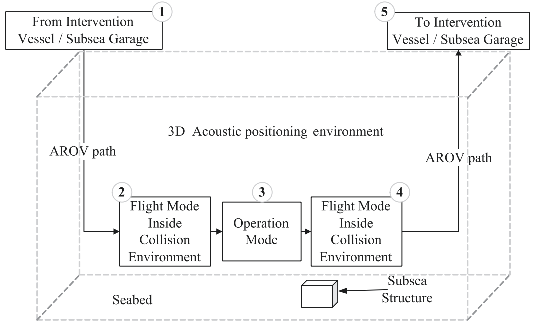

Fig. 4. Modes of operation for AROVs.

the wrong side of the SPS, appropriate course correction action can be suggested by the SPS to the AROV system. The AROV relays the vehicle status to the graphic user interface, which is observed by the human supervisor. The human supervisor can override the control system of the AROV when needed (on demand basis) as shown by the *override of control* block.

4.2. Accidental collision scenarios - step 2

In the second step, it is assumed that the surroundings of the AROV during the IMR operation are known. By studying the modes of operation of the AROV, three collision scenarios are considered, as illustrated in Fig. 6. Collision is viewed as an accidental event, which may occur in the following ways:

(i) The AROV can collide with the subsea structure with which it interacts during the IMR operation
(ii) The AROV can collide with the seabed during any of the five modes of operation
(iii) The intervention operation may require multiple AROVs functioning simultaneously. Therefore, the AROV can collide with other underwater vehicles operating in the vicinity; in the case study simplified to a 2nd AROV.

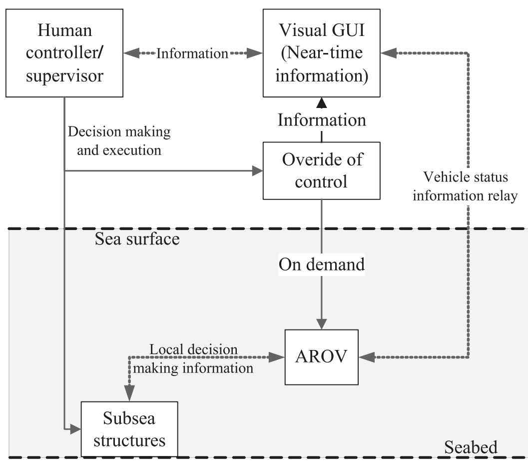

Fig. 5. Architecture for shared AROV autonomy.

4.3. Indicator identification - step 3

From the collision avoidance systems/metrics used in other vehicular industries (Table 1), three fundamental variables/RIFs can be identified; namely distance to target, vehicle velocity, and vehicle acceleration. A simple RIF model is illustrated in Fig. 7, which shows the RIFs that affect the risk of a collision. Such influence diagrams assist in identifying risk indicators, which can capture the change in RIF values. In Fig. 7, the RIFs are vehicle acceleration, distance to target, and vehicle velocity. To calculate the maximum achievable velocity of the AROV, the vehicle drag forces have to be calculated. time to collision (TTC), mean time to collision (MTTC), and mean impact energy are the three proposed collision risk indicators.

4.3.1. Time to collision indicator

The TTC indicator is an operational indicator, which can be used by the AROV manufacturers or by AROV service providers to obtain an estimate of TTC during live or simulated missions. The TTC indicator requires an approximate estimate of distance to the collision objects or targets, acceleration, and velocity. Equation (1) results in the distance to the chosen targets from the AROV where $x_1, \ y_1, \ z_1$ are point coordinates on the AROV and $x_2, \ y_2, \ z_2$ are point coordinates on the target. Targets in the case study are the subsea structure, seabed, and 2nd AROV. Equation (2) expresses the resultant velocity where v_x , v_y , v_z represent velocity vectors at x, y, and z directions. The velocity of the AROV is measured in meters per second (*m/s*) and distance to target is measured in meters (*m*). The TTC indicator can be calculated by using Equation (3).

$$Distance_{Target} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (1)$$

$$Resultant\ velocity = \sqrt{(v_x)^2 + (v_y)^2 + (v_z)^2} \quad (2)$$

$$Time\ to\ collision\ (TTC) = \frac{Distance\ to\ target}{Resultant\ velocity\ of\ AROV} \quad (3)$$

4.3.2. Mean time to collision indicator

The TTC indicator is dynamic and sensitive to change because at every point in the AROV path the TTC indicator value is continuously updated. To minimize and make sense of the risk between the two selected waypoints of the AROV path, the MTTC value can provide a single value approximation.

The MTTC indicator can be defined as a preoperational (planning) collision risk indicator depending on the status of the mission completion in the AROV path. To calculate the MTTC indicator, between two waypoints in the AROV path, a mean of the TTC is calculated for all three targets, i.e., the SPS, the seabed, and the 2nd AROV. The advantage of the MTTC indicator is that it allows for a simplified process to calculate the risk between a set of waypoints in the AROV path. The MTTC indicator can be represented by Equation (4), where *i* is prior waypoint and *i+1* is the next waypoint in the AROV path, and *N* is the total *TTC* data points between $Waypoint_i$ and $Waypoint_{i+1}$.

$$Mean\ Time\ to\ collision\ (MTTC) = \frac{\Sigma_{Waypoint_i}^{Waypoint_{i+1}}\ TTC}{N} \quad (4)$$

4.3.3. Mean impact energy indicator

Ideally, the impact energy needs to be lower when approaching a target of interest during an AROV intervention on the SPS. Limiting the potential impact energy of the AROV is vital for both the asset safety (AROV and other AROVs) and the SPS. An indication of the impact energy can be used to assess the energy dissipated should a collision occur. This indicator can inform the AROV or the human supervisor about the consequence of an AROV collision with the target or an unknown obstacle in the subsea environment. This indicator is dependent on the velocity of the AROV, but also the mass of the AROV. Hence, it provides important information, in addition to the TTC and MTTC. Equation (5) represents the kinetic energy dissipated during an AROV collision.

$$Impact\ Energy = \frac{1}{2} * a * m * v_{AROV}^2 \quad (5)$$

In Equation (5), the term *a* is the added mass coefficient, *m* is the AROV displacement in kg (water displaced in kg), v_{AROV} is the velocity of AROV in m/s. An added mass value of 1.05 is assumed as suggested for frontal collisions (Dai et al., 2013). A mean impact energy is calculated between the chosen waypoints in the AROV path, as represented in Equation (6). *N* is the total impact energy data points between $Waypoint_i$ and $Waypoint_{i+1}$.

$$Mean\ Impact\ Energy = \frac{\Sigma_{Waypoint_i}^{Waypoint_{i+1}}\ Impact\ Energy}{N} \quad (6)$$

4.4. Data collection to calculate the risk indicators - step 4

AROV vehicle logs can be used to obtain the RIF values and for calculating indicator values online during a mission. When the collision risk indicators are used for planning of an IMR operation, such as in this case study, the simulation of an AROV mission is used. A simulation program is necessary to obtain the RIFs values required to calculate the proposed indicators along a given AROV path. Vpython is a visual animation/computational programming tool, which can perform parallel mathematical computations (Sherwood and Chabay, 2011) and is chosen to simulate the proposed collision risk indicators. In the case study simulation, it is assumed that the AROV changes velocity vectors in five waypoints (0–4). In a real life scenario, the AROV may change velocity vectors

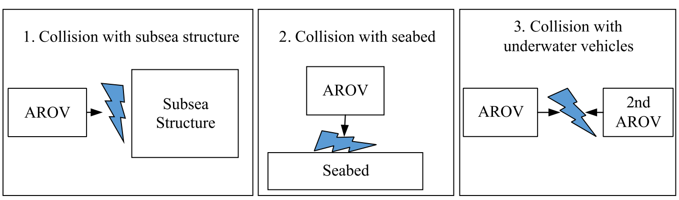

Fig. 6. Collision scenarios for AROVs.

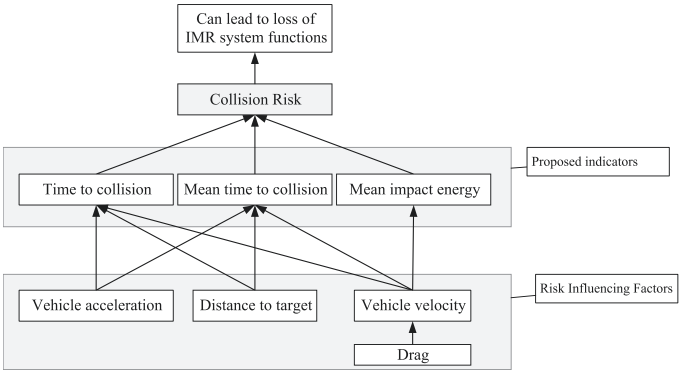

Fig. 7. Risk Influencing Factor model for AROV collision risk.

more than the assumed number of times. However, the number of waypoints do not change the overall method for calculating the proposed indicators.

Fig. 8 illustrates a simulation model of the AROV path to the targets. For the case study, Fig. 8 shows the AROV path, which has five waypoints where the AROV changes the propulsion direction. The AROV collects information on distance to the three targets, namely subsea structure, seabed and 2nd AROV by using different sensors. The white marked waypoints in Fig. 8 are start and end waypoints in the AROV path, while the black marked waypoints are intermediate waypoints in the AROV path.

The AROV dimensions are based on a data sheet of a current/traditional work class ROV (DeepOcean, 2014). Fig. 9 is the simulation window running on a predetermined path. The indicator calculations are converted to iterative functions within each point of the path. The values of TTC and impact energy are obtained at all points of the path. The MTTC indicator is also calculated between all waypoints in the AROV path. Appendix A describes the pseudocode of the program.

4.4.1. Indicator calculation process

Data of RIF values are required to calculate the proposed risk indicator values as described in Equations (3), (4) and (6). To obtain data of the RIF values, either historic data or a simulated data can be used. Fig. 10 illustrates the general process to calculate the proposed collision risk indicators. Simulation of IMR operation in the given AROV path results in RIF values. RIF values, such as current acceleration, distance and velocity are collected along the AROV

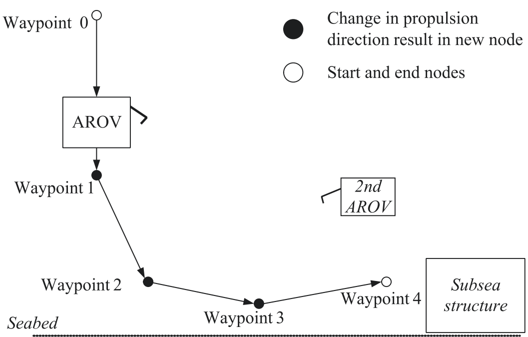

Fig. 8. Simple illustration of AROV path in Vpython simulation.

path. The simulation program calculates the risk indicator values.

4.4.2. RIF and indicator values from simulation

The simulation of the AROV path, as illustrated in Fig. 9, results in RIF values presented in Table 3. The acceleration in the simulation program is constant between waypoints, while velocity and distances change along the different waypoints. It is observed that the AROV mean velocity is highest between Waypoints 3 to 4 and distance to targets is highest in Waypoints 0 to 1. The values of mean velocity and mean distances listed in Table 3 do not correspond to the same data point, this is because there is variation of velocity in the given case study.

The results of a simulation provide values for the MTTC indicator and mean impact energy indicator, as presented in Table 4. Note that the deduction of MTTC from Table 3 values will differ when compared to MTTC values in Table 4 due to the presence of both changing acceleration and velocity vectors in the different waypoints in the AROV path. The simulation program applies Equations (5) and (6) to calculate the MTTC and mean impact indicators. The results obtained from the simulation program is further used as input to Step 6 (see Section 4.6).

4.4.3. Establish threshold for risk indicator values - step 5

Threshold values for the MTTC and mean impact energy indicators are presented in this subsection. In Subsection 4.6, the thresholds are used to compare the results from the simulations. The TTC thresholds are not established because for the given case study the analysis is focused on MTTC indicator. However, if the method is applied for online AROV missions, thresholds for TTC indicators also have to be established.

4.4.4. Thresholds for proposed indicators

Currently, none of the AROV standards dictate the minimum safe distances from targets or velocities for AROVs (Hegde et al., 2015). Therefore, for the current case study, a safety response time of 150 s is assumed to avoid a collision scenario by an AROV. This can involve tasks to be performed by AROVs or human supervisor, such as detecting the obstacle, assessing the risk of collision and performing evasive actions. Obviously, high MTTC values are favorable as compared to low MTTC values to reduce the chances of collision with the targets. Since, the 2nd AROV can move in the opposite direction to the AROV, conservative threshold values are established. The threshold values for *MTTC* to the subsea structure, the seabed and 2nd AROV can be divided into three categories; *low*, *intermediate* and *high* (in seconds), as listed in

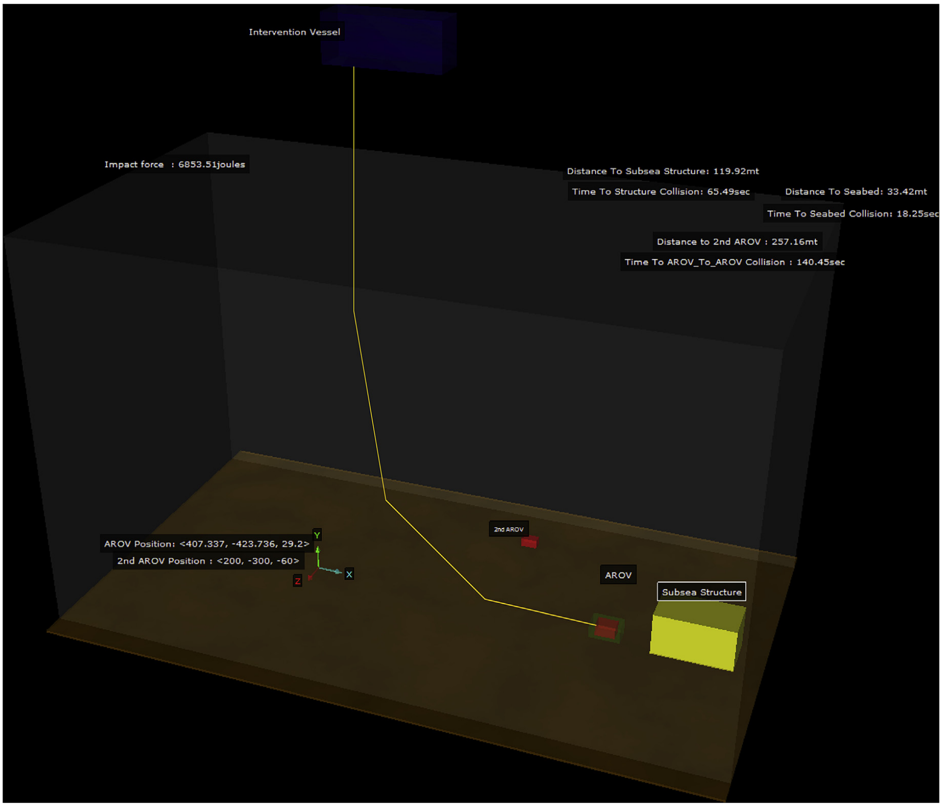

Fig. 9. Simulation of proposed risk indicators in Vpython.

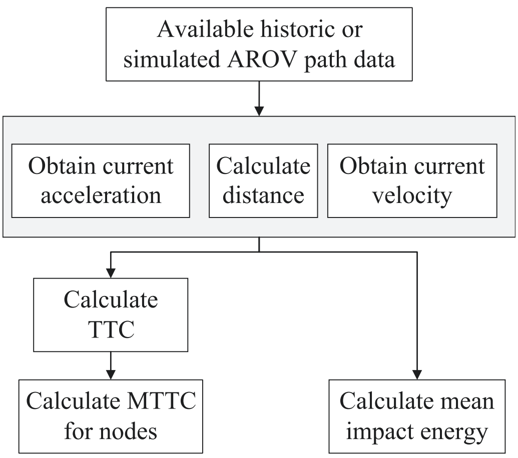

Fig. 10. Calculation process of proposed collision risk indicators.

Table 5.

To determine the thresholds for the impact force, the requirement to impact collision energy is traced from (ISO 13628-1, 2005), which allows a point impact load of 5000 J on a SPS in form of a dropped object. The impact energy depends on the added mass of the chosen AROV. Hence, to determine the approximate AROV impact energy, it is necessary to choose the most adequate volume of the AROV. Hence, a stepwise increase in the AROV volume is considered to compensate for water ingress in the AROV body. A conservative AROV volume estimate of 0.6 times the AROV volume is assumed. Since the mass is constant for the given AROV, the variable in the mean impact energy equation is the velocity of the AROV.

The thresholds for impact force is divided into three categories; low, intermediate and high (in Joules) as listed in Table 6. In this case study, the threshold values are obtained by assumption of severity to the AROV functions. A low mean impact energy will not endanger the functions of the AROV, while a high mean impact energy can endanger the SPS or AROV functionality.

4.5. Collision risk — safe waypoints in the AROV path - step 6

In this step, the calculated indicator values from Table 4 are compared with the established threshold values in Tables 5 and 6to generate an overview of collision risk. A multi-criteria decision making approach is suggested to be able to rank the waypoints in terms of highest or lowest risk. This requires allotting a risk priority

Table 3
Simulated values for RIFs.

Waypoints	Acceleration (m/s^2)	Mean velocity (m/s)	Mean distance structure (m)	Mean distance seabed (m)	Mean distance 2nd AROV (m)
0 to 1	$3 * 10^{-3}$	1.5985	1050.4283	959.5005	877.9469
1 to 2	$1 * 10^{-4}$	0.9083	648.5374	397.6500	389.3665
2 to 3	$3 * 10^{-3}$	1.6140	452.8281	123.9516	189.4313
3 to 4	$2 * 10^{-3}$	1.6744	235.7267	47.7320	176.9055

Table 4
Calculated values for indicators.

Waypoints	MTTC to structure (s)	MTTC to seabed (s)	MTTC to 2nd AROV (s)	Mean Impact Energy (J)
0 to 1	712.78	657.96	602.48	5468.58
1 to 2	714.08	437.99	428.81	1686.82
2 to 3	283.73	78.58	119.06	5345.69
3 to 4	143.46	28.87	104.94	5748.12

number (RPN) for each of the different threshold values of the collision risk indicators. In general, a RPN is based on the general definition of risk, i.e.,

$$Risk = Occurance * Severity$$

Here, we choose a conservative approach assuming that the AROV is on collision course, which means that the RPN reflects the severity.

In this article, the RPNs range from low = 1, intermediate = 2, to high = 3. Table 7 presents the RPNs allotted for the indicator threshold values. For the MTTC indicator, high values are favorable (1) and for the impact energy indicator, low values are favorable (1).

To determine the overall risk picture, MTTC values for all three targets need to be considered resulting in different RPN for each target. This can be observed in Waypoint 1–2 and Waypoint 2–3 where $MTTC_{structure}$ and $MTTC_{seabed}$ have different RPNs. The minimum total RPN can be 4 ($MTTC_{structure}$ high, $MTTC_{seabed}$ high, $MTTC_{2ndROV}$ high, mean impact energy low) and the maximum total RPN can be 12 ($MTTC_{structure}$ low, $MTTC_{seabed}$ low, $MTTC_{2ndROV}$ low, mean impact energy high), as presented in Table 8.

Fig. 11 illustrates the established RPN chart where the favorable/low RPNs are from 4 to 6, less-favorable from 6 to 9 and least favorable from 9 to 12. A low RPN relates to indicator thresholds values, which do not pose a threat to primary AROV functions. An intermediate RPN relates to indicator thresholds values, which pose a threat to AROV functions and can result in degraded performance of primary AROV functions. A high RPN relates to indicator thresholds values, which can lead to failure of AROV functions, leading to an aborted mission.

From established threshold values in Tables 5 and 6, the risk indicators values obtained from the calculation (Table 4) can be classified, as shown in Table 8. Further, the classification of risk indicator values (high, intermediate and low) are allotted RPNs by using Table 7. This results in RPN for each waypoint, which are added to get the total RPN. Table 8 presents calculation of total RPN based on established threshold values for mean impact energy and *MTTC* for the three targets.

In combination with the total RPN from Table 8, Fig. 12 illustrates the overall collision risk picture for the given AROV path.

Table 5
Classifying thresholds for MTTC.

MTTC	Low (s)	Intermediate (s)	High (s)
To subsea structure and seabed	0–250	250–500	500 and above
To 2nd AROV	0–150	150–300	300 and above

Table 6
Classifying thresholds for mean impact energy.

Low (J)	Intermediate (J)	High (J)
0–2000	2000–4500	4500 and above

Table 7
Risk priority number for the threshold values.

Indicators	Low	Intermediate	High
MTTC	3	2	1
Mean impact energy	1	2	3

According to the established RPNs, Waypoints 2 to 3 and Waypoint 3 to 4 are identified as high risk waypoints. While Waypoint 0–1 has intermediate RPN, Waypoints 1 to 2 is the favorable/low risk waypoint in the AROV path.

The red zone in Fig. 12 shows that the indicator values are at a high threshold level. This means that reducing the values of the RIFs affecting the indicators, will reduce risk of collision. For example, reducing velocity when approaching the subsea structure (Waypoint 3–4) during operation will reduce the risk of collision. Another option could be to reduce the mass of the vehicle during planning by choosing a smaller AROV. Through simulation it is then possible to assess the optimum RIF values versus mission or operation time, since mission time affects costs.

5. Discussion

The case study focusing on AROV and collision risk for subsea intervention shows how risk indicator values can be used to identify risk prone waypoints in the AROV path. In the following, the application of the proposed method on a case study is discussed and five specific challenges are addressed:

- Assessment criteria of proposed indicators
- Planning of AROV paths and online risk assessment
- Advantages and disadvantages of the proposed method
- Challenges in quantifying impact energy of AROVs
- Application of TCAS philosophy to AROVs

5.1. Assessment criteria for proposed indicators

There are different ways of assessing the quality of indicators, e.g., see (Kjellèn, 2000; Gray and Wiedemann, 1999; Vinnem, 2010; Øien, 2013). The proposed indicators in this article can be evaluated

Table 8
Calculation of overall risk priority number.

Waypoints	MTTC Structure	MTTC Seabed	MTTC 2nd AROV	Mean Impact Energy	Total risk priority number
Waypoint 0 – 1	High	High	High	High	6/12
Waypoint 1 – 2	High	Intermediate	High	Low	5/12
Waypoint 2 – 3	Intermediate	Low	Low	High	11/12
Waypoint 3 – 4	Low	Low	Low	High	12/12

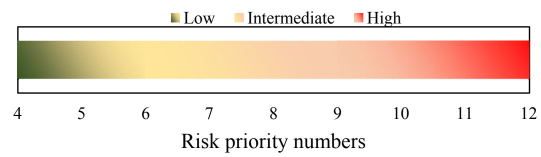

Fig. 11. Risk priority number chart.

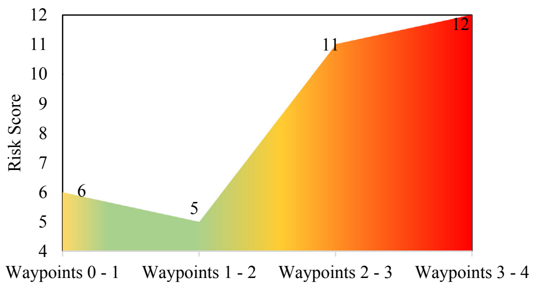

Fig. 12. Risk picture for the given AROV path.

using the recommendations from Vinnem (2010), which are feasible for underwater vehicles, as well:

- Easily observable performance: All three proposed indicators (time to collision, mean time to collision and mean impact energy) are observable.
- The proposed indicators are intuitive, and do not require complex calculations and reflect hazard mechanisms: They are based on simple physics formulas and are very easy to understand and interpret by the end user.
- The proposed indicators are sensitive to change, robust to manipulation and not influenced by campaigns. They dependent on factors, which are constantly changing. For example, a sudden change in velocity can either decrease or increase the indicator values. The simulation of the indicators through a simulator ensures robustness against manipulation or campaigns.
- The proposed indicators can show trend values of the collision risk, which can be observed as the major hazard risk during autonomous subsea IMR operations.

5.2. Planning of AROV paths and online risk assessment

The results from the case study demonstrate that the collision risk of AROVs depend on vehicle related RIFs and the mission path. If the AROV mission path is known, collision risk indicators can be used to plan safe operations by implementing risk reducing measures (for example, adjusting the vehicle RIFs to the acceptable safe values) across all modes of operations. On the other hand, if the mission path is unknown, a live implementation of the indicators could provide a continuous risk picture of the mission to both the AROV and the human supervisor by highlighting risk prone waypoints in the mission path. The risk picture provides a chronological update of the risk level throughout the given AROV path. This input can be used to choose the least risk prone mission paths/RIF values for upcoming missions.

The case study presented uses a simulation of an AROV path to collect RIF values and calculate risk indicator values, which are further assessed to determine the collision risk, manually. This approach is suitable for applications where offline decision support is sufficient. However, to derive collision risk for live AROV mission (online mission), the simulation program has to be able to calculate the collision risk without operator involvement.

A selected roadmap-based method (for example, visibility graph) can be combined with a rule-based method (for example, TCAS) to avoid loss of AROV functions due to existing collision risk.

A roadmap-based method is suitable because the subsea field layout is known and therefore contingency paths can be development before the start of the operation. When an intruder is sighted/detected in the AROV path by the AROV sensor system, a rule-based method can be used to first avoid accidental scenarios. Simultaneously, a roadmap-based approach can form a basis for analyzing the second or third alternative path to the intendent subsea structure.

In online risk assessment applications, the risk indicators presented in this paper could be used as an activity before or while the AROV detects a potential intruder. When a new collision free path is chosen by the AROV, the proposed indicators can be used to determine the risk prone waypoints in the updated or contingency AROV path by using the updated values of the RIFs.

5.3. Advantages and disadvantages of the method

Fundamentally, there are two generic parts in the proposed method: firstly, to calculate the collision risk indicators and secondly, to evaluate their output for minimizing collision risk. The collision indicators mentioned in Table 1 share three main parameters related to vehicle and target; velocity, distance, and time. It is evident that the vehicle specifications (vehicle specific RIFs) and the environment influence the collision time and energy dissipation.

The results from the case study show that appropriate risk reducing measures can be proposed by reducing the values of the RIFs affecting the indicator values for a given AROV path. For example, AROV velocity can be maintained within a low threshold during the approach to the SPS or when the AROV is a short distance away from the seabed or other AROVs. In addition, the advantage of the proposed generic method is that it can also be applied to other autonomous systems, for example, UAVs, autonomous automobiles, etc.

Different models of AROVs may have different structural design,

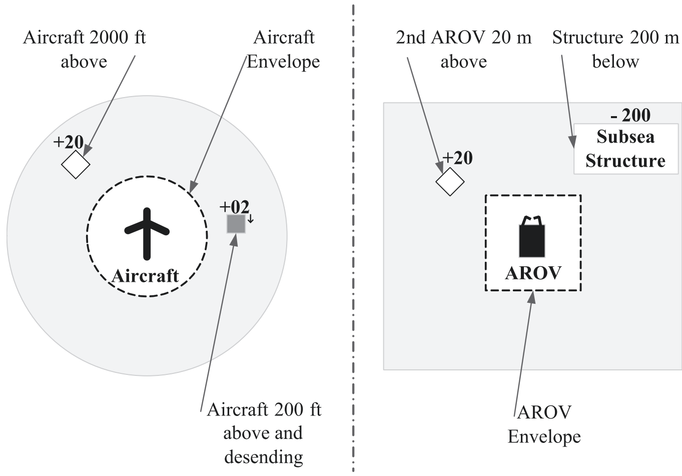

Fig. 13. Example of TCAS applied to AROV operations.

which can lead to different volumes covered by the AROV. Since volume of water dissipated is linked to the actual mass of the AROV, the added mass of the AROV is important to consider in future design implementations of AROVs. In this article, the authors have considered 60% volume of the total volume of the AROV box model during the calculations of the indicators. The case study has not considered the possible errors in estimation of the vehicle parameters, such as velocity and acceleration. In an autonomous system, such errors can lead to wrong situation awareness both by the AROV and the human supervisor. Therefore, reliable vehicle data from position and navigational sensors are important inputs to the proposed method.

5.4. *Impact energy of AROV*

In the case study, the impact energy indicator has shown presence of high impact energy dissipated to the structure. The mean impact energy at Waypoint 0 to 1, Waypoint 2 to 3, and Waypoint 3 to 4 exceed the 5000 J requirement laid down by (ISO 13628-1, 2005). Requirements for collision energy absorption from autonomous vehicles need to be addressed by relevant subsea structural design standards. Since this study is a proof-of-concept, it has not assessed the damage potential in terms of force and displacement both locally on the AROV and globally on the target.

5.5. *Safety philosophy in traffic collision avoidance system (TCAS) applied to underwater vehicles*

Aviation systems have many similarities with the underwater vehicles. A key difference is that the aviation industry has to ensure safety of not only the aircrafts, but also of passengers and crew. In contrast, a collision with an AROV can result in financial and environmental consequences. Hence, AROVs need to incorporate safety functions to avoid loss of production from the SPS, loss of the AROV, and negative impact on the environment.

Fig. 13 illustrates a possible setup for AROV missions, based on safety philosophy in TCAS. This specifies vertical and horizontal separation between known objects and unknown obstacles present in the AROV vicinity. Current ROV systems are dependent on human operators' ability to perceive and avoid collision scenarios and in AROV operations the safety philosophy must be implemented in the system.

6. Conclusions

This article presents a method for developing collision risk indicators for subsea IMR operations. Current literature demonstrates that collision risk indicators for AROVs are not addressed with an asset safety perspective. Collision risk is extensively researched in other vehicular industries, such as aviation, automotive, marine, and railways. The method presented should be applicable to other accident scenarios than collision only, and for different types of underwater vehicles, including AUVs and regular ROVs.

Three collision risk indicators, namely time to collision, mean time to collision, and mean impact energy are proposed in the article and are validated by comparing with recommended indicator assessment criteria. To collect input data used in the calculation of the proposed indicators, a simulation of AROV path is performed in a case study. The results from the simulation when compared to the established threshold values generate a risk picture of the planned mission path. If data on the RIFs can be collected online, the proposed method can be used for risk assessment and improved situation awareness during operation.

Applications of underwater vehicles in the oil and gas industry will continue to grow in the coming decades. With the advent of new subsea operating concepts, continued focus on loss prevention is paramount. Technology transfer from other industries should be the preferred strategy to close technology gaps in design and operation of AROVs for subsea interventions. Development of asset risk management techniques are crucial to maintain high availability of systems, such as AROVs. These risk management techniques are not limited to future oil and gas industry applications. They can also provide learnings, which are applicable to other marine application, such as fisheries, seabed mining, marine biology, archeology and others.

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Appendix

Appendix A. Pseudocode for Vpython program

Data: Position of AROV, subsea structure, seabed and 2nd AROV (targets)

Result: TTC, impact energy, Mean TTC in each waypoint, mean impact energy in each waypoint, velocity, acceleration

Initialize variables;

Defining functions;

While t < t_{end} (Waypoint 0 to 1, Waypoint 1 to 2, Waypoint 2 to 3, Waypoint 3 to 4) **do**

Update AROV position;

Calculate distance to targets, resultant velocity vector, TTC, impact force, acceleration;

Calculate mean distance to targets, mean TTC, mean velocity, mean impact energy;

End

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Article 3

A Bayesian approach to decision making applied to autonomous subsea IMR operations

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A Bayesian approach to risk modeling of autonomous subsea intervention operations

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Abstract

The introduction of autonomy in subsea operations may affect operational risk related to inspection, maintenance, and repair (IMR). This article proposes a Bayesian Belief Network (BBN) to model the risk affecting autonomous subsea IMR operations. The proposed BBN risk model can be used to calculate the probability of aborting an autonomous subsea IMR operation. The nodes of the BBN are structured using three main categories, namely technical, organizational, and operational. The BBN is tested for five unique scenarios using a scenario generation methodology for the operational phase of the autonomous IMR operation. The BBN is quantified by conducting a workshop involving industry experts. The results from the proposed model may provide a useful aid to human supervisors in their decision-making processes. The model is verified for five scenarios, but it is capable of incorporating and calculating risk for other combinations of scenarios.

Keywords: Bayesian Belief Network; decision-support; risk; subsea IMR; autonomy

1. Introduction

Globally, the number of subsea oil and gas installations are increasing leading to the adoption of new subsea intervention technologies. In the subsea oil and gas industry, inspection, maintenance, and repair (IMR) of subsea production systems (SPS) is key to maintaining production uptime. However, maintaining the SPS is challenging due to the risks involved in performing subsea IMR operations. Water depth, weather disruptions, job complexity, job uncertainty, and IMR equipment availability, for example, may affect subsea IMR operational performance [1–3]. Rough weather conditions can disrupt intervention schedules resulting in an increased operational cost. On the other hand, concepts, such as subsea factories, are envisioned by the oil and gas industry to maximize recovery, minimize costs, and accelerate production [4]. Studies to support the claims set forth for the development of subsea factories are currently limited; in that, the scope of autonomous IMR operations for subsea factories are not investigated. New SPS technologies, such as subsea compressors, storage, and garages, increase the need for safe, reliable, and efficient IMR systems in the years to come.

One of the proposed alternatives to achieving safe and cost efficient IMR activities is to introduce autonomous functionality into the SPS and related IMR systems [5,6]. Currently, autonomous IMR systems are still in the conceptual or testing stages of development. A number of research projects have or are currently investigating development and implementation of autonomous functionalities and shared control in underwater vehicles [7–17]. As observed in the literature, the underwater vehicle development trend is to merge abilities of human controlled Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). These future underwater vehicles can be termed *Autonomous Remotely Operated Vehicle (AROV)*. Future *AROVs* can be defined as underwater vehicles, which are able to function autonomously, reside in designated subsea docking areas, independently control manipulator functions, permit shared-control between the vehicle and the human supervisor, navigate autonomously, perform self-diagnostics, and are equipped with automatic Remotely Operated Tools (ROT) systems requiring limited operator control [18].

In general, Bayesian approaches are widely used to support decisions in the presence of uncertain input parameters. Related to the offshore oil and gas industry, Sklet et al. [19], for example, propose the barrier and operational risk analysis method (BORA) focused on hydrocarbon releases, using risk influence diagrams. A further development of the BORA method is the operational technical safety (OTS) project [20], followed by the Risk OMT (risk modelling - integration of organizational, human and technical nodes) project, which proposes quantitative modelling of organizational, human, and technical risk influencing factors (RIFs) using a Bayesian approach [21,22]. The resulting Bayesian believe network (BBN) model captures the relationships between different RIFs, emphasizing the prevention of hydrocarbon leaks. Yang et al. [23] develop a Bayesian network to model subsea pipeline failures due to corrosion.to corrosion. Cai et al. [24] propose a Bayesian network to evaluate the reliability of subsea blowout preventer control system.

Currently, limited research has been performed on identifying, analyzing, modeling risk and interrelationships between various hazards affecting autonomous subsea IMR operations. So far, most of the research works focus on mission success for AUVs. Since AROVs shall adopt certain autonomous capabilities, findings from past research on risk related to AUV operations need to be considered. Griffiths and Brito [25] investigate the use of BBN to estimate risk in missions under different sea ice conditions. Brito and Griffiths [26] extend the Bayesian approach to analyze the risk of loss of AUVs during missions. Vehicle type, ice concentration, thickness, environmental constraints, etc. are highlighted to contribute to loss of the AUVs. Expert elicitations are extensively used to quantify BBN models in both oil and gas and AUV applications [21,22,25,26]. The model proposed by Thieme and Utne [27] present a BBN to assess the probability of monitoring success for an AUV mission focusing on human supervisor's actions. Involvement of experts in the development process aids in verifying the BBN structure and quantifying the BBN model. Since BBNs are visualized, they can also aid in risk communication across various engineering disciplines. In addition, the results from operations can be used to update the parameters of the BBN model.

The objective of this article is to present a BBN model, which can provide decision-support to human supervisors during autonomous subsea IMR operations. Consider a decision scenario where an AROV incurs one or more technical failures and the visibility in the subsea environment is low during an IMR operation. What is the probability that the IMR operation needs to be aborted? Finding answers to questions like these are vital for achieving safe autonomous IMR operations, and are addressed in this article through the proposed BBN risk model. Thus, important factors affecting the failure of IMR operation can be identified and necessary risk reduction measures may be implemented. In addition to useful decision input to human operators and managers, such information can also be important for system developers. By developing a novel BBN focusing on autonomous IMR operations, this article aims to add to the body of knowledge in applying BBN modeling to subsea oil and gas applications.

The article is structured as follows: Section 2 describes the method used to develop the BBN model. The BBN development method is applied to an autonomous IMR operation in Section 3. Discussion and significance of the findings from BBN modeling are described in Section 4. Section 5 presents the conclusions of the study and scope for future work.

2. BBN modeling methodology

BBNs are directed acyclic graphs (DAG), which represent the causal dependency between a set of variables using directed links/arcs [28]. Each variable in the BBN consists of finite mutually exclusive states. Conditional probability tables (CPTs) are constructed to determine the probability of the state of "child" variable. The state of child variable is dependent on the occurrence of parent variables. Variables in BBNs can be discrete or continuous in nature. For more general information on BBN, see Jensen and Nielsen [28].

A node in BBN consists of variables with different states. Three basic requirements need to be considered to develop a BBN, 1) Nodes can be identified, 2) State of nodes can be represented by measurable variables, and 3) The target node and any other node in the network have known traceable direct/indirect relationships. A target node is a node for which the joint probability distribution is calculated. In this article, the nodes represent human, technical and organizational RIFs. According to Øien [29], a RIF can be defined *as an aspect of a system or activity that affects the risk level of this system/activity*.

Fig. 1 illustrates the eight steps involved in BBN model development used in this article. The steps highlighted are based on a generic approach for developing BBNs, see Jensen and Nielsen [28], Sigurdsson et al. [30] and Langseth and Luigi [31].

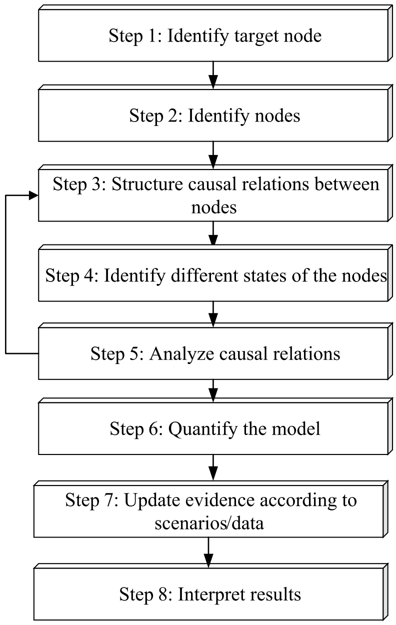

Fig. 1 Generic BBN modeling method used in the article

Step 1 – Identify target node

A target node is a node where the joint probability distribution is calculated in a BBN model. Identification of target node is, therefore, the first step in the BBN development process. This step allows defining the problem, which the BBN model will solve. It also highlights and determines the scope of the BBN.

Step 2 – Identify nodes

The identification of the nodes can be achieved by observing the real world application of the system under study and the potential hazards it is exposed to. This step may resemble the first step in risk analysis; Hazard Identification (HAZID). Empirical data may also be used, for example, extracted from accident investigation reports, see, e.g., Aktar and Utne [32] and Mazaheri et al. [33]. The boundary of the system under study must be established to avoid including nodes, which may not be significant in contributing to the target node. However, the assessor determines this boundary as applicable on a case-by-case basis. Experiences related to the system (literature), the modes of operation, and knowledge about the functions of the system can be used to identify relevant nodes.

Step 3 - Structure causal relations between nodes

The identified nodes from Step 2 are investigated for causal relationships with other nodes. Arcs represent the causal relationships; connecting a parent node to a child node. The outcome of this step is to ensure that the BBN model represents real-world causal relationships between the selected nodes. A complex BBN model can be clustered by use of methods, such as parent divorcing [28]. According to Martin et al. [34], a large-scale BBN can be constructed by a combination of idioms using simple rules or by object oriented BN approaches. Mazaheri et al. [33] and Aktar and Utne [32] also demonstrate that the causal relationships between the nodes can be structured from accident models and past accident investigation reports.

Step 4 - Identify different states of the nodes

The identified nodes can have different states, which have to be determined. One way of determining the states is to identify the best and the worst possible conditions for a given node. Intermediate states can be identified if necessary. The outcome of this step should provide a basis for constructing CPTs for different states at the child node. Nodes can be either deterministic or probabilistic in nature. Statistically, deterministic nodes have states, which have known relationships to an outcome. For example, spare parts available in a warehouse are known deterministic quantity. On the other hand, a probabilistic node consists both a deterministic quantity and a certain uncertainty in the form of random event influencing it. For example, the velocity of falling object has a deterministic parameter in the form of gravity constant and other uncertain random quantities in the form of wind direction, drag, etc. Therefore, a BBN may be constructed using a combination of deterministic and probabilistic nodes.

Step 5 - Analyze causal relations

During the construction of the BBN, causal relationships may be assumed between nodes. However, some of these relationships may not be observable in real-life conditions and are not quantifiable. In such cases, the BBN model needs to be updated by deleting corresponding arcs between the nodes, which render them independent of each other or d-separated. The BBN model should be reviewed to satisfy the d-separation theorem. D-separation occurs when two nodes of a BBN are inter-connected through or blocked by an intermediate node [28]. Identifying de-separated nodes is important because it supplements in structuring the nodes, which are independent of each other and doing so decreases the need to allocate additional CPTs. Once the review is completed, the structure of the BBN model will change, and it might be necessary to iterate from Step 3.

Step 6 - Quantify the model

The outcome of this step is to allocate CPTs for all identified nodes in the model. In large and complex BBNs, allotting CPTs can be a challenge when the node consists of many states and has many incoming causal arcs from its parents. Literature suggests to use techniques, such as parent divorcing [28], or organize the fragments of the BBN into objects [34]. However, if the BBN cannot be fragmented to smaller manageable units, there are proposed methods, such as fuzzy logic to decrease the number of required CPT elicitations [35,36] and expert judgment based CPT elicitations, as reviewed by Mkrtchyan et al. [37,38].

In this article, the method proposed by Røed et al. [39] is utilized to allocate CPTs in the BBN model. This method is preferred for the following reasons:

1) It provides a structured way to derive the CPTs thereby making it relatively less time consuming when compared to other CPT allocation methods involving experts.
2) It ensures that expert knowledge is incorporated during CPT assignments by defining the weights of the arcs and assessing closeness of the relationship between parent and child states.
3) The method can be setup using software tools and can handle a high degree of parent arcs and parent states.

When the assignment of CPTs is completed, the model output based on prior beliefs can be obtained by calculating the joint probability distribution. BBN software tools, such as GeNIe modeling environment developed by the Decision Systems Laboratory of the University of Pittsburgh can be used to develop the BBN model and calculate the joint probability distribution for the target node [40].

Step 7 - Update evidence according to scenarios/data

In this step, either existing data (known updated evidence) or a scenario generation (assumed updated evidence) approach can be used to update evidence of the states. If the new evidence on the state of a node is available, it is updated in the model to obtain the new joint probability distribution. An alternative approach is to generate scenarios in which the updated evidence for a given state of the node is predefined.

Step 8 - Interpret results

In this step, inferences can be made by assessing the resulting probabilities of the target node from Step 7. The effect of different states of the nodes of the target node can be observed. This step can support in examining the result from the model against current decision-making process.

3. BBN development for a case study of autonomous subsea IMR operations

In this section, the method presented in Section 2 is applied to an autonomous subsea IMR operation.

3.1 Identify target node – Step 1

3.1.1 Description of the autonomous IMR operation

Fig. 2 illustrates the AROV operation considered in this article. The autonomous IMR system consists of AROVs, which can perform inspection and maintenance missions. The AROVs (resident AROVs) reside in a subsea-garage, which houses charging pods for charging the AROVs battery. The AROVs do not require running of an umbilical cord or a tether from the subsea garage and rely on acoustic communications. A communication network is established from the subsea garage to either onshore or offshore facility with monitoring from human supervisors.

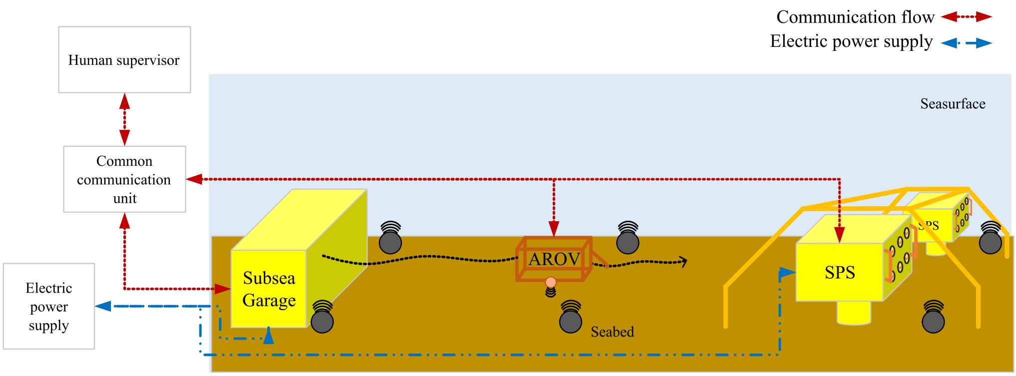

Fig. 2 Illustration of an AROV operation

The unified common communication network can communicate with the AROV, subsea garage, and the subsea control module (SCM) housed in the SPS. The AROVs use an acoustic based positioning system to determine their reference positions in a reliable manner. The AROVs interact with the subsea-garage, subsea environment, and the SPS. A human supervisor monitors the operation but may intervene during contingency situations using a shared control architecture [17]. Either the AROVs can be summoned on a mission by the human supervisor when required, or when a failure alert from the SPS is communicated (on demand).

According to Clough [41], an autonomous system has four levels of autonomy, namely (i) remotely piloted, (ii) remotely operated, (iii) remotely supervised, and (iv) fully autonomous. The current traditional remotely operated vehicles can be categorized into autonomy levels (i) and (ii), while future AROVs may have functionality in also levels (iii) and (iv). Considering the implementation of subsea compression in the Åsgard field and the adoption of electric actuators, the Åsgard field is the leading the all-subsea-vision of Subsea Factories [4]. Therefore, the Åsgard field is chosen as a case study in this article.

3.1.2 The scope of proposed BBN risk model

The decision process in autonomous IMR operations can be divided into two different phases, as illustrated in Fig. 3. In Fig. 3, the planning phase is the duration when the IMR operation is being planned for an intervention operation. In t_0, both the human supervisor and the AROV evaluate their conditions and compare with requirements of the upcoming intervention operation. In this phase, a simulation using historical data or latest available data can be used to calculate probability of aborting the operation.

However, the scope of this article is limited to the operational phase of IMR operations, as marked with blue shade in Fig. 3. The proposed BBN model shall assist the human supervisor to make decisions based on information about relevant factors influencing the IMR operation in the period t_1 to t_n.

The GeNIe software allows modeling the BBN with a time-step method. Each time-step refers to one static BBN. The advantage of this approach is that the resulting joint probability distribution of the target node can be derived as a continuous curve from t_1 to t_n. This is further explained in Section 3.9. Since the BBN network is developed in the GeNIe software tool, it is possible to customize the network for the chosen case. The AROV will also have its own decision support system during the operational phase, but is not the scope of the proposed BBN.

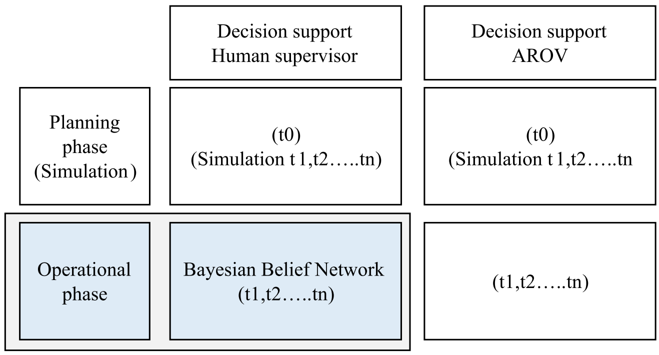

Fig. 3 Scope of the proposed BBN and article

Degradation or failure of the AROV system can lead to either loss of the vehicle or exposure to collision hazards with the SPS and other underwater vehicles [42]. Similarly, unfavorable conditions in the subsea environment and human supervisor’s action can also affect the chances of aborting the operation. The decision support system should be capable of providing the human supervisor a probability estimate for aborting the IMR operation. In summary, the operational activities, AROV availability, and the subsea environment influence the overall probability of aborting the IMR operation. The target node for the proposed BBN is named as the *probability of aborting an autonomous IMR operation* and is illustrated in Fig. 5 and Fig. 7.

3.2 Identify nodes – Step 2

Two approaches are utilized to identify nodes affecting autonomous IMR operations. Firstly, identifying hazards and RIFs through studying the different modes of operation of an AROV and grouping nodes into categories. Grouping of nodes into categories of technical, organization and operational nodes promotes the structuring the BBN. Secondly, a review of existing literature on the topic of subsea IMR can highlight the hazards affecting current/traditional IMR operations, which may also apply to future autonomous IMR operations.

3.2.1 Modes of operation of AROVs

Modes of operation can be defined as the change in functionality or behavior of a system during the period of intended operations. For example, an automobile may have two modes of operation: an economic mode and a sports mode. A change in operating mode alters the functionality and behavior of an automobile. Similarly, in each mode of operation of the AROV, different RIFs can affect the target node. Investigating modes of operation of AROVs can highlight the system's interactions with the surroundings systems. The surroundings can either be technical or non-technical systems. For autonomous IMR operations, AROVs are expected to function in five modes of operations, as illustrated in Fig. 4:

1. Launch: The AROV is launched from a subsea garage.
2. Flight to SPS: The AROV maneuvers to the intended SPS location.
3. Intervention mode: The AROV performs the intended intervention operation on the SPS.
4. Flight to the subsea garage: The AROV returns to the subsea garage once the intervention operation is completed.
5. Recovery: Once the intended IMR operation is complete and the AROV returns to the subsea garage.

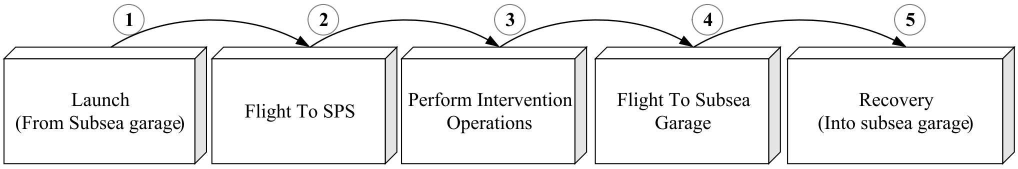

Fig. 4 Modes of operation of AROVs

By studying the modes of operation, it can be inferred that the AROV will interact with the subsea garage during launch and recovery modes, the subsea environment in all modes, the SPS in the intervention mode, operational nodes, which includes the common communication unit, and the human supervisor in all five modes. Each of these subcategories of nodes is required to be included while constructing the BBN model.

3.2.2 Nodes affecting traditional subsea IMR operations

The literature provides input to the identification of numerous nodes affecting the development of subsea fields, service duration of subsea IMR activities and the development of SPS, see, e.g., Uyiomendo and Markeset [1,3]. Markeset et al. [43] present the challenges in maintenance practices for SPSs, including factors leading to SPS failures. The design of the SPS system, maintenance service, and spare parts management are highlighted. Moreno Trejo et al. [44] discuss factors, which influence the installation and maintenance strategy for subsea equipment. Factors related to Health Safety Environment and Quality (HSEQ), costs, experience and competence, technology, legislation, logistics, geographical location, external processes, and surrounding environment were scored by interviewing experts in subsea engineering domain. The findings show that HSEQ costs and experience and competence related factors receive high impact scores.

The review of the literature provides a starting point for identification of nodes affecting autonomous IMR operations. However, they do not highlight any nodes generated due to interactions between AROVs and the subsea infrastructure in an autonomous setting. Technical nodes related to subsystems, such as AROVs, nodes related to the subsea garage, and the level of autonomy are required to develop a holistic decision support BBN.

3.3 Structure causal relations between nodes – Step 3

In this section, the structural description of the proposed BBN model is provided. Fig. 5 illustrates the condensed BBN model with respective casual links between the intermediate nodes and the target node. The three intermediate nodes identified as operational activities, AROV availability and subsea environmental conditions are linked with identified technical, organizational and operational nodes.

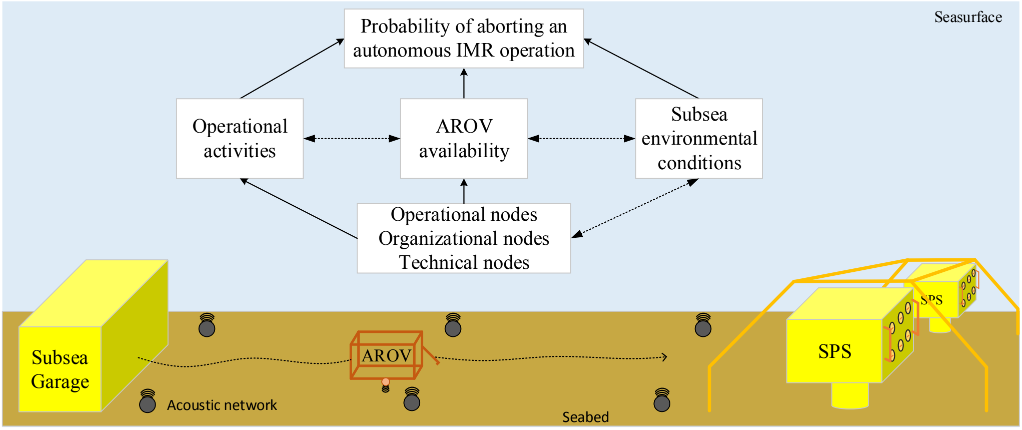

Fig. 5 Overview of nodes influencing the probability of aborting an autonomous IMR operation

3.3.1 Technical nodes

Technical nodes are categorized as nodes, which are directly related to a technical system. The three technical systems are a subsea garage, AROV, and the SPS. Fig. 7 illustrates the developed BBN model and the technical nodes are highlighted in orange ellipses.

Subsea garage

The subsea garage can be powered from an onshore electric supply unit. The electric power is distributed to the SPS and the subsea garage at the subsea field location. The introduction of subsea garages for autonomous IMR operations can result in two identified nodes; namely subsea garage communication system (SGCS) and subsea garage power supply (SGPS). The function of the *SGCS* is to communicate the vitals, such as power capacity, the number of AROVs stationed, etc., to a unified communication unit in a remote location. The function of the *SGPS* is to provide uninterrupted electric power to the battery system of the AROV. The SGCS is dependent on the SGPS for electric power.

AROV system

The BBN model structure for the AROV system is based on a functional hierarchy. The battery system is dependent on the subsea garage power supply node. The battery system and the basic control systems are essential for the functioning of a subsystem of the AROV. Therefore, they are parent nodes to the communication system, manipulator system, safety system, sensor system, lighting system, propulsion system and buoyancy system. The acoustic transducer network communicates with the sensor system. The sensor system consists of various sensors (for example, inertia navigation sensors, echo sounder, cameras, sonars, etc.) and inertia navigation sensors are dependent on the state of the acoustic network. The sensor system provides data required by the navigation system in the form of position, velocity and other nearby vehicle states.

The safety system can override the navigation system because, during collision avoidance maneuvers, the safety system shall dictate the alternative navigational path. During fault scenarios, the safety system can override the state of buoyancy system to surface to the sea surface. The state of buoyancy influences the propulsion required to propel the AROV. AROV availability, an intermediate node aggregates the nodes resulting from the AROV system.

The Subsea production system

The SPS nodes are related to the condition of the subsea equipment. Need for IMR operation is generated only when the subsea equipment requires intervention. This need is dependent on the condition of the subsea equipment. Therefore, the need for IMR operation can arise by three distinct cases. Fig. 6 illustrates the three cases.

- Case 1: a functioning subsea control module (SCM) communicates the condition of the subsea equipment and informs about the required corrective/preventive operations to the human supervisor.
- Case 2: the SPS requires an unscheduled corrective IMR operation (corrective maintenance) when the SCM or other components of the SPS are faulty or failed.
- Case 3: the SPS requires an unscheduled corrective IMR operation when external damage is observed and there is a structural or component fault or failure.

These cases need to be reflected in the proposed BBN model. This is achieved by introducing a need corrective IMR node, which covers the three cases of unscheduled and scheduled corrective IMR operations. The SCM node accounts for the scheduled preventive and corrective IMR operations (i.e., when the SCM is functioning and failed). The node detection of SPS condition aggregates the three cases and propagates it to the type of intervention node.

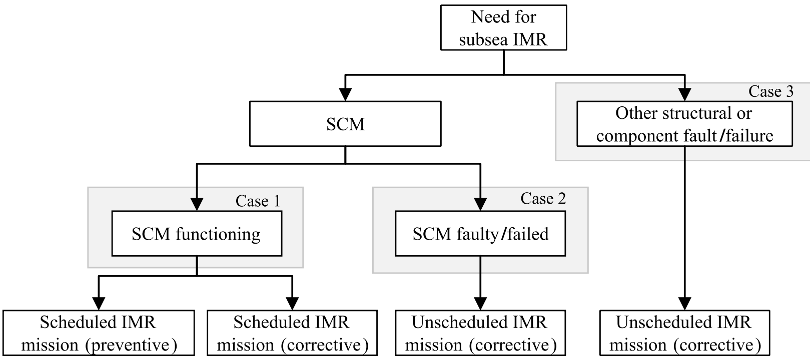

Fig. 6 Cases when subsea intervention is required

The acoustic network in and around the SPS field influences the mission path selection and the sensor system. The acoustic network is dependent on the subsea environmental nodes. For example, if the subsea environment is experiencing turbulent currents, this can degrade the acoustic network.

3.3.2 Operational nodes

Operational activities is an intermediate node that aggregates the operation specific nodes in autonomous IMR operations. Fundamentally, three areas of interests can be identified within this category.

1. Autonomous IMR operations are specialized missions, i.e., they shall comprise strict mission requirements. Aspects that need to be considered are, for example, is the mission an inspection mission?; how far is the subsea structure from the AROV?; is there a need for spare parts and tools?
2. Even though the focus is on autonomous operations, human involvement in the autonomous IMR operation should be evaluated. For example, what level of human supervision is planned for a given IMR operation in the different phases or modes of operation?
3. A common communication system is vital to allow data and information transfer between various technical systems, which is presented to the human supervisors.

The need for intervention has to be translated into detailed requirements. The type of intervention node provides an answer to what type of intervention is needed. Relevant spare parts and tools need to be identified after classifying the type of intervention. As different types of AROV differ in specifications, both, type of intervention and spare parts strategy influence the selection of the AROV required for the IMR operation. Distance to the subsea structure needs to be evaluated because it influences the mission path selection. The type of AROV influences the mission path selection. For example, if the AROV is an inspection vehicle, the mission path selection can highlight suitability of the vehicle for the chosen path by simultaneously considering the available acoustic network and the required travel distance to be covered by the AROV.

3.3.3 Subsea environmental nodes

In contrast to other operational nodes, the modeling of subsea environmental nodes can benefit from referring to existing literature on underwater vehicles. Brito and Griffiths [25,26] provide insight into modeling subsea environmental nodes by focusing on Autonomous Underwater Vehicle (AUV) operations. According to Brito and Griffiths [25,26], subsea nodes, such as objects, seabed slope, underwater hazards, met-ocean conditions, ice concentration, and ice thickness can affect the probability of loss of AUV in open sea, around coastal waters and under ice covers. Consideration has been given to these identified nodes, and this article improves works from Brito and Griffiths [26] on the subsea environmental BBN model by identifying additional nodes for the presented IMR operation.

The thermohaline circulation, which occurs due to the combination of sea depth, water temperature, and salinity, influences the water density. Surface waves together with gravitational tides and water depth can result in underwater currents. The underwater currents also depend on the density of the water layer. The underwater current and seabed characteristics can influence the subsea visibility. For example, if the seabed contains fine grains of sand, a turbulent underwater current can hinder visibility. The terrain obstacles in the seabed can be influenced by the presence of fishing trawls in the region and seabed terrain in the region. Nodes, namely visibility, the terrain obstacles, and the underwater current are aggregated to form a single intermediate node called subsea environment.

3.3.4 Organizational nodes

The level of autonomy influences the human supervisor action. The level of autonomy configured for a given case, i.e., a higher level of autonomy means less intervention from the human supervisors. For example, in the remotely piloted level of autonomy (level i), the operator is responsible for controlling the AROV. However, if the level of autonomy was set to remotely supervised (level iii), the operator has to function as a supervisor and not actively intervene in the operation. The state of the human supervisor can also influence his or her action. The common communication unit provides information to the human supervisor about the state of other systems working simultaneously. The training provided to the human supervisor can influence the actions taken by the human supervisor in both known and unknown operational situations. The physical and mental state of the human supervisor can also influence the actions taken by the human supervisor.

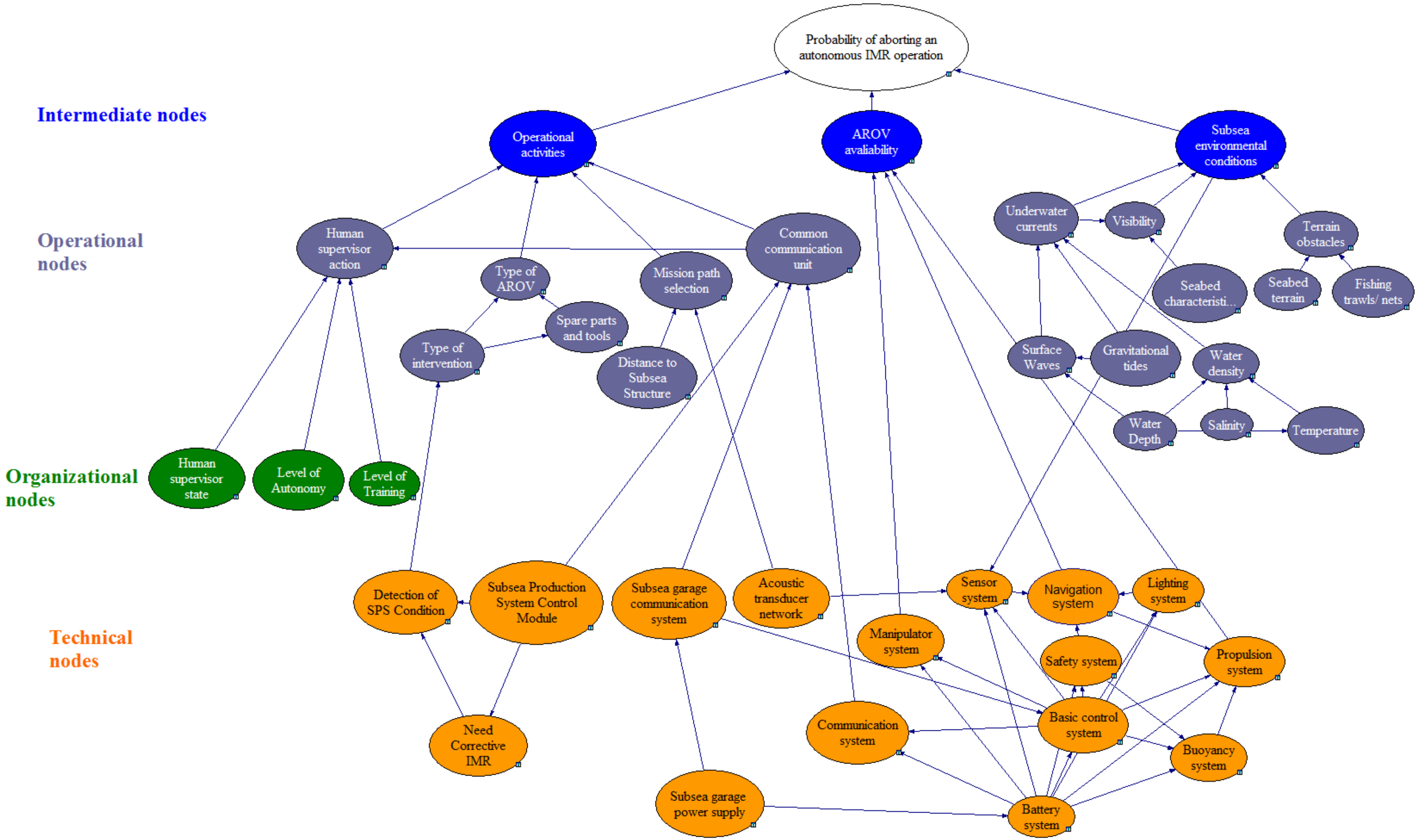

Fig. 7 Proposed BBN model to provide decision-support making process. Node colors: Orange-Technical, Green-Organizational, Light purple-Operational, Dark blue-Intermediate, White-target

3.4 Identify different states of the nodes – Step 4

Each identified node from Step 2 is scrutinized for its possible states. A summary of all the states of the nodes and a brief description of each identified node is described in Table 1.

Table 1 Identified nodes affecting the probability of aborting an autonomous IMR operation

Category	Node	States	Description
Probability of aborting an autonomous IMR operation	Target node	Continue operation, Abort operation	Relates to the outcome node of the network. It provides the human supervisor with a high-level decision support, based on provided evidence in the BBN model.
Intermediate nodes	Operational activities	Acceptable, Unacceptable	Refers to the state of the IMR operation specific requirements (spare parts, type of AROV, etc.,)
	AROV availability	Functioning, degraded, failed	Refers to the availability of the AROV.
	Subsea environmental conditions	Safe, unsafe	Refers to overall assessment of subsea environmental conditions.
Operational nodes	Type of AROV	Inspection AROV, Work-class AROV	Refers to inspection and work class AROVs
	Spare parts and tools	Available, not available, not required	Refers to availability of spare parts in the subsea garage
	Type of intervention	Inspection, maintenance/repair	Refers to what kind of IMR operation is required.
	Distance to SPS	Close, intermediate, long	Refers to distance to the target SPS equipment, i.e., point-of-interest equipment
	Mission path	Predetermined, ad hoc	Refers to the AROV path chosen to carry out the intervention mission
	Common communication unit	Functioning, failed	A communication hub/unit, which connects all subsystems to share data.
	Human supervisor action	Correct action, no action, wrong action	Refers to ability of the human supervisor to take required actions
	Temperature	Warm, cold	Refers to subsea local water temperature
	Water salinity	High, low	Refers to level of salinity in the subsea environment
	Gravitational tides	High, low	Refers to periodic tide changes due to gravitational forces
	Surface waves	Strong, calm	Refers to waves on the surface of the sea
	Water density	High, low	Refers to water density in the subsea environment
	Water depth	Deep, shallow	Refers to depth at which AROV shall operate
	Underwater currents	Turbulent, calm	Refers to water currents along the Subsea garage, AROV path, and SPS systems
	Seabed characteristics	Hard, soft, fine grain, gravel muddy	Refers to the coarseness of the seabed.
	Seabed terrain	Flat, peaks, slope	Refers to the seabed terrain or geographical terrain.
	Fishing trawls/nets	Present, not present	Refers to fishing trawls and nets used by fishing fleets
	Terrain obstacles	Present, not present	Refers to peaks and crests in the seabed
	Visibility	Good, poor	Refers to the visibility of the underwater environment.
Organizational nodes	Human supervisor state	Adequate, Inadequate	Refers to the ability of the human supervisor to focus on the supervision process.
	Level of autonomy	Remotely piloted, Remotely operated, Remotely supervised, Fully autonomous	Refers to the level of autonomy the IMR system is configured. Autonomy level classification is derived from [41]
	Level of training	Adequate, inadequate	Refers to the completion of required training to work as a human supervisor for an autonomous IMR operation.
Technical nodes	Battery	Fully charged, half charged, not charged	Provides electrical power supply to AROV subsystems
	Basic control system	Functioning, degraded, failed	Refers to the control system of the AROV
	Navigation system	Functioning, degraded, failed	Provides navigational ability to the AROV
	Lighting system	Functioning, degraded, failed	Provides required illumination to carry out the IMR operation

Propulsion system	Functioning, degraded, failed	Includes thrusters of the AROV
Manipulator system	Functioning, degraded, failed	Refers to the technical condition of the manipulator system
Communication system	Functioning, degraded, failed	Includes internal communication protocols and connections in the AROV
Buoyancy system	Functioning, degraded, failed	Refers to the ability of the AROV to control buoyancy
Safety system	Functioning, degraded, failed	Refers to the ability of the AROV to execute safety protocols
Detection of SPS condition	Detected, not detected	Relates to the capacity of the diagnostic system onshore to highlight faults and failures to the human supervisors.
Subsea Control Module (SCM)	Functioning, degraded, failed	SCM provides communication, electric supply, and hydraulic power to sensors, logic solvers, and final elements.
Acoustic network	Functioning, degraded, failed	Refers to working condition of acoustic transducers.
Need corrective IMR	Needed, Not needed	Refers to a preventive IMR measure planned.
Subsea garage power supply	Available, not available	Refers to the availability of power supply from onshore power grids, subsea local power generation, etc.
Subsea garage communication system	Functioning, degraded, failed	The communications network established with onshore locations and with AROVs.

3.5 Analyze causal relations – Step 5

In the initial version of the BBN model, certain causal relationships were assumed. Numerous edits to the structure were made for each iteration of the proposed BBN model to streamline and ease the quantification process.

3.6 Quantify the model – Step 6

3.6.1 Constructing conditional probability tables

The complex interactions between the BBN nodes lead to challenges in quantifying and constructing CPTs for the child nodes. Since the autonomous IMR system under study is still in nascent development stages, limited CPT data is available from the literature. Mkrtchyan et al. [37,38] provide a review and application of five existing methods to develop CPTs for BBN applications. In the proposed BBN model, the method proposed by Røed et al. [39] is used to quantify the CPTs of respective child nodes. The CPT allocation method proposed by Røed et al. [39] can be summarized in the following three steps.

Step 1 - Distance calculation: The modular distance between the child state and the parent state is calculated by using Equation 1, where $|Z_{ij}|$ is modular distance unit and S represents state. For example, for parent state 3 and child state 1, the modular distance is 2.

$$|Z_{ij}| = Child_S - Parent_S \qquad (1)$$

Step 2 - Weighted distance: Weights are designated by assessing the influence of the parent node on the child node. Weights are allocated for the arches linking the parent node to the child node in the BBN, which signifies the importance of the parent node linking the child node. Equation 2 calculates the weighted distance. Where $|Z_{ij}|$ is modular distance unit, W_i is assigned weights, and S represents state.

$$Z_j = \sum |Z_{ij}| * W_i \qquad where\ Z_j \in [S_0, S_n] \qquad (2)$$

Step 3 – Probability distribution: Equation 3 represents the formula to calculate the probability distribution where the numerator term is the probability mass for *j* possible states. The denominator term provides a normalization factor, which results in $P_j \in [0, 1]$. The term R is an index value, which distributes the probability mass among the j states. An R-index signifies the strength of the relationship between the parent and the child node. In essence, the R index can either increase or decrease the uncertainties in the quantification of the joint probability distribution.

If experts allot a high value to the term R, it means that the probability of a child state being closer to its parent's state is high. In this article, the term R is bound between values of 0 to 3 to aid the expert judgement process.

$$P_j = \frac{e^{-R*Z_j}}{\sum_{S_0}^{S_n} e^{-R*Z_j}} \quad where\ P_j \in [0,1] \tag{3}$$

3.6.2 Expert elicitation of weights and R index

According to Røed et al. [39], the weights W_i and index R are the two parameters required to be collected from experts in the field. The required data for this article are sourced from experts in industry and research groups working with development of subsea and underwater vehicle technologies.

Design of workshop

Four industry experts working in a subsea supplier company participated in a one-day workshop. The scope of the workshop was communicated to the four experts prior to and during the start of the workshop. The copy of the proposed BBN was also shared as a reference document to the experts one week prior to the workshop. The experts suggested changes to the causal relationships in the BBN, which were implemented before the workshop. The BBN and the relationships between the nodes were explained to the experts at the start of the workshop. The workshop was divided into two parts. Part 1 of the workshop focused on eliciting weights from parent nodes to child nodes and the R index. In Part 2 of the workshop, the experts where provided five different scenarios and where asked to provide their probability estimate to abort the IMR mission.

Table 2 lists the expertise and the years of experience of the four experts involved in this study. Expert 1 (E1) has in total 15 years of subsea engineering experience which includes 9 years of experience in subsea systems engineering and 6 years of experience in assembly and test of ROV tooling. Expert 2 (E2) has 10 years of experience in mechanical engineering which includes 8 years in ROV tooling design. Expert 3 (E3) has in total 31 years of subsea engineering and technology development. Expert 4 (E4) has in total 21 years of experience which includes 8 years of experience in real time ROV simulations.

The values obtained from the experts are averaged and used as input to calculate the CPTs for child nodes. The experts who participated in the study provided inputs to update the causal links between different nodes thereby also verifying the causal structure of the BBN. The calculated CPTs are input to the BBN model using the GeNIe software.

Table 2 Information about the experts involved in the CPT allocation

Expert	Industry application field	Total years of relevant work experience
E1	Subsea systems engineering	15
E2	ROV tooling	8
E3	Subsea engineering	31
E4	Subsea intervention	8

Allocation of expert probability estimation for target node given the scenarios

In the workshop, the experts were given the set of scenarios, as described in Section 3.7.1, and asked to provide their belief about the probability of the target node. The probability estimate from the experts can be used to compare with the probabilities obtained from the proposed BBN model for the same scenarios. A root mean squared error (RMSE) metric was utilized to verify the proposed model as represented by Equation 4, where e_i is estimated probability of target node from experts and m_i is probability of target node obtained for the BBN model, n is the number of scenarios and i is in range (1 to 5).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(e_i - m_i)}{n}} \quad (4)$$

3.6.3 Available historical data

Due to unavailability of open-access AROV failure data sources, CPTs for selected states are traced from existing data of traditional ROVs. Narayanaswamy et al. [45] highlight failure probability of components making the ROSUB 6000 ROV, as shown in *Table 3*. The suggested probabilities of failures for the real-time controller, sea battery, and brushless DC motors of thrusters, tether cable, halogen lamps, and navigational sensors are input to the respective nodes in the BBN model as prior beliefs. These values are input in the CPTs of relevant nodes of the BBN.

Table 3 Probabilities for AROV related nodes from Narayanaswamy et al. [45]

Nodes in proposed BBN	Components in ROSUB 600 ROV	Component failure rate
Control system	PLC processor with memory	0.003
Battery system	Sea battery	0.088
Propulsion system	Brushless DC motors	0.0037
Communication system	Tether cable	0.0038
Lighting system	Halogen lamps	0.00017
Navigation system	Navigational sensors	0.253
Communication unit	Umbilical	0.0021

The base probabilities for subsea environmental nodes for Åsgard subsea gas compression installation are traced from a variety of sources and are listed in *Table 4*.

Table 5 lists the data obtained from different sources on the SPS-related nodes [46].

Table 4 Probabilities for subsea environmental nodes for the Åsgard field

Subsea environmental nodes	Data source	Data
Water Depth	Norweigan Petroleum Directorate and Statoil [47,48]	240 – 300 meters
Fishing trawls/nets	Bai et al. [49]	<1 per year – Low frequency
Seabed characteristics	Statoil [48]	Gravel and mud
Terrain obstacles	Buhl-Mortensen et al. and MAREANO [50,51]	Low
Seabed terrain	Buhl-Mortensen et al. and MAREANO [50,51]	Smooth continental slope

Table 5 Probabilities for SPS and subsea garage from SINTEF and NTNU [46]

OREDA data handbook	SPS and subsea garage related nodes	Failure data
Subsea control module	Subsea control module	$1.917 * 10^{-6}$
Control system - multipurpose - static umbilical	Subsea power supply	$1.086 * 10^{-6}$
Control system - multipurpose - fiber optic	Subsea garage communication system	$2.86 * 10^{-6}$

The quantification of the BBN model with CPT inputs results in an initial probability value of 0.42, which relates to the probability of aborting an autonomous IMR operation. Table 6 lists the results from the BBN model with the allocated CPTs.

Table 6 Results from BBN model with base probabilities

State	Probability of aborting an autonomous IMR operation
Continue operation	0.58
Abort operation	0.42

3.7 Update evidence according to scenarios – Step 7

A scenario generation approach is utilized to test the proposed BBN model. The beliefs for the state of nodes are updated in the BBN model, according to the scenarios listed in Table 7. The scenarios follow the modes of operations and the time-steps used. Scenario 1 starts at T1 where all nodes are simulated to be in their best possible states. This allows the model to calculate the probability of loss of AROV when all nodes are in favorable states.

3.7.1 Multiple nodes in unfavorable states

In T2, the AROV is in the flight mode and moving through a muddy terrain with poor visibility; a sudden fault degrades the buoyancy system, the safety system and the acoustic network of the AROV. In T3, the AROV is in intervention mode and incurs faults in the propulsion and lighting system. In T4, during the flight back to the subsea garage, the AROV's basic control system, navigation system, communication system, buoyancy system degrade. Simultaneously, the lighting, navigation and propulsion systems fail. Multiple technical faults during operations confuse the human supervisor resulting in low situation awareness. The state of the human supervisor changes to inadequate and the supervisor is assumed untrained to handle such sudden operational deviation. Due to these failures, the AROV chooses an ad hoc mission path. In T5, the system starts to diagnose the faults and tries to recover to normal working conditions, but the AROV remains in a degraded state.

Table 7 Scenario generation – to simulate multiple nodes in unfavorable states

Node	Scenario 1 T1 Launch	Scenario 2 T2 Flight	Scenario 3 T3 Intervention	Scenario 4 T4 Flight	Scenario 5 T5 Recovery
Type of AROV	Inspection	Inspection	Inspection	Inspection	Inspection
Spare parts and tools	Not required	Not required	Not required	Not required	Not required
Type of intervention	Inspection	Inspection	Inspection	Inspection	Inspection
Distance to SPS	Far	Intermediate	Close	Intermediate	Far
Mission path selection	Predetermined	Predetermined	Predetermined	Ad hoc	Predetermined
Common communication unit	Functioning	Functioning	Functioning	Functioning	Functioning
Human supervisor action	Correct action	Correct action	Correct action	Wrong action	Correct action
Temperature	Warm	Warm	Warm	Warm	Warm
Water salinity	Low	Low	Low	Low	Low
Gravitational tides	Low	Low	Low	Low	Low

Surface waves	Calm	Calm	Calm	Calm	Calm
Water density	Low	Low	Low	Low	Low
Water depth	Shallow	Shallow	Shallow	Shallow	Shallow
Underwater currents	Calm	Turbulent	Calm	Turbulent	Calm
Seabed characteristics	Hard	Gravel muddy	Hard	Gravel muddy	Hard
Seabed terrain	Flat	Slope	Flat	Slope	Flat
Fishing trawls/nets	Low	Low	Low	Low	Low
Terrain obstacles	Low	High	Low	High	Low
Visibility	Good	Poor	Good	Poor	Good
Human supervisor state	Adequate	Adequate	Adequate	Inadequate	Adequate
Level of autonomy	Remotely supervised	Remotely supervised	Remotely operated	Remotely supervised	Remotely supervised
Level of training	Adequate	Adequate	Adequate	Inadequate	Adequate
Battery	Fully charged	Fully charged	Half charged	Half charged	Half charged
Basic control system	Functioning	Functioning	Functioning	Degraded	Degraded
Navigation system	Functioning	Functioning	Functioning	Failed	Functioning
Lighting system	Functioning	Functioning	Degraded	Failed	Degraded
Propulsion system	Functioning	Functioning	Degraded	Failed	Degraded
Manipulator system	Functioning	Functioning	Functioning	Functioning	Functioning
Sensor system	Functioning	Functioning	Functioning	Functioning	Functioning
Communication system	Functioning	Functioning	Functioning	Degraded	Functioning
Buoyancy system	Functioning	Degraded	Degraded	Degraded	Failed
Safety system	Functioning	Degraded	Degraded	Functioning	Functioning
Detection of SPS condition	Detected	Detected	Detected	Detected	Detected
Subsea Control Module (SCM)	Functioning	Functioning	Functioning	Functioning	Functioning
Acoustic network	Functioning	Degraded	Functioning	Degraded	Functioning
Need corrective IMR	Not needed	Not needed	Not needed	Not needed	Not needed
Subsea garage power supply	Available	Available	Available	Available	Available
Subsea garage communication system	Functioning	Functioning	Functioning	Functioning	Functioning

3.8 Interpret results – Step 8

As described in Step 7, the scenario-based evidence is updated in the BBN model using the GeNIe tool. Fig. 8 illustrates the results of the joint probability distribution obtained at the target node for each generated scenario. In Scenario 1, all nodes of the model are in favorable state and this results in a probability of mission abortion of 0.26. On the contrary, in Scenario 4, many faults were induced; the proposed model considered these faults to result in a probability value of aborting an autonomous IMR operation as 0.57. Fig. 8 and Fig. 10 provide an overall change in the probability of target node as the operation goes from favorable to unfavorable states.

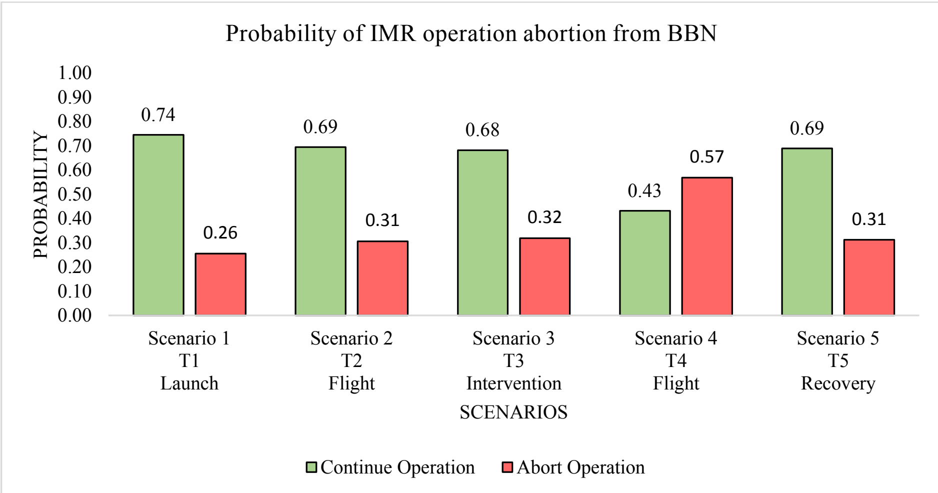

Fig. 8 Results from BBN model with simulated scenario evidence

Fig. 9 illustrates the probability of aborting an autonomous IMR operation for the selected scenarios as allocated by the four experts. The input from the experts is used as expected value. To verify the proposed model a root mean square error is calculated between the expected (from experts) and the estimated (from the model) probability values. Equation 4 is used to calculate the root mean square error, which results in a probability difference of 0.25 between the expected value from experts and the estimated value of the proposed BBN.

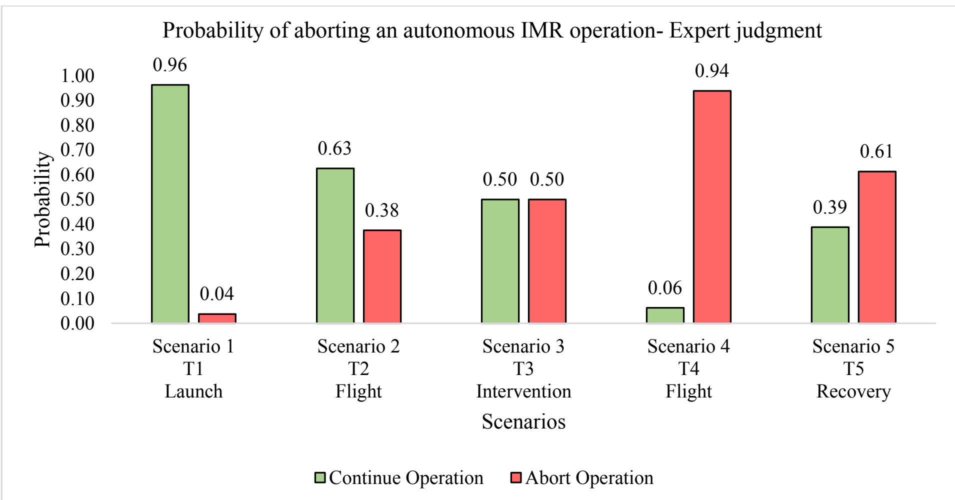

Fig. 9 Allocated probabilities by experts to abort IMR operation

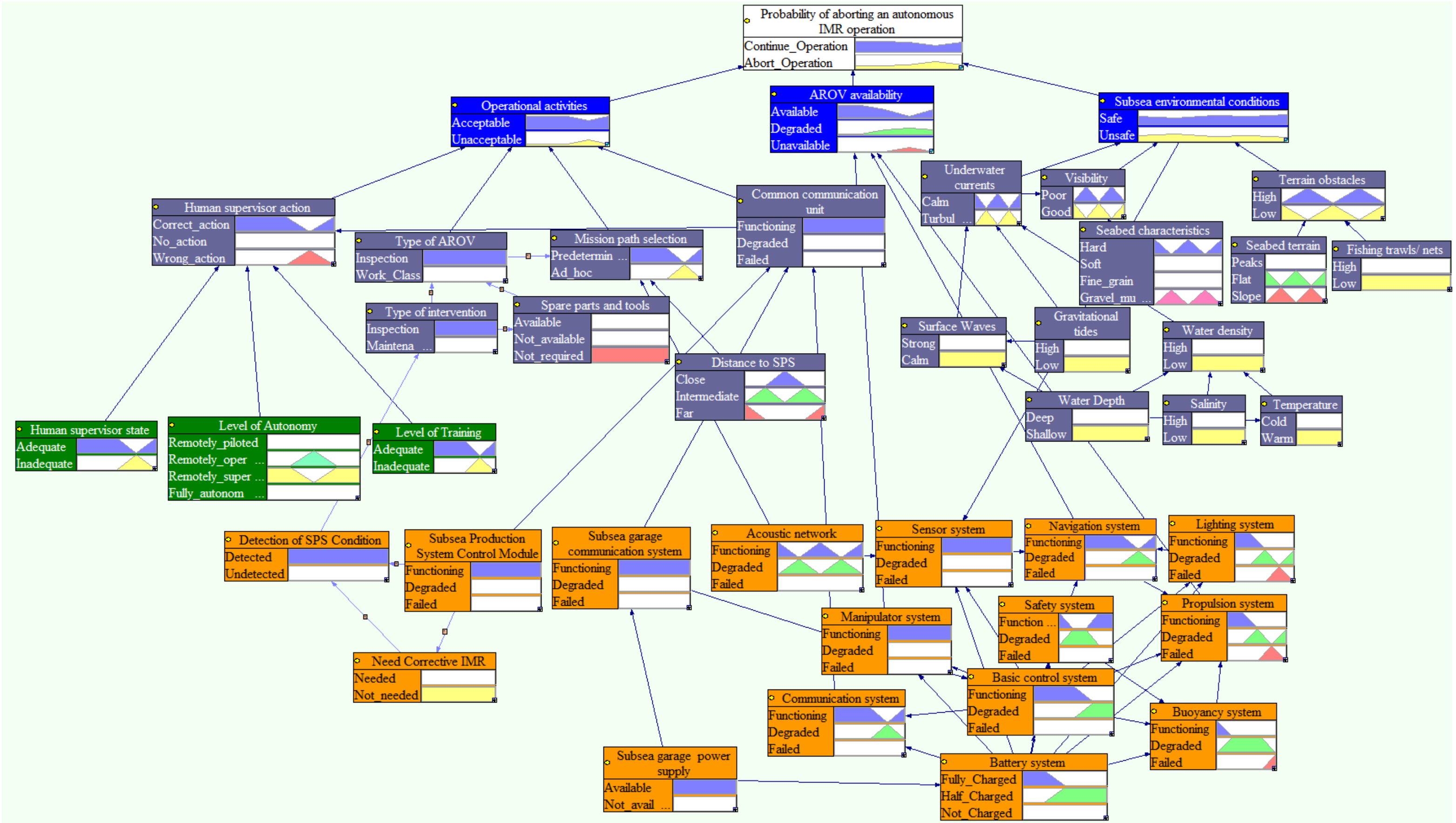

Fig. 10 Resulting joint probability distribution with generated scenarios

3.9 Sensitivity analysis

The GeNIe software incorporates the sensitivity analysis method, as proposed by Boutilier and Goldszmidt [52]. The aim of a sensitivity analysis is to examine the relationship of the posterior distribution of a target node to its parent nodes [53]. In short, the effect of small changes in parent node probabilities is compared with the resulting posterior probability in the target node. If a slight change in the parent node probability results in a substantial change in the posterior probability, the target node is said to be sensitive to the parent node. Therefore, by choosing a target node, the strength of all nodes, which contribute to the posterior probability of the target node, can be observed. Identification of sensitive nodes shall allow end users of the BBN to be mindful of the effect these nodes can have on aborting an IMR operation.

To identify the sensitive nodes in the proposed BBN, the best and worst state for each RIF or node is used as input evidence in the BBN. For example, the best state for the *propulsion system* is *functioning* and the worst state is *failed*. The best and the worst states for all nodes are presented in Table 8. With the base probability in the BBN, the evidence (best and worst state) for each node are updated in the BBN. During the sensitivity test, all other nodes are unchanged (no evidences are updated except the node being tested). The resulting probability of aborting the mission is observed. Fig. 11 illustrates the sensitivity of each node in the proposed BBN. From Fig. 11 it can be observed that technical RIFs contribute significantly to the overall probability of aborting an autonomous IMR operation.

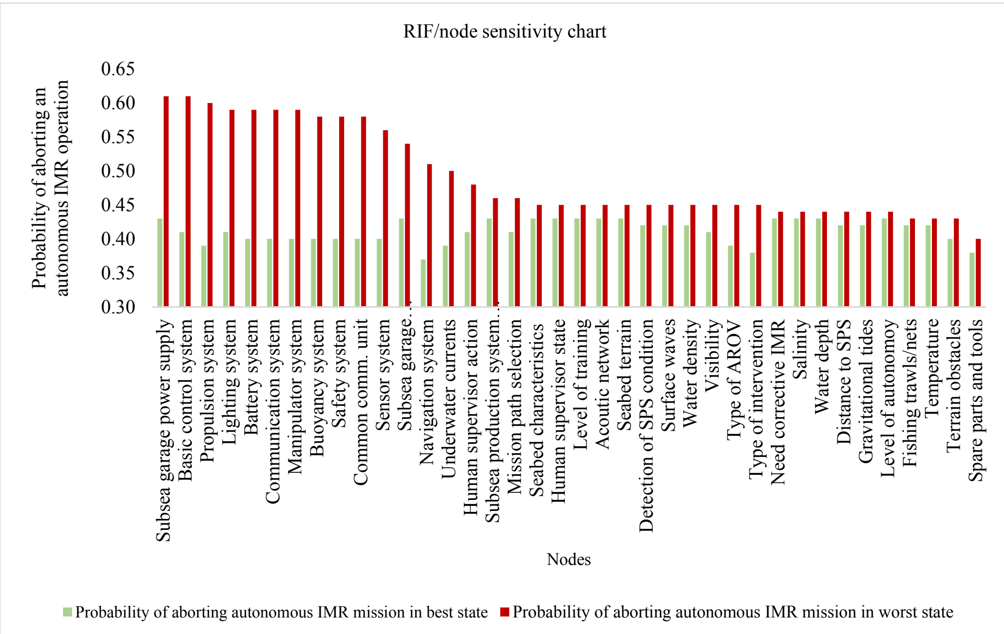

Fig. 11 Sensitivity chart when nodes are in best and worst states

Fig. 12 illustrates the sensitivity of the proposed BBN where *Probability of aborting an autonomous IMR operation* is the chosen target node. When base probabilities from the CPT calculations are utilized, the probability of aborting an autonomous IMR operation ranges from 0.38 to 0.61. Highly sensitive nodes are highlighted in dark red colors, and less sensitive nodes are in a shade of light red. Fig. 12 shows that the influence of subsea power supply, battery system, subsea garage communication system, basic control system, propulsion system and common communication unit nodes on the final node are higher than the other identified nodes. These sensitive nodes need to be considered as a starting point to propose appropriate risk reducing measures. For example, for the battery system, techniques like increasing component redundancy may decrease the probability of aborting a mission. In addition, it can be observed that all nodes in the network contribute to the joint probability distribution. This means that the identified nodes are relevant and are tightly coupled to the target node.

Table 8 Best and worst states for nodes in the proposed BBN

BBN Node	**Best node state**	**Worst node state**
Subsea garage power supply	Available	Not available
Basic control system	Functioning	Failed
Propulsion system	Functioning	Failed
Lighting system	Functioning	Failed
Battery system	Full charged	Not charged
Communication system	Functioning	Failed
Manipulator system	Functioning	Failed
Buoyancy system	Functioning	Failed
Safety system	Functioning	Failed
Common communication unit	Functioning	Failed
Sensor system	Functioning	Failed
Subsea garage communication system	Functioning	Failed
Navigation system	Functioning	Failed
Underwater currents	Calm	Turbulent
Human supervisor action	Correct action	Wrong action
Subsea production system control module	Functioning	Failed
Mission path selection	Predetermined	Ad hoc
Seabed characteristics	Hard	Fine grained
Human supervisor state	Adequate	Inadequate
Level of training	Adequate	Inadequate
Acoustic network	Functioning	Failed
Seabed terrain	Flat	Peaks
Detection of SPS condition	Detected	Undetected
Surface waves	Calm	Strong
Water density	Low	High
Visibility	Good	Poor
Type of AROV	Inspection	Work class
Type of intervention	Inspection	Maintenance repair
Need corrective IMR	Needed	Not needed
Salinity	Low	High
Water depth	Shallow	Deep
Distance to SPS	Close	Far
Gravitational tides	Low	High
Level of autonomy	Remotely supervised	Remotely operated
Fishing trawls/nets	Low	High
Temperature	Warm	Cold
Terrain obstacles	Low	High
Spare parts and tools	Not required	Not available

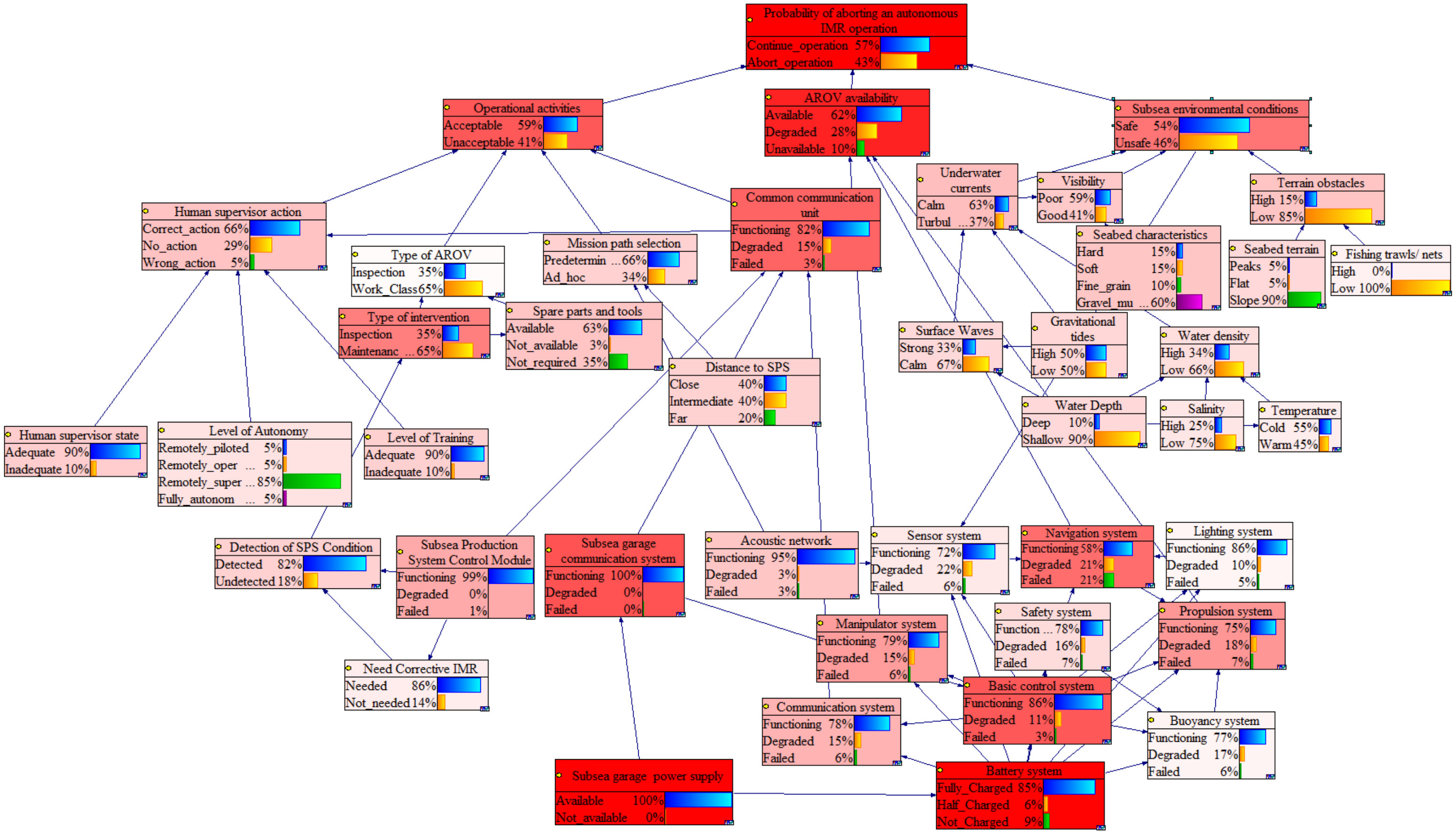

Fig. 12 Sensitivity analysis for BBN with base probabilities in GeNIe software

4 Discussion

From the development of the proposed BBN model, topics for discussions arise, which pertain to the following aspects:

- Inference of results from the proposed BBN
- Usefulness of the proposed BBN
- Challenges with application of BBN to autonomous IMR operations
- Challenges in quantification of CPTs
- Uncertainties in the proposed BBN
- Fully automated evidence updating process

4.1 Inference of results from the proposed BBN

From Table 6, the proposed BBN estimates a probability of 0.42 to the abort an autonomous IMR operation when only base probabilities, i.e., the evidence is not updated in the BBN. The 0.42 probability value can be linked to the CPT allocation method used in the study, which distributes the probabilities using the weights of parent nodes to child nodes and R index, as discussed in Section 3.6.2.

When scenario evidence of nodes are updated in the BBN, the probability of aborting an IMR operation decreases to 0.26. The probability value 0.26 refers to results obtained in Scenario 1 as illustrated in Fig. 8 of Section 3.8. The 0.26 probability value resembles real-life expectations, i.e., when all nodes are in favorable states, the probability of aborting an operation should logically be less. Nevertheless, absolute values from a predictive model is not always a reality due to induced modeling and quantification uncertainties, as discussed in Section 4.5.

When considering Scenario 4, the results from the proposed model vary from the expert judgments. According to experts, Scenario 4 is a high risk scenario because many nodes in the BBN are in their unfavorable state resulting in a mission abortion probability of 0.94. The results from the proposed model, gives a mission abortion probability of 0.57. In Scenario 5, the model provides a probability of mission abortion at 0.31. However, experts allocate the probability of mission abortion for Scenario 5 as 0.61. One of the reasons for the difference in results may be the perception of degraded and failed state by experts. A degraded state could mean that the equipment is not able to function properly and therefore the experts may have allocated a higher probability of mission abortion citing to decreased changes of recovery from a degraded state.

The generated scenarios in this article were used to simulate multiple nodes in their unfavorable states and to check how these changes affected the final probability of aborting the IMR operation. In real-life conditions, the fluctuations in the state of the node, may or may not be similar to the scenarios stated. Nevertheless, generating fault and failure scenarios has benefited the demonstration of how Bayesian decision support model may be used by subsea IMR operators.

The results also highlight that the proposed model has a root mean square error of 0.25 probability when compared with the expert estimation of aborting the IMR mission for the generated scenarios. This deviation between the BBN estimation and expert opinion can be due to three specific reasons: firstly, uncertainties in expert's judgment during the elicitation workshop could have introduced biased allocation of weights and R-index resulting in the model's estimation. Secondly, since the experts have a wide range of expertise within the subsea field, it may have resulted in an availability bias (value based on their recent experiences) while allocating abortion probabilities for the five scenarios. Thirdly, experts may perceive the scope of autonomy in different manner resulting in different operational expectations.

4.2 Usefulness of the proposed BBN

The novelty of this article is the proposed BBN and the quantification of the probability of mission abortion. Literature regarding decision making for autonomous IMR operations are limited and do not focus exclusively on subsea oil and gas industry applications. Therefore, the proposed model contributes to the body of knowledge in the field of subsea IMR. The identification of the nodes present in autonomous subsea IMR operations provides vital information to human supervisors and managers of IMR operations, but also system designers, IMR equipment manufacturers, and contractors can benefit. The proposed BBN model highlights the inherent complex interrelationships between different nodes, which can affect the performance of the autonomous IMR systems. The visual representation of the nodes can help to convey the importance of nodes from one field of discipline to another. Since the proposed BBN provides both a visual and an analytical tool to support decision-making, the industry participants of the NetGenIMR research project have valued the development of the proposed model [54].

By including historical data on the state of the node, decision makers can take risk-informed decisions during future IMR operations. The method presented and the BBN model developed can be adapted and applied to other underwater vehicles, such as snake robots, as well as AUVs. It should be noted that, unlike traditional technical safety assessments (Safety Integrity Level-SIL assessments) where simultaneous/multiple failures are not considered during the estimation of the probability of failures, the proposed BBN model allows updating of multiple failures in the model. Accidents and incidents occur due to both linear and non-linear models of accident propagation [55]. The BBN approach allows capturing both linear and non-linear scenarios leading to accidents.

4.3 Challenges with application of BBN to subsea IMR operations

Developing a BBN for subsea autonomous IMR operations is challenging in that the nodes affecting the IMR operations are plentyful, and they may be sensitive to each other. The nodes also pan across different categories, space and time. The proposed model has tried to provide an overview of this complexity by tracing the relevant nodes affecting autonomous IMR operations. However, it can be observed that the design of future subsea fields and underwater vehicle technology can change the way subsea IMR operations are carried out. For example, in the Åsgard field the IMR operation to open and close electrically actuated subsea valves can be performed from a remote location [48]. This may result in decreased need for work-class AROVs to perform value open/closure operations.

In the future, there might be a need for cooperating AROVs, which depend on the functions of each other. If one of the vehicles is in a degraded or failed state, that may pose a risk in the form of loss of execution time. These aspects are not covered in the proposed BBN model, but the model can be adapted to encompass these future use cases as well. This may also be true for other industries, such as fish farming, deep-sea mining who may rely on AROVs for their routine IMR operations.

4.4 Challenges in quantification of CPTs

One of the main challenges in developing BBNs is the quantification of the model. Data regarding scenarios (conditional probabilities) where two or more nodes are in different states is difficult to source. Nevertheless, quantification of the model is vital to be able to make sensible estimations for a given application.

The first iteration of the quantification phase utilized authors' judgments to generate CPTs to test allocation biases. The resulting joint probability distributions did not correlate to real-life expectations. Therefore, quantifying CPTs using a single assessor method was not practical. The second iteration utilized a scaled CPT allocation as suggested by Renooij and Witteman [56,57]. This method resulted in optimistic joint probability distributions for the target node, which was also not practical. The reason for this can be linked to assessors anchoring to a suggested probability scale, which may lead to biases in CPT allocation. In the third iteration, the method proposed by Røed et al. [39] was adopted. This method provided two unique advantages. Firstly, the method being a way to allocate CPTs was faster to implement in an excel sheet. Secondly, the ability to include expert judgments made it ideal for a conceptual case, such as the one presented in this article.

4.5 Uncertainties in the proposed BBN

BBNs are one of the effective alternatives to reason in the presence of uncertainty. However, the construction of the BBNs can introduce modeling uncertainties: an induced uncertainty. The induced uncertainty can be credited to the subjective nature of BBN development, which applies to the way BBNs are structured, the definition of states, and their allotted conditional probabilities. Contrastingly, the subjective nature of BBN can also promote flexibility in the model, which can be tailored to fit the requirements from one or more application fields.

The presented type of autonomous subsea IMR operations can also induce uncertainties. Bradley and Drechsler [58] classify such induced uncertainties as *Normative uncertainties*. Normative uncertainty is defined as *uncertainty about what is desirable in the case*. For example, if an IMR operation requires two or more AROVs, failure of one AROV can result in a different probability of aborting the IMR operation than that presented in this article. Hence, it may be beneficial to construct BBNs on the basis of a particular IMR case where the requirement of each subsystem is precisely known. This approach can decrease the normative uncertainties. On the contrary, building a generic BBN model, as proposed in this article, can also be advantageous by providing a roadmap to developing application specific BBN models. This approach can also decrease modeling uncertainties.

4.6 Fully automated evidence updating process

In this article, the nodal evidence is updated through generated scenarios, i.e., the state of the node is manually updated in the GeNIe software. This process of manually updating nodal evidence may not be feasible during live IMR operations. A classifier module is required to develop a fully automated BBN. The module shall collect data about the nodes and classify the state of the node during live operation (real-time). For example, the classifier module collects data on remaining AROV battery capacity and classifies it to either fully charged, half charged or not charged states. The output of the classification module can be fed to the proposed BBN to generate a live posterior probability for the target node.

5 Conclusions

Decision making in uncertain environments is challenging. This is particularly the case in dynamic environments, such as a subsea environment. Autonomous system solutions should be designed and operated and not add to the present challenges; rather they should be safe and reliable to realize the goals set for subsea factories. All engineered systems are susceptible to failure, but to know which factors or nodes in the BBN that can affect the process can provide vital information to human supervisors, managers and system developers.

This article presents a BBN that can be used to calculate the probability of aborting an autonomous subsea IMR operation. Thirty-eight nodes have been identified, along with causal relationships. The method used in this article considers a systemic and a holistic approach to BBN modeling, including all relevant technical, organizational, operational nodes. The proposed BBN model is quantified using data from literature and expert judgment. The model is tested by updating the state of the nodes in five different operational scenarios, and the resulting probabilities from the BBN are scrutinized against real-life expectations of experts.

From the results obtained, it can be concluded that a BBN approach for providing decision-support may be advantageous during autonomous subsea IMR operations. In comparison to other risk-modelling techniques, such as event sequence diagrams, fault trees, event trees etc., BBNs can provide a risk model that utilize new evidences in form of empirical data or expert judgements. The probabilities suggested by the proposed model may be used in an operational setting by the human supervisors to determine when to intervene during autonomous IMR operations. The BBN can promote situation awareness among the human supervisors, which is an important means to reduce risk. A further work scope to ease implementation of proposed BBN is to automate the process of updating evidence by developing classifiers, which can classify the state for each identified node in real-time.

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Article 4

Application of fuzzy logic for safe autonomous subsea IMR operations

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Application of fuzzy logic for safe autonomous subsea IMR operations

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ABSTRACT: Numerous technical and knowledge gaps pose challenges towards implementation of autonomous subsea intervention, maintenance, and repair operations. One such gap is related to development of methods for ensuring subsea asset and operational safety during autonomous subsea interventions. This paper describes a novel approach of using fuzzy logic to develop an asset safety decision support basis in resident underwater vehicles. A fuzzy inference system is developed with remotely operated vehicle envelope and sensor condition as input variables. Fuzzy sets and their respective membership functions are defined. On the basis of existing subsea knowledge in subsea operations, fifteen fuzzy rules are derived. The aggregated conclusions vary for different range values of ROV envelopes and conditions of the sensor system. The initial findings from simulation of the fuzzy inference system show that application of fuzzy logic to subsea intervention operations can be valuable for development of asset safety related aspects, such as for consequence analysis, operational safety, and development of safety philosophies.

1 INTRODUCTION

Remotely operated vehicles (ROVs) are controlled by human operators to install, maintain, and repair subsea oil and gas installations. With increased number of subsea installations worldwide, the need for subsea interventions also continue to rise (Zijderveld, Tiebout, Hendriks, & Poldervaart 2012). The demand for subsea ROV interventions has impacted the cost of mobilizing resources in performing such interventions. Currently, adoption of subsea autonomy is viewed by the Norwegian oil and gas industry and associated research centres as one of the solutions to optimize subsea intervention, maintenance, and repair (IMR) operations (Schjølberg & Utne 2015).

As successful concept trials of using ROVs for autonomous IMR operations steadily increase, ROV manufacturers and operators have also started to develop ROVs capable of performing autonomous IMR operations (Saul & Tena 2007, Cohan 2008). *Marlin* from Lockheed Martin (McLeod & Jacobson 2011, McLeod, Jacobson, & Tangirala 2012, McLeod, Jacobson, Hardy, & Embry 2013) and *Seaeye Sabertooth* from SAAB are examples of commercially available ROVs with autonomous inspection functionalities (SAAB 2014, Johansson, Siesjä, & Furuholmen 2010). However, introduction of autonomy brings new challenges related, but not limited to, safe subsea IMR operations. Hegde et al. (2015) highlight that the standards recommending requirements to development of autonomous underwater vehicles do not address the technical safety aspects of such vehicles (ASTM 2006, ASTM 2007a, ASTM 2007b, ASTM 2007c). The boundaries of safe and unsafe operations in an autonomous subsea setting is dependent on the interactions between the underwater vehicle, the subsea equipment, and their corresponding sub-systems. This paper describes application of fuzzy logic to ensure subsea asset safety during autonomous IMR operations. Subsea asset refers to ROVs and the subsea equipments.

The literature shows application of fuzzy logic to develop adaptive and dynamic control of underwater vehicles. Shimmin et al. (1996) describe development of a self-tuning fuzzy controller for ROVs. Smith et al. (1993) describe a goal based fuzzy algorithm capable of docking autonomous underwater vehicle (AUV). Lea et al. (1999) review and describe various control techniques used in underwater vehicles and suggest a fuzzy logic controller approach. Nag et al. (2013) describe development of a fuzzy logic controller for autonomous underwater vehicles (AUVs). Ayob et al.

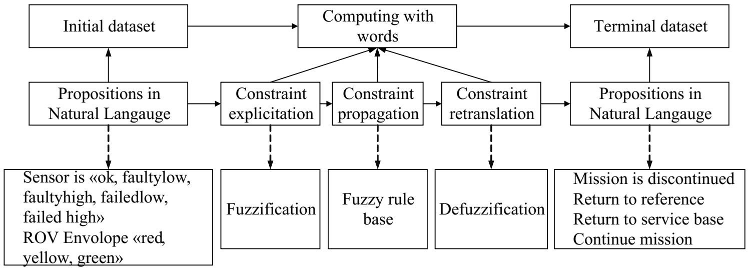

Figure 1: Computing with words- ROV decision support adapted from Zadeh (1996, 1999).

(2013) describe development of a wireless self balancing fuzzy logic controller to maintain vertical positioning of the ROV. However, the scope of the above mentioned studies relate to the vehicle control system and do not cover the safety control system. In addition, these studies do not relate to safety decision support of ROVs.

In an autonomous setting, ROVs or other underwater vehicles will need a stored knowledge base to determine scenarios that are safe and scenarios that are safety critical to the subsea asset. For example, a failure of a redundant sensor will call for a different safety response from the ROV than the scenario where multiple sensors are failed. Currently, the human operators controlling the ROVs can be classified as one layer of operational barrier during subsea interventions. In the future, if ROVs have to operate in an autonomous setting (in presence of supervisory human operators), an on board decision support system is necessary for safe ROV intervention operations.

Citing the need for a decision support system, this paper demonstrates adoption of fuzzy logic for developing the basis for ROV decision support during autonomous IMR operations. Grzesik & Czapla (2015) propose a method of using fuzzy logic to develop decisions basis for aircraft ejection seats. The methodology suggested by (Grzesik & Czapla 2015) is adapted to develop asset safety decision support for resident ROVs performing subsea intervention operations in the current paper.

The main contribution of this work is the development of a decision support basis for resident ROVs to operate safely in presence of faults and failures in the sensor system. A conceptual case study is used to demonstrate the generation of a asset safety decision basis for resident ROVs. In this paper, resident ROVs refer to conceptual ROVs, which are capable of residing in subsea service stations and perform a selected number of IMR operations autonomously on demand.

The paper is organized as follows: section 2 describes the fuzzy inference system (FIS) setup for the study with descriptions on fuzzy variables, fuzzy sets, and their membership functions. Section 3 presents the knowledge base required to derive fuzzy rule set followed by section 4, which describes the simulation setup, and the results obtained from the fuzzy inference system. Section 5 holds conclusions and further work scope.

2 FUZZY INFERENCE SYSTEM

Fuzzy logic theory delivers precise outputs from imprecise inputs, similar to real-life scenarios, where input parameter values vary within a given range of values. Figure 1 is adapted from (Zadeh 1996, Zadeh 1999) and describes the overall methodology used in this paper.

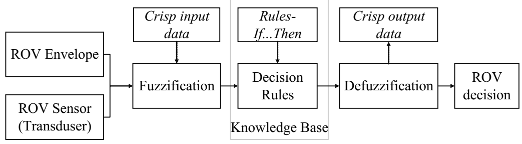

Figure 2: Overview of the fuzzy inference system.

In a fuzzy inference system, input and output variables contain n number of fuzzy sets with shared memberships among other fuzzy sets. This process of converting crisp input to range values is known as fuzzification. A fuzzy operator is used to connect the antecedent to a consequent through a *IF - THEN* logic. Defuzzification is achieved by calculating the membership of input variable fuzzy sets against the output variable fuzzy sets. Defuzzification results in a crisp value, which can further be used as input to make decisions. Figure 2 illustrates the fundamentals of fuzzy logic and relation to the current paper. The sub-sections 2.1 to 2.3 describe the application of the fuzzy inference system for this study. Figure 3 illus-

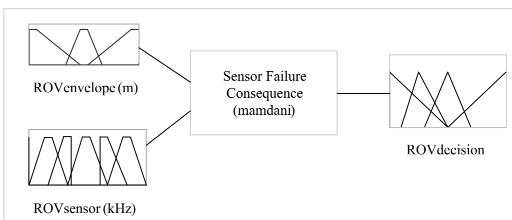

Figure 3: Decision making from Fuzzy Logic Toolbox in Matlab.

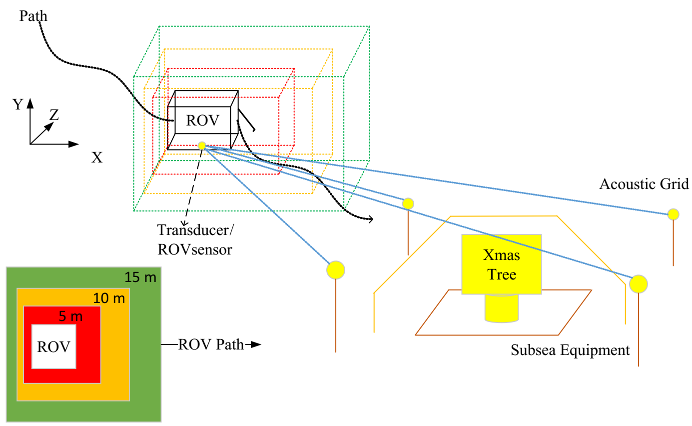

Figure 4: Illustration of ROV envelopes.

trates the Fuzzy Logic ToolBox with two input variables, the rule sets, and output variable. Range specifications of the subsea envelopes and sensor status of the underwater vehicle are established as part of the membership functions of the two input variables in Matlab Fuzzy Logic Toolbox. The Mamdani method is chosen to set up a fuzzy inference system (FIS).

2.1 *Fuzzification- Fuzzy input variables*

Two fuzzy input variables are used in the case study, namely ROV envelope, and ROV sensor. The following subsection describes the two fuzzy input variables in detail.

2.1.1 *ROV envelope*

In the aviation industry, aircrafts are equipped with a Traffic Collision Avoidance System (TCAS). The TCAS operates based on the principle of operational and safety flight envelopes. These flying envelopes are calculated based on the forward movement of the aircraft and differ during take-off and landing situations. Breach in the envelopes trigger different corresponding responses by the flight control system (U.S Department of Transportation- Federal Aviation Administration 2011). In recent years, vehicular based envelopes are also applied to ground automobiles, such as cars. Papp (2012) describes the application of vehicular envelopes in the automobile industry and the advantages to overall situational awareness. Similarly, ROV flying envelopes are essential to ensure safe launch, approach, preparation, and intervention operations on the subsea structure. Since the main goal of ROV operations is to maintain and restore the subsea production equipments, they need to be safe and reliable even in an autonomous setting.

Knowledge transfer approach is adopted, and ROV envelopes are defined similarly to envelopes in TCAS. Breach in the ROV envelopes shall trigger different actions from the ROV flight control system. The ROV will behave differently in each envelope to avoid collision with other resident ROVs and subsea structures. ROV envelopes can be defined as different flying envelopes of the ROV; namely green (safe), yellow (moderately safe), and red (safety critical).

Figure 4 illustrates the three ROV envelopes. The envelopes are offset towards the heading direction of the ROV. For example, in Figure 4 the ROV is heading in x-axis and the envelope is adjusted to the x-axis. The green envelope is the area, where the ROV can safely fly and obstructions existing within this envelope are not a threat to the ROV. For example, the distance when the ROV is approaching towards the subsea structure is more than 15 meters. The defined ROV envelopes are not dynamic in nature i.e, the envelopes are assumed to remain static and not change with the speed of the ROV flight.

The range defined for green envelope is 15 meters from the manipulator arms of the ROV. The yellow envelope is the area where the ROV may collide with obstructions existing within this envelope leading to a safety incident. The yellow envelope ranges from 10 to 5 meters. The red envelope is the area where the ROV has high probability of collision with the obstructions ahead leading to a certain safety critical incident/accident. The red envelope ranges from 5 meter to the external surface or till the manipulator arms of the ROV.

2.1.2 *ROV sensor*

ROVs consist of numerous on-board sensors to assist navigation and control of the ROV during a subsea flight. Typical sensors on a ROV are pressure, depth, camera, inertia measurement unit (IMU), Doppler velocity log (DVL), etc. In this study, the echo sounder transducers of the ROV is used as an example for a ROV sensor. To ensure practical assumptions in setting up the fuzzy sets and respective membership functions, the study assumes the resident ROV to be equipped with a multi beam echo sounder- EM 2040 produced by Kongsberg Maritime.

There are two functions of an echo sounder sensor: Firstly, it can generate a three-dimensional map of the seabed/subsea structures. Secondly, it serves as an altimeter. The system usually consists of receiver and transmit transducer along with a processing unit. The model EM 2040 has three modes of operations, but to keep scope manageable this study chooses the ideal operating frequency of this product, which is from 200 kHz to 400 kHz frequency (Kongsberg Maritime AS 2012). The frequency rating is chosen to be the main parameter to asses the condition of the echo-sounder.

Table 1 lists range values for each fuzzy set for this input variable. Sensor is in a faulty state when the sensor inputs are near the extremities (faulty low and faulty high) of the operating frequency. Sensor is in a failed state when the sensor inputs are outside the frequency range (failed low and failed high). Note that the *faulty* fuzzy sets (faulty low and faulty high) partly encompass areas of *Ok* and *failed low and high* fuzzy sets.

2.1.3 *Fuzzy sets and membership functions*

In this study, a total of eight input fuzzy sets and four output fuzzy sets are defined. Table 1 highlights the input variables, fuzzy set, type of membership functions (trapezoidal or triangular), and the crisp input parameters of fuzzy sets in the fuzzy inference system.

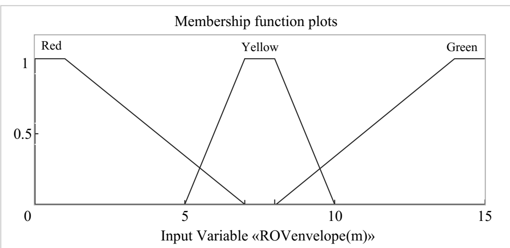

Figure 5: Membership functions for fuzzy sets of the ROV envelope variable.

Figure 5 illustrates the three membership functions for the *ROV envelope* variable. Figure 6 illustrates the four membership functions for the *ROV sensor* variable. Figure 7 illustrates the membership functions of the output variable- ROV decision.

2.2 *Fuzzy Rule Set*

Fuzzy sets and ROV decision possibilities are predetermined and a set of fuzzy rules are established by combining the knowledge base. Table 2 lists the fifteen fuzzy rules defined and implemented in the FIS.

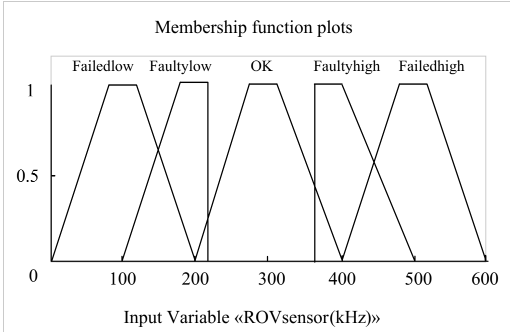

Figure 6: Membership functions for fuzzy sets of ROV sensor variable.

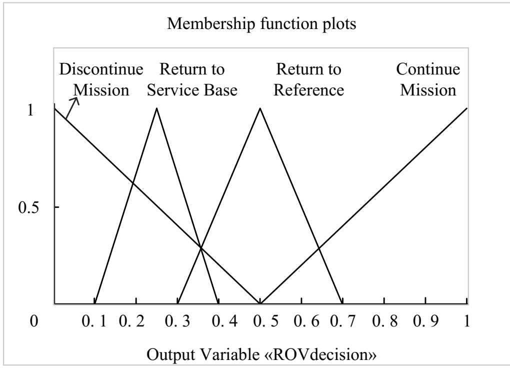

Figure 7: Output membership functions for fuzzy sets of ROV decision variable.

Figure 8 provides the knowledge base for determining the consequent fuzzy sets. The fuzzy logic operator AND is used to derive the inference from input variables.

2.3 *Defuzzification*

The centroid defuzzification method is used to obtain crisp output values in the Fuzzy Logic Toolbox. The centroid defuzzification method provides the best output possible within the uncertainty constraints. It calculates the center of gravity of the two areas and results in an overall centroid of the combined area (Sivanandam et al. 2007). Multiple input variables can result in complex centroid calculations, and therefore this method is suitable for FIS with one to three input variables.

3 KNOWLEDGE BASE

A main analysis step in fuzzy logic is the optimal use of existing knowledge to build easy to interpret logical rule sets. Zadeh (1999) describes this process as using existing knowledge base to leverage the antecedent (variables) and develop consequent rule set. For example, fuzzy logic is used to determine the

Table 1: Fuzzy sets and membership functions.

Input and Output Variables	Fuzzy Set	Membership Function	Fuzzy Set Parameters
ROV Envelope: 0-15 m	Red	Trapezoidal membership function	-7 -1 1 7
	Yellow	Trapezoidal membership function	5 7 8 10
	Green	Trapezoidal membership function	8 14 16 22
ROV Sensor: 0-600 kHz	Failedlow	Trapezoidal membership function	0 80 120 200
	Faultylow	Trapezoidal membership function	100 180 220 220
	Ok	Trapezoidal membership function	200 280 320 400
	Faultyhigh	Trapezoidal membership function	380 380 420 500
	Failedhigh	Trapezoidal membership function	400 480 520 600
ROV Decision (Output)	Discontinue mission	Triangular membership function	-0.5 0 0.5
	Return to service base	Triangular membership function	0.1 0.25 0.4
	Return to reference	Triangular membership function	0.3 0.5 0.7
	Continue mission	Triangular membership function	0.5 1. 1.5

Table 2: Rule sets in the fuzzy inference system.

Rule number	Antecedent	Consequent	Transit Paths
1	ROVenvelope IS Red AND ROVsensor is Ok	ROVdecision IS Continuemission	NA
2	ROVenvelope IS Red AND ROVsensor is Faultyhigh	ROVdecision IS Returntoreference	3
3	ROVenvelope IS Red AND ROVsensor is Faultylow	ROVdecision IS Returntoreference	3
4	ROVenvelope IS Red AND ROVsensor is Failedhigh	ROVdecision IS Discontinuemission	1,3
5	ROVenvelope IS Red AND ROVsensor is Failedlow	ROVdecision IS Discontinuemission	1,3
6	ROVenvelope IS Yellow AND ROVsensor is Ok	ROVdecision IS Continuemission	NA
7	ROVenvelope IS Yellow AND ROVsensor is Faultyhigh	ROVdecision IS Returntoreference	3
8	ROVenvelope IS Yellow AND ROVsensor is Faultylow	ROVdecision IS Returntoreference	3
9	ROVenvelope IS Yellow AND ROVsensor is Failedhigh	ROVdecision IS Discontinuemission	1, 3
10	ROVenvelope IS Yellow AND ROVsensor is Failedlow	ROVdecision IS Discontinuemission	1, 3
11	ROVenvelope IS Green AND ROVsensor is Ok	ROVdecision IS Continuemission	NA
12	ROVenvelope IS Green AND ROVsensor is Faultyhigh	ROVdecision IS Returntoreference	3
13	ROVenvelope IS Green AND ROVsensor is Faultylow	ROVdecision IS Returntoreference	3
14	ROVenvelope IS Green AND ROVsensor is Failedhigh	ROVdecision IS Returntoservicebase	1, 2, 3
15	ROVenvelope IS Green AND ROVsensor is Failedlow	ROVdecision IS Returntoservicebase	1, 2, 3

wash setting in a washing machine; IF the clothes are *dirty* AND the clothes are *heavy*, THEN use *heavy* wash setting. In this example, the knowledge base is to know the dirtiness of the clothes and the weight of the clothes. This knowledge can further be leveraged to make logic rules.

In this paper, knowledge base of subsea operations of ROVs is leveraged to make logical rules and decisions. The two input variables ROV envelope and ROV sensor are divided into eight fuzzy sets. For example, consider the rule number 11 from Table 2: IF ROVenvelope is *Green* AND ROVsensor is *Ok*, THEN ROVdecision is *Continue mission*. The knowledge base in this example is the ROV's perception of exact position to a reference point and the condition monitoring of the ROV sensor. These two known values can contribute to defining a rule set. In total, there are fifteen rules in the current FIS.

Figure 8 illustrates the possible return paths of the ROVs subject to the ROV envelopes and condition of ROV sensors. Consider the ROV performing an intervention task. There are four possible states to which the ROV can transit due to the combination of ROV envelopes and ROV sensor conditions. If both variables are in their respectively safe values; for example, green envelope and 300 kHz frequency output from the sensor, then the ROV can continue the mission as planned. Since rules number 1, 6, and 11 satisfy this criteria, the ROV will continue the mission as planned. In other words, this is the ideal intervention operation, without any faults or failure.

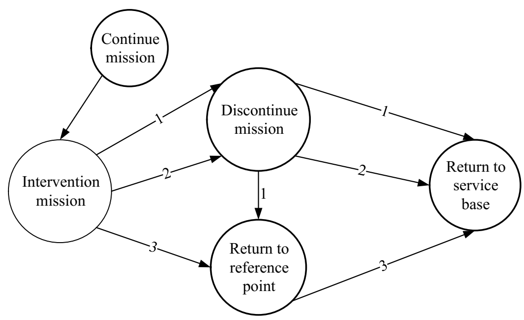

Figure 8: ROV decisions during intervention operations.

On detection of a sensor fault (low or high value) by the vehicle diagnostic system, the ROV will need to behave differently. Since there is no gross failure of the sensor system, the ROV will return to a reference point for further internal diagnostics. Such a transition state will provide the ROV with an opportunity to identify the abnormalities in a safer area. It also decreases the need to travel back to the service base, thereby decreasing overall operational time. Rules number 2, 3, 7, 8, 12, and 13 satisfy these criteria. The ROV can transit through two separate states: Firstly,

Table 3: Simulation result from Simulink.

Data Point	ROV Envelope (m)	ROV Sensor (kHz)	Crisp Output	ROV Decision
1	8.2	308.2	0.84	Continuemission
2	7.4	277.8	0.84	Continuemission
3	5.9	210.9	0.39	Returntoservicebase
4	2.3	57.9	0.17	Discontinuemission
5	7.1	260.8	0.83	Continuemission
6	10.9	425.8	0.42	Discontinuemission
7	2.6	70.5	0.17	Discontinuemission
8	2.1	47.8	0.18	Discontinuemission
9	6.2	222.2	0.79	Continuemission
10	1.5	21.1	0.22	Discontinuemission
11	3.7	116.1	0.26	Discontinuemission
12	7.6	283.3	0.84	Continuemission
13	3	87.8	0.18	Discontinuemission
14	11	431.0	0.41	Discontinuemission
15	10.3	397.4	0.53	Returntoreference
16	7.0	259.7	0.83	Continuemission
17	7.2	268.2	0.83	Continuemission
18	8.1	305.5	0.84	Continuemission
19	8.4	317.3	0.83	Continuemission
20	9.0	344.2	0.81	Continuemission
21	6.1	217.1	0.41	Returntoservicebase

when the mission is discontinued (transit path 1) and secondly, a direct transit to the reference point as illustrated in Figure 8 (transit path 3).

On detection of a sensor failure (low<200 kHz or high>400 kHz) by the vehicle diagnostic system, the ROV discontinues the mission. Upon discontinuing the mission, the ROV can transit to either the reference point through transit path 1 or return to the service base through transit path 1 and 3. However, if the ROV identifies failure of sensors while approaching the subsea structure (in the green envelope), the ROV will return to the service base directly via transit path 2. Transit path 2 provides shorter flying distance to the service base, thereby decreasing travel time and decreased restoration time of the ROV.

4 SIMULATION SETUP AND RESULTS OF FUZZY INFERENCE SYSTEM

The Simulink software in MATLAB has been used to set up a simulation model of the FIS. The main aim of the simulation is to demonstrate the usability of the FIS with random inputs. The two fuzzy variables (ROV envelope and ROV sensor) are generated by using a uniform random number generator between the given limits of the respective membership functions of the fuzzy sets. For the ROV envelope variable, the random number generated is between 0 m and 15 m. For the ROV sensor variable, the random number generated is between 0 kHz to 600 kHz. Note that both these ranges satisfy the membership functions of the respective fuzzy sets.

In total, 21 data input variables were generated as listed in Table 3. The Simulink software uses the generated input values in the FIS to generate defuzzified crisp output values. The FIS uses the centroid

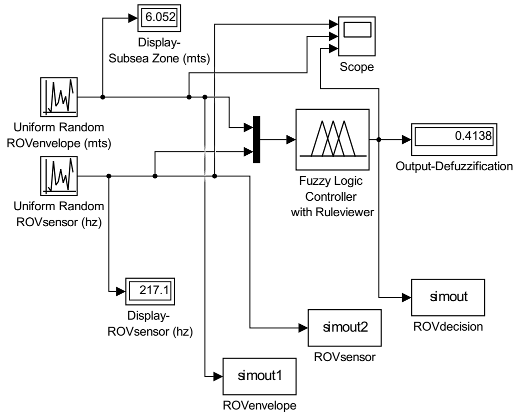

Figure 9: Simulink simulation model.

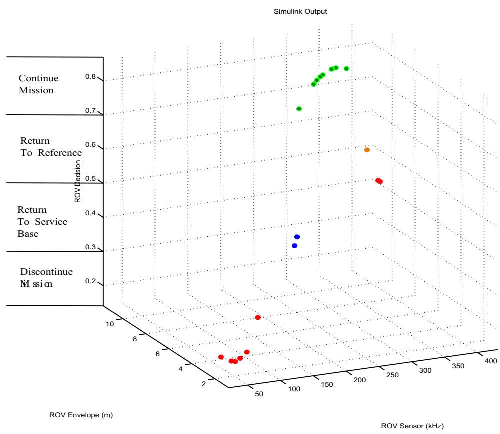

Figure 10: Scatter plot- output from simulation.

method to calculate the center of gravity of intersected membership functions to defuzzify the imprecise outputs. Figure 9 illustrates the simulation model. The model contains two uniform random number generators, which provide input values to the Fuzzy Logic Controller with Ruleviewer block. For ease of identification of input and output variables, three display blocks are connected. Similarly, to extract the values generated from the simulation, three simout blocks are linked to input and output variables. A scope box aggregates all input and output values to generate a graph with respect to the number of runs in the simulation.

21 data points listed in Table 3 are plotted on a 3 dimensional scatter plot in Figure 10. The ROV decision is based on the output values and the corresponding membership functions as illustrated in Figure 7. For example, for data point 21 in Table 3, the defuzzified output value is 0.41, which corresponds to the fuzzy set *return to service base* in Figure 7. In Figure 10, the green plot points fall under the operating frequency of the ROV sensor variable (200 kHz

to 400 kHz) and reflect scenarios where the ROV can *continue mission*. The red points fall outside the operating frequency. The blue plot points fall under the *return to service base* decision, while the single orange plot point infers to *return to reference* decision.

Considering Figure 11, the red dotted line on the surface graph corresponds to the input values listed in Figure 12 demonstrating the fuzzy rule viewer, i.e, ROVenvelope = 15m and ROVsensor = 300 kHz resulting in ROV decision output value of 0.837, which corresponds to continue mission fuzzy set in Figure 7. The different color shades in Figure 11 infers the control surfaces of the ROV with respect to input and output variables.

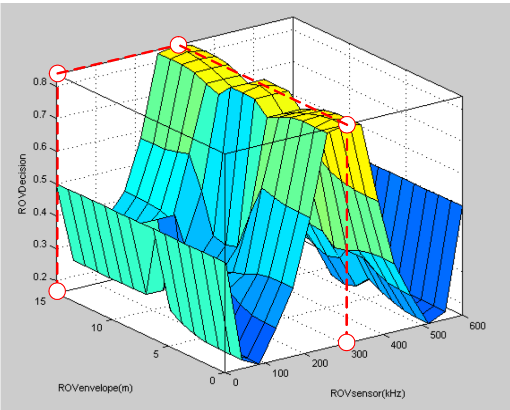

Figure 11: Surface output from FuzzyToolbox.

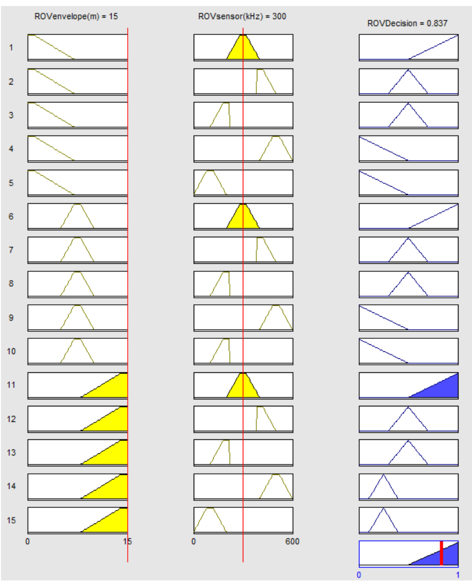

Figure 12: Fuzzy inference diagram from FuzzyToolbox.

5 CONCLUSIONS AND FURTHER WORK

Applications of Fuzzy logic to design and develop engineering systems spans across different research fields and is well documented in the literature. In recent years, with advent of higher computing capabilities, the field of fuzzy logic is gaining increased attention. Demonstration of fuzzy logic to develop safety decision basis for resident ROVs is provided in this paper.

Subsea autonomous IMR operations need to utilize the existing knowledge from within and across different industries. Knowledge transfer from the aviation industry is important for safe autonomous IMR operations. In addition, knowledge transfer from industries developing intelligent vehicles, such as the automobile industry is also vital to develop future underwater vehicles. The ROV envelopes described in this paper is an attempt towards knowledge transfer across three industries (aviation, automobile, and subsea) facing similar operational challenges.

The FIS provides a systematic basis and viable approach for deriving a decision support basis. However, this study uses simulation with random inputs to validate the FIS and does not incorporate live ROV sensor input data. If live ROV sensor data is used, the validity of the method can be increased. Since the simulation uses random numbers within the given input range, it may not reflect the normal working of the sensor, i.e, the range of output values may not occur during a single intervention mission. Contrastingly, the use of random input variables in the simulations reflects the nature of random faults and failures in the ROV subsystem.

The decision support basis can be integrated with the flight control system of the ROV to be used during operations. Interfaces between the decision basis and flight control systems of the ROV is therefore essential. The study identifies the need for further work to incorporate other ROV sub-systems as input variables into the FIS, for example, the propulsion systems and the buoyancy system.

Introduction of a third input variable- ROV movement in the FIS may improve the validity of decision support basis. Definition of dynamic ROV envelopes, which can increase or decrease the envelope size proportional to the displacement of the ROV is needed. A further work scope is to scale the method to capture additional ROV sub-systems and use the decision basis as an input/feedback to the corrective flight control system of the ROV. The scaling of the method should consider a systems engineering perspective to ensure that the model captures the dynamic nature of autonomous subsea IMR operations.

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Article 5

Development of safety envelopes and subsea traffic rules for autonomous remotely operated vehicles

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Development of safety envelopes and subsea traffic rules for autonomous remotely operated vehicles

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Abstract: This article presents the process used to develop safety envelopes and subsea traffic rules for autonomous remotely operated vehicles (AROVs) used in subsea inspection, maintenance, and repair (IMR) operations. Preventing damage to subsea assets and the AROVs is the overall goal of the proposed safety envelopes and subsea traffic rules. Currently, no such envelopes and rules exist. The safety envelope for the AROV is constructed using an octree method. The proposed subsea traffic rules are derived by combining existing traffic regulations in marine and aviation industries. The proposed safety envelopes and traffic rules are tested using both a novel modular open robot simulation engine (MORSE) based underwater simulator and in the laboratory. The results from the laboratory tests show that the proposed safety envelopes and subsea traffic rules can be used during simulated or real IMR operations to recommend subsea traffic rules to the AROV and the human supervisor.

Keywords: Autonomy; safety envelopes; collision avoidance; subsea IMR; octree

1. Introduction

Subsea inspection, maintenance, and repair (IMR) operations are essential for maintaining the technical condition of the subsea production systems (SPSs). However, current subsea intervention activities are resource intensive and are dependent on uncertain factors, such as suitable weather conditions and vessel and equipment availability [1]. The Norwegian oil and gas industry has set a vision of extracting, processing, and transporting hydrocarbons by using subsea installations within the year 2020, termed subsea factories [2,3]. Robust IMR techniques and development of autonomous underwater vehicles is needed to maintain these future subsea factories [4]. Introduction of autonomy in subsea IMR operations may reduce uncertainties faced in current IMR operations by employing remotely operated vehicles (ROVs) with autonomous capabilities (AROVs) to perform routine subsea intervention tasks [5]. AROVs can be defined as tethered/untethered underwater vehicles, which can function autonomously. AROVs can independently control manipulator functions, permit shared control between the vehicle and the human operator, navigate autonomously, perform self-diagnostics, and be equipped with remotely operated tool systems requiring limited operator control [6]. As an advantage, AROVs in the future can either autonomously perform selected IMR operations or can be remotely operated by a human operator, making them functionally versatile.

In the future, subsea IMR operations may be performed using closely collaborating AROVs. Autonomous underwater vehicles (AUVs) can also be envisioned to be collaborating with AROVs to assist in mapping and inspection operations. In such situations, collision risk may increase due to several autonomous vehicles working simultaneously close to the SPS. Yang [7] suggest that accidents can be classified based on three dimensions, namely uncertain occurrence, unwanted consequence and uncontrolled development. Collision accidents of AROVs with subsea infrastructure can also be classified as uncertain events, which may have serious unwanted consequence if their development is not controlled.

According to Huffman [8], accidents in autonomous systems can be avoided if the system is running within safe operating parameters. However, the increase in risk of collision may endanger functional capabilities of both the AROV and the SPS. In worst cases, impact energies of vehicular collision with sensitive equipment of the SPS may lead to structural damage and, in worst case, to hydrocarbon release. At present, requirements to avoid subsea collisions safely using systems to locate obstacles in the subsea environment, such as rocks, wrecks, pipelines, and offshore structures are recommended [9].

Currently, human operators perform a variety of subsea intervention operations using ROVs, thereby acting as an integral part in avoiding underwater collisions with the subsea infrastructure and the seabed. Human operators use standard user interfaces, which display a live camera feed from the ROV and the relative velocity, position, and heading of the ROV, etc., in the control room of the intervention vessel. With the future introduction of AROVs, this process may change by the emergence of intelligent AROV control systems. Consider a scenario where an obstacle is detected in the AROV path. What should the AROV do? As fundamental as it sounds, knowing what action the AROV can perform either autonomously or by inputs from human supervisors is one of the important challenges to overcome when ensuring subsea asset safety.

In the automobile industry, safe spatial areas are termed safe driving envelopes, where a predefined envelope of the vehicle and obstacles are used to set collision avoidance behavior [10,11]. In the maritime industry, ship domains are used to identify safe areas around the ship [12–14]. In the aviation industry and space industry, safety envelopes are also used to avoid midair collisions and collisions with space debris, respectively [15–17]. Currently, safe envelopes for underwater vehicles and traffic rules required to avoid subsea collisions do not exist. Some recent studies show how AROVs and the SPS can be exposed to collision hazards during autonomous IMR operations [8,9]. The literature, however, lacks a definition of safety envelopes around the AROV and subsea traffic rules necessary to avoid loss of vehicle or SPS functions during collision scenarios.

The objective of this article is to develop safety envelopes and subsea traffic rules for AROVs to detect and avoid known static obstacles, based on a technology transfer approach from other industries. The two main contributions of this article are i) development of safety envelopes and subsea traffic rules applicable to AROVs and ii) simulating and demonstrating the proposed safety envelopes and subsea traffic rules through a prototype user interface. The proposed safety envelopes and subsea traffic rules can be used during IMR operations and may improve situation awareness of the human supervisors and the AROV during different collision scenarios. The proposed subsea traffic rules can assist in determining the maneuvering action of the AROV when obstacles are detected in the safety envelopes.

The article extends the work by Candeloro et al. [20] in which simple traffic rules applied to AUVs are proposed by combining collision regulations from the aviation and marine industries. The term safety envelope in this article is defined as a 3D spatial area around the underwater vehicle, which forms a virtual protective barrier (in space and time) against collision with known and unknown obstacles in the subsea environment, influencing the behavior of the AROV.

The article is structured as follows: Section 2 describes the development process used in this article. Section 3 provides a description and implementation of the safety envelopes in a simulator and during a live lab test. Observations from the laboratory test are described in Section 4. The observations are discussed in Section 5, followed by conclusions in Section 6.

1.1 Scope of the Article

Obstacles in the subsea environment can be categorized into four distinct types as illustrated in Figure 1. Static obstacles and moving obstacles both can be either a known or an unknown obstacle to the AROV.

The application of the proposed safety envelopes and subsea traffic rules can encompass all four types of obstacles either using the local sensor system on the AROV or other external sensors in the subsea environment. If active sensor readings from the AROV are available (e.g., sonar data), even unknown obstacles can be categorized as known obstacles. AROVs are required to approach known and static subsea structures to perform the IMR operations. Avoiding AROV collisions with known static subsea structures is vital to ensure safe IMR operations. Therefore, the scope of the proposed safety envelope and traffic rules in this article are limited to cover static known obstacles in the subsea environment, as highlighted in the green box in Figure 1.

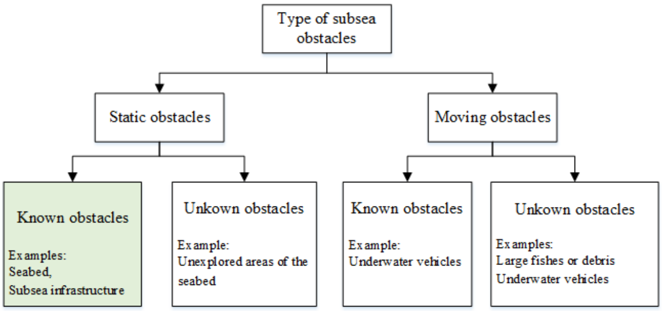

Figure 1. Scope of the article.

2. Method

Figure 2 illustrates the process used in the article to develop the safety envelopes and subsea traffic rules for the AROV. The process can be divided into three main parts; the first focusing on the development of the safe traffic rules, the second addressing the properties of the safety envelopes, and the third the decision options and selection by the AROV. The development of the rules and envelopes is explained more in detail in the following subsections

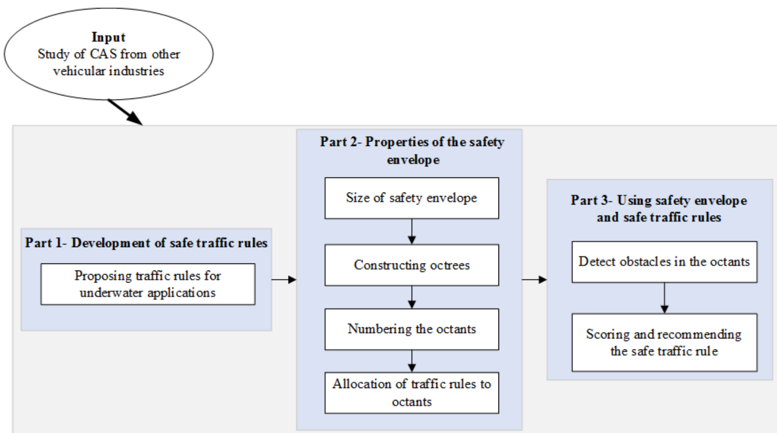

Figure 2. Developing safe underwater traffic rules and safety envelopes and application during IMR operation. CAS is collision avoidance system.

2.1. Input - Study of Collision Avoidance System from Other Vehicular Industries

The knowledge on CAS from the maritime industry, aviation and space was first collected and adapted to underwater vehicles.

2.1.1. Ship domain in the maritime industry

Fuji & Tanaka [12] present the concept of ship domain to aid marine traffic modelling. Goodwin [13] defined the term ship domain as the "sea around the ship, which the navigator would like to keep free, with respect to other ships and fixed objects". Goodwin [13] describe three different zones of a ship domain; namely starboard sector, port sector and astern sector. The three zones are as illustrated in Figure 3. Davis et al. [14] propose an improved ship domain by smoothening the area covered by the different sectors of the ship domain by placing a phantom ship at the center of the domain and placing the ship in an offset position from the phantom ship. The areas covered by the three zones from Goodwin [13] match the area covered by the three zones from Davis et. al. [14]. This simplification is used to allow for practical ship domain calculations [21]. It is to be noted that, terms like collision diameters and encounter areas, are also used as synonyms for the term ship domain in the literature [12,22]. Tam et al. [21] review various methods proposed to determine the optimal ship domain and collision avoidance using statistical, analytical and artificial intelligence (AI) methods. According to Pietrzykowski, & Uriasz [23], ship domains provide two key advantages: first, ship domains can estimate navigational risk and suggest safe trajectories. Second, ship domains can specify a time window in which the collision avoidance maneuvers is executed.

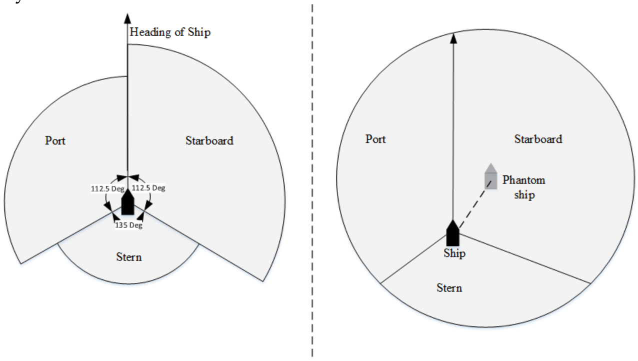

Figure 3 Examples of a ship domain as described by Goodwin [13] and Davis et. al. [14]

In summary, ship domains can support the decision making process of the ship navigators. Along with ship domains, regulations to follow during collision scenarios is also well documented for surface maritime vessels and is described in the following subsection.

2.1.2. *Collision regulations for maritime vessels*

The International Maritime Organization [24] provides rules to avoid collisions between two or more maritime vessels at sea. Collision regulations (COLREGs) provide a broad set of rules, which a vessel needs to satisfy, especially when there is a risk of collision. Rules 7 and 8 describe the scenarios where the risk of collision must be considered and describes the required action to avoid collision, respectively. Rules 13, 14, and 15 describe the maneuver the ships shall make during overtaking, head-on, and crossing scenarios. Rules 16 and 17 describe the actions that a give-way vessel and stand-on vessel need to take, respectively. Figure 4, Figure 5, and Figure 6 illustrate Rules 13-17, as described by the International Maritime Organization [24]. In the marine industry, the obstacle detection system is dependent on a functioning radar unit and the automatic identification system (AIS), which detects nearby vessels and their relative positions and velocities to the vessel. The fundamental aim of the COLREGs is to try to increase the horizontal separation distance between two marine vessels, which can be observed from Rules 13-17 of COLREGs.

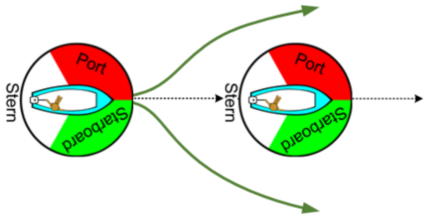

Figure 4. Rule 13 of COLREGS

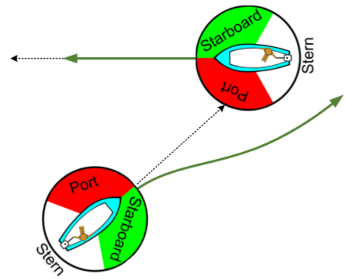

Figure 5. Rules 15, 16, and 17 of COLREGS.

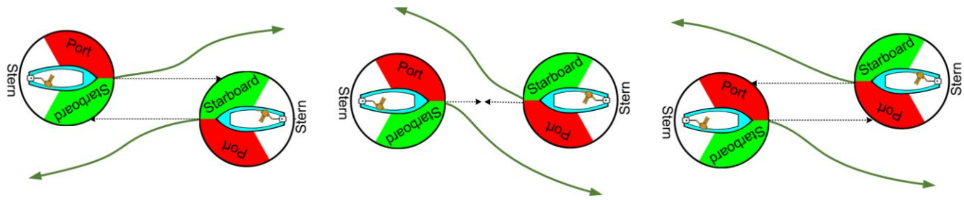

Figure 6. Rule 14 of COLREGs [24].

2.1.3. *Collision avoidance regulations in aviation*

Due to the inherent nature of aviation operations and the potential risk to human lives, collision risk is addressed extensively in the aviation industry. Traffic collision avoidance systems (TCASs) can detect, assess and recommend corresponding corrective actions to avoid midair aircraft collisions [16,17]. The TCAS system is based on three fundamental modules; namely, the surveillance module, threat detection and display module, and threat resolution module. The surveillance module is tasked with detecting the intruding aircraft and obtaining its relative velocity, position, and heading. This is carried out by a set of surveillance sensors (transponders) on board the aircraft. When the intruding aircraft is assessed as a threat by the threat detection module, a traffic advisory alert is issued to the pilots. If the threat persists, an appropriate response is suggested by the threat resolution module of the TCAS in the form of a resolution advisory.

Figure 7 illustrates the TCAS envelopes, which consists of a caution envelope, which is approximately 20 to 48 s away from the intruding aircraft. A secondary envelope is the warning area where the resolution advisory is suggested and is 15 to 35 s away from the intruding aircraft. The recommended vertical separation is 850 ft both at the lower and upper regions of the aircraft for the caution area. The vertical distance covered by the warning area is 600 ft in both upper and lower directions of the aircraft [17]. The recommended vertical and horizontal separation is followed during normal flights and after an evasive maneuver is performed.

The presence of TCAS in the intruding aircraft triggers a protocol to avoid the same threat response recommendation to both aircrafts. The safety function of the TCAS system is to prevent midair collisions by monitoring vertical and horizontal separation between aircrafts. The human pilots execute the response suggested by the TCAS. Other than the TCAS envelopes, some national and international airspace may be classified as restricted airspace and no fly zones. The area of no fly zones can change depending on various geopolitical issues. For this reason, legal no fly zones are not included to describe aviation regulations in this section.

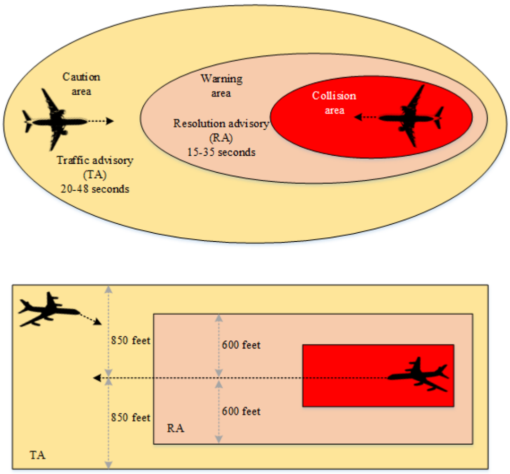

Figure 7. Safety envelopes in aviation traffic collision avoidance systems (TCAS- II) [17]

2.1.4. *Collision avoidance in space*

In the space industry, as the space shuttle orbits, the space control center scans for debris in space that could collide with the space shuttle. There are two envelopes of different sizes that are used to safeguard the space shuttle, as illustrated in Figure 8. The space surveillance network (SSN) calculates intruding objects within the area of 10 km x 50 km x 10 km, known as the alert box (illustrated in yellow). If a threat is detected, the SSN estimates the possibility of the object intruding the maneuver box (orange box), which covers an area of 4 km x 10 km x 4 km around the space shuttle [25].

If the risk of collision is greater than the operational effects of the maneuver, an avoidance maneuver as stated in the Debris Avoidance Criteria for Predicted Conjunctions shall be performed. The probability of collision in the yellow threshold area is set to 10-5 but less than 10-4, and probability of collision in the red threshold is set to greater than 10-4 [15].

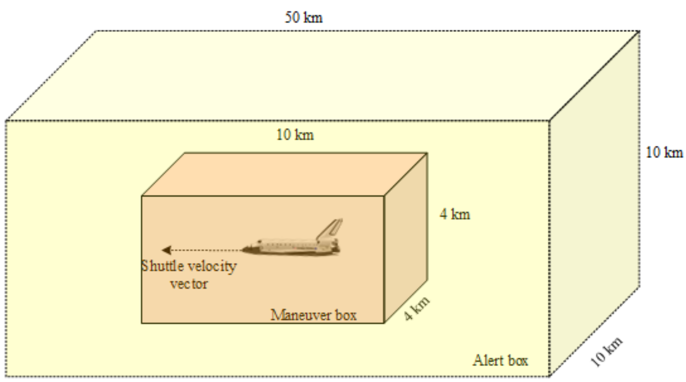

Figure 8. Shuttle alert and maneuver boxes adapted from National Research Council [25].

2.1.5. *Collision avoidance methods for autonomous underwater vehicles*

In the past, occupancy-based CASs have been proposed for underwater applications. Table 1 lists various literature describing the collision detection and avoidance methods developed for AUV applications. Among the reviewed literature, only one article describes the development of collision avoidance rules to be applied by the underwater vehicle when an obstacle is detected [20], as previously mentioned.

Since the proposed underwater navigation rules in this article are based on a grid occupancy method, review of other CAS methods, such as image processing techniques and simultaneous localization and mapping (SLAM), are deemed to be out of the scope of this article. The grid occupancy method is chosen for two main reasons: first, as observed by Ganesan et al. [26], a local grid-based envelope on the frame of the underwater vehicle makes the performance of the proposed obstacle detection and traffic rule suggestion insensitive to underwater vehicle's positioning error increase. Second, the detection of obstacles does not need to be in high resolution as it does in other methods (i.e., if information of detailed shape of the obstacles is known (known obstacles) only the grids occupied by the obstacles are of interest).

Table 1. Summary of literature review on underwater collision avoidance based on 2D and 3D grid occupancy methods.

Method	Publications	Description	Proposed subsea traffic rules	Recommended size of safety envelope
3D Grid Occupancy	Fairfield et al. [27]	Present a SLAM-based method to explore underwater caves and tunnels. Octree data structure is used to reduce processing and storage requirements.	No	No
	Horner et al. [28]	Present a method to combine sonar images in a horizontal and vertical plane to a single 3D model. This model plans a path where the grid cells are not occupied by obstacles.	No	No
	Zhang and Jia [29]	Present a reactive path-planning method by combining octree and improving the ant colony algorithm to avoid obstacles in a 3D grid.	No	No
	Vallicrosa et al. [30]	Present an occupancy grid-mapping method using the Octomap library. The resulting map is used in terrain-based navigation of the Girona 500 AUV. A multibeam sonar is used as a sensor and the sonar data is compared with the known map.	No	No
	Hernández et al. [31]	Present a framework for planning paths free of collision for AUV applications. An octree is used to represent the environment.	No	No
	Huang et al. [32]	Present a method to solve multi-AUV hunting issue using the bio-inspired neural network in a 3D environment. A neural network is used as a guidance system to avoid collisions. The application is focused on moving obstacles.	No	No
	Ganesan et al. [26]	Present an obstacle detection and avoidance algorithm for AUVs using a local occupancy grid on an AUV frame and probabilistic approaches to avoid false alarms and noise/clutter in the sonar data. The obstacles are detected in the AUV local occupancy grid.	No	No
	Candeloro et al. [20]	Present a 3D dynamic path-planning system for AUVs using 3D Voronoi diagrams and Dublin's path along with underwater traffic rules.	Yes	No
2D Grid Occupancy	Martin et al. [33]	Present a grid occupancy search method to detect obstacles underwater when using a forward-looking sonar.	No	No
	Jakuba and Yoerger [34]	Present a method to identify hydrothermal vents using hydrothermal tracer data collected by an AUV using occupancy grid mapping.	No	No
	Hernández et al. [35]	Present algorithms to design a new motion control system for a reactive obstacle avoidance applied to an AUV. Sonar scans are fused to an occupancy grid-mapping algorithm.	No	No
	Zhu et al. [36,37]	Present a biologically inspired neural dynamics and map planning method. Readings from ultrasonic sensors are fused to a 2D occupancy grid.	No	No

2.2 Part 1 - Development of Subsea Traffic Rules

In principle, the collision avoidance rules in the maritime and aviation industries recommend increasing the horizontal or vertical separation distance between the obstacle and vehicle. The same logic can be applied to AROVs, wherein the obstacle can occupy a given spatial area around the AROV, and the AROV attempts to avoid the obstacle by increasing either the horizontal or vertical distance from the obstacle.

2.2.1 Proposing traffic rules for underwater applications

From Table 2, referring to Rule 1, the obstacle is to the left side of the AROV. According to COLREGS, the vehicle needs to move to the right. In Rule 1, the obstacle is above the AROV. The TCAS would recommend the vehicle to move down or descend. When these two behaviors from the COLREGs and TCAS are incorporated for other scenarios, it leads to a set of rules to avoid known static obstacles, as listed in Table 2.

Table 2. Traffic rules developed to avoid known static obstacles in the subsea environment.

Rule No.	**Condition**	**Horizontal Position of Obstacle**	**Vertical Position of Obstacle**	**Recommended Evasive Action**
1	If obstacle	Front left	Above	AROV turn right and descend
2	If obstacle	Front left	Same altitude	AROV turn right and climb
3	If obstacle	Front left	Below	AROV turn right and climb
4	If obstacle	Front right	Above	AROV turn left and descend
5	If obstacle	Front right	Same altitude	AROV turn left and climb
6	If obstacle	Front right	Below	AROV turn left and climb
7	If obstacle	Front	Above	AROV turn right and descend
8	If obstacle	Front	Same altitude	AROV turn right and climb
9	If obstacle	Front	Below	AROV turn right and climb
10	If obstacle	Adjacent left	Above	AROV turn right and descend
11	If obstacle	Adjacent left	Same altitude	AROV turn right and climb
12	If obstacle	Adjacent left	Below	AROV turn right and climb
13	If obstacle	Adjacent right	Above	AROV turn left and descend
14	If obstacle	Adjacent right	Same altitude	AROV turn left and climb
15	If obstacle	Adjacent right	Below	AROV turn left and climb
16	If obstacle	Rear left	Above	AROV turn right and descend
17	If obstacle	Rear left	Level	AROV turn right and climb
18	If obstacle	Rear left	Below	AROV turn right and climb
19	If obstacle	Rear right	Above	AROV turn left and descend
20	If obstacle	Rear right	Same altitude	AROV turn left and climb
21	If obstacle	Rear right	Below	AROV turn left and climb
22	If obstacle	Rear	Above	AROV turn right and descend
23	If obstacle	Rear	Same altitude	AROV turn right and climb
24	If obstacle	Rear	Below	AROV turn right and climb
25	If obstacle	Center	Above	AROV turn right and descend
26	If obstacle	Center	Below	AROV turn right and climb
27	If obstacle	Center	Same altitude	Stop – Collision Alert

2.3. Part 2 - Properties of the Safety Envelope

The AROV and subsea infrastructures are assumed to be the equipment under control (EUC) during the subsea interventions. The EUC is defined as equipment, machinery, apparatus, or plant used for manufacturing, process, transportation, medical, or other activities [38]. A safety instrumented function

(SIF) is a safety function with a specified safety integrity level, which is necessary to achieve functional safety. A SIF can be either a safety instrumented protection function or a safety instrumented control function [39]. Since the function of CAS is to protect the AROV and subsea structures from collisions, the CAS of the AROV can be assumed to be one of the SIFs within the safety integrated system of the AROV. The following subsections describe the development of the proposed safety envelope.

2.3.1 Size of safety envelope

A detection area around the AROV is needed to identify intruding obstacles by the underwater CAS. However, the size of the safety envelope needs to be either predefined for known obstacles or optimized to cater for unknown obstacles. An optimized safety envelope size decreases the computational time required to detect obstacles in the AROV path. Since the AROV can move in all three directions (x, y, z), a cuboid-shaped safety envelope is proposed in this article.

Static safety envelope

Static envelopes can be used when the AROV approaches known obstacles. Some IMR operations may require AROVs to be able to move close to the subsea structure, like Christmas trees and manifolds. Therefore, the AROV should have a system to avoid or minimize the likelihood of close contact collisions while approaching known obstacles. The process safety time (PST) is used to recommend a static safety envelope. The PST is the period between a failure occurring in the process or the basic process control system (with the potential to give rise to a hazardous event) and the occurrence of the hazardous event if the SIF is not performed [39].

Figure 9, based on [40], illustrates the various time periods included in the PST. The green area in the figure refers to the process variable within safe limits. For example, as process variable in AROV operations can be the position of the AROV. An initiating event occurs when the process variables shifts from a safe limit. When a SIF threshold is reached, the SIF activates and starts to perform the predefined safety function. The PST in this article is a union of time to trip (TTT), SIF response time (SRT), and safety margin time (SMT).

Table 3 allocates time budgets to each of the time parameters illustrated in Figure 9. The SRT starts when the process is at the trip point and ends when the final elements reach safe state and prevent the hazard [39]. A trip point represents the start of the SIF response time [40]. For example, AROV CAS reaches a trip point when an obstacle is detected in the safety envelope.

Table 3. Allocating time budgets to underwater CAS tasks.

Time Budgets	**Description**	**Applied to AROV CASs**	**Allocated Time Budgets in Seconds**
Time to trip (TTT)	Time taken from an observed process deviation till the activation of SIF.	Time taken to detect an obstacle and recommend a safety rule.	1
SIF response time (SRT)	The response time requirements for the safety instrumented system to bring the process to a safe state.	Time taken by the CAS to perform the required avoidance action and observe the success of the chosen obstacle avoidance maneuver.	3.5
Safety margin time (SMT)	The buffer time allotted to the process response time.	A buffer time in addition to the process response time.	0.5
Process safety time (PST)	Total time available to safeguard the EUC from a hazard.	Total available time to avoid a collision with the obstacle.	5

To recommend a static safety envelope, the AROVs velocity is assumed to be 0.5 m/sec when it approaches known obstacles. Considering the allocated time budget for the process response time (i.e., 5 seconds in

Table 3), the static safety envelope is calculated to be 2.5 m. The AROV can move 2.5 m in 5 seconds with a velocity of 0.5 m/s. This provides the AROV with 2.5 m of safety envelope area (cube-shaped) along the three directions of movement. The overall safety envelope size is therefore a 5-m cube, and the AROV is placed in the center of the envelope.

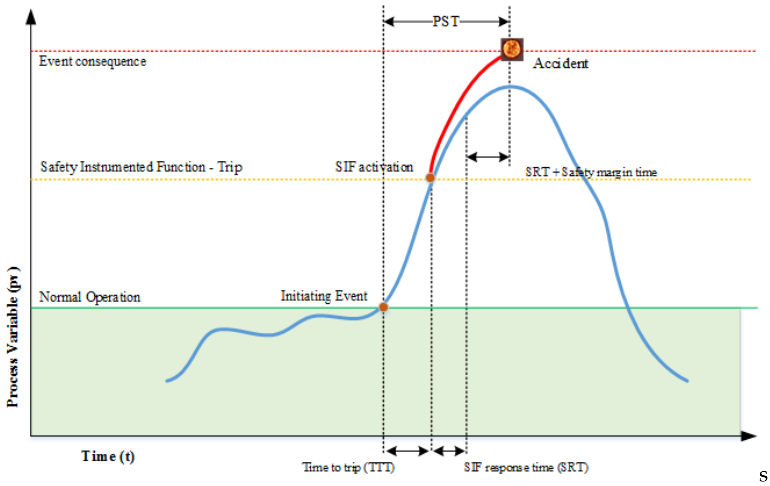

Figure 9. Time budgets for the process safety time, as defined by [40].

2.3.2 Constructing Octrees

A local 3D spatial grid around the AROV has been constructed using octrees. Octrees are recursive tree structures consisting of spatial cubes termed octants. Each parent cube can be divided into eight different octants, and the process can be continued until a suitable level of resolution is reached. According to Hornung et al. [41], octrees allow volumetric representation of 3D environments and can build 3D models. Octrees allow the increase or decrease of the resolution of the detection area required around an object. Octrees allow probabilistic representation of data measurements from multiple sensors (i.e., measurements from multiple sensors can be fused to update evidence of occupied grid cells). With inputs from active or passive sensor readings, octress can be used to detect obstacles in both known and unknown areas in the subsea environment.

Constructing an octree allows organization of the spatial grid around the AROV. The obstacle can either be to the right, left, front, or rear of the AROV in the horizontal axis. In the vertical axis, the obstacle is either above, below, or at the same altitude of the AROV. To include both horizontal and vertical spaces, the spatial grid around the AROV is modeled as a 5 m x 5 m x 5 m cube (i.e., an octree of level 2). The AROV is assumed to be in the center of the constructed octree, as illustrated in Figure 10. In level 0, there is one cube. In a level 1 octree, there are eight cubes, and in a level 2 octree, there are 64 cubes. The individual cube size in level 0, level 1, and level 2 are 5, 2.5, and 1.25 m, respectively.

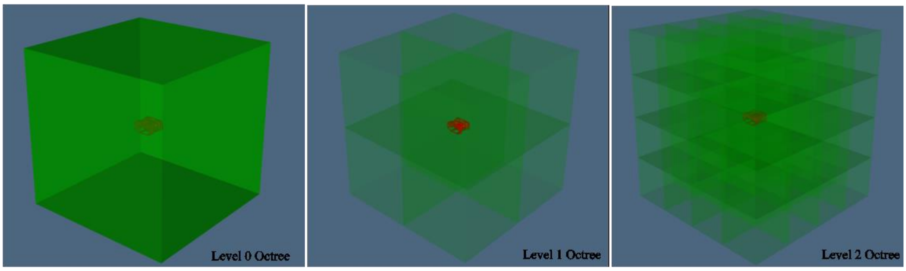

Figure 10. Construction of octree level 0, level 1, and level 2 with AROV positioned in the center.

2.3.3 Numbering the octants

The octants from a level 2 octree need a unique identifier for two reasons: first, the detection algorithm can identify the octants occupied by an obstacle using the numbered octants. Second, numbering the octants is performed to link a specific traffic rule to each octant. In Figure 11, the orange shaded octants represent occupancy by AROV, and any obstacle intruding into these octants are assumed to be colliding with the AROV, which obviously is not a favorable condition. The detection algorithm continuously scans the octants for occupancy by an obstacle.

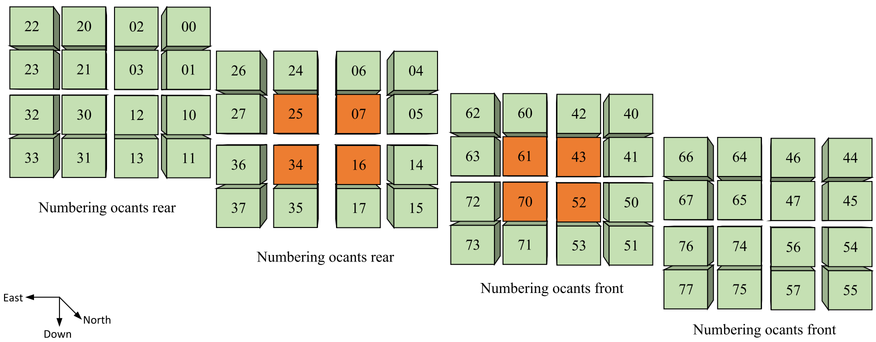

Figure 11. Construction of octree level 0, level 1, and level 2 with AROV positioned in the center

2.3.4 Allocation of subsea traffic rules to octants

The numbered octants are linked with the rules proposed in Table 2. Each octant is checked for its relative position with the AROV. For example, in Figure 11Octant 66 is to the right side of the AROV and above the AROV. This relative position of Octant 66 is checked against Table 2 conditions, which results in Rule 4 (i.e., turn left and descend). The same process is repeated with all other octants. Table 4 lists the octants and the corresponding subsea traffic rules.

Table 4. Allocating subsea traffic rules to the octants of the octree.

Octant	Safe Traffic Rule	Octant	Safe Traffic Rule	Octant	Safe Traffic Rule
00	Turn right and descend	26	Turn left and descend	54	Turn right and climb
01	Turn right and climb	27	Turn left and climb	55	Turn right and climb
02	Turn right and descend	30	Turn right and climb	56	Turn right and climb
03	Turn right and climb	31	Turn right and climb	57	Turn right and climb
04	Turn right and descend	32	Turn left and climb	60	Turn right and descend

05	Turn right and climb	33	Turn left and climb	61	Stop – Collision Alert
06	Turn right and descend	34	Stop – Collision Alert	62	Turn left and descend
07	Stop – Collision Alert	35	Turn right and climb	63	Turn left and climb
10	Turn right and climb	36	Turn left and Climb	64	Turn left and descend
11	Turn right and climb	37	Turn left and climb	65	Turn right and climb
12	Turn right and climb	40	Turn right and descend	66	Turn left and descend
13	Turn right and climb	41	Turn right and climb	67	Turn left and climb
14	Turn right and climb	42	Turn right and descend	70	Stop – Collision Alert
15	Turn right and climb	43	Stop – Collision Alert	71	Turn right and climb
16	Stop – Collision Alert	44	Turn right and descend	72	Turn left and climb
17	Turn right and climb	45	Turn right and climb	73	Turn left and climb
20	Turn right and descend	46	Turn left and descend	74	Turn right and climb
21	Turn right and Climb	47	Turn right and climb	75	Turn right and climb
22	Turn left and descend	50	Turn right and climb	76	Turn left and climb
23	Turn left and climb	51	Turn right and climb	77	Turn left and climb
24	Turn right and descend	52	Stop – Collision Alert		
25	Stop – Collision Alert	53	Turn right and climb		

2.4 Part 3 - Using the Safety Envelope and Subsea Traffic Rules

The constructed safety envelope should detect intrusions into it. Every intrusion (occupancy) is then compared to the rule allocated to the occupied octant, and a relevant traffic rule is suggested.

2.4.1 Detect obstacle in the octants

It is assumed that a subsea environment model exists with seabed and subsea infrastructure and that the position and orientation of the AROV is known. Typical objects in the model are the subsea templates. The next step is to position the safety envelope. This is done by translating and rotating the envelope in the subsea world model so that the center of the envelope is at the same position and orientation in the subsea environment model similar to the AROV position and orientation.

With the envelope octree positioned in the correct location in the subsea environment model, we first check whether there is a collision between the outline box of the envelope and objects. The collision check is a geometrical check that assesses whether there is an overlap between the objects in the present moment [42]. If there is, the algorithm goes on checking collisions between each octant of the envelope and the obstacle in the subsea model. Table 5 shows the pseudocode of the detection algorithm.

Table 5. Pseudocode of detection algorithm

```
Function collisionCheck

Get position of AROV
Get orientation of AROV
position envelope at position
rotate envelope to orientation
make empty list collisions
IF envelope collides with world
        FOR EACH octant in envelope:
                IF octant collides with world
                        ADD octant name to collisions
RETURN collisions
```

2.4.2 Scoring and recommending the safe traffic rule

If the identified obstacle occupies more than one octant at a given time, this may lead to contradicting predictions from the proposed CAS. To avoid this, a scoring approach is established, which recommends the most appropriate rule by a voting scheme. The assumption in this section is that the detection algorithm can relay the occupied octant from the obstacle. The detection algorithm provides the number of the octant, which is occupied by the obstacle.

In Table 4, each octant is linked to one rule for horizontal separation (i.e., left or right), and one rule for vertical separation (i.e., climb or descend). The horizontal separation rules and vertical separation rules are scored independently for all octants where a collision is detected. The result is that each of the four possible avoidance maneuvers gets a score. Based on the score, one vertical and one horizontal rule are chosen.

For example, if the obstacle occupies octant 40, 41, and 42, the rules of octant 40, 41, and 42 are checked. Octant 40 and 42 share the same rule (i.e., turn right and descend), and the rule for octant 41 states "turn right and climb." The scoring algorithm aggregates to three votes for "right," two votes for "descend," and one vote for "climb." The final suggested traffic rule will be "turn right and descend."

3. Application of Proposed Underwater CAS in the Simulator and Laboratory

The proposed safety envelope and traffic rules have been tested in a simulator environment and in an ocean laboratory (lab). The objective of the test was to verify whether the proposed safety envelopes can detect the obstacle present in the vicinity. The second part of the test was to confirm that the scoring algorithm recommended the correct traffic rule to the CAS. In both the simulator and lab demonstrations, known objects were placed in the path of the AROV to represent known obstacles. Depending on the relative position of the obstacle, the expected outcome should reflect one of the rules presented in Table 4. It was expected that, with a change in the direction of the AROV motion, the rules would change accordingly.

3.1 Application in the MORSE Simulator

To test the logic, a simulator setup was made in the underwater MORSE simulator [43]. The main objective of the setup was to test the logic of collision detection and rule-based advice of the proposed underwater CAS.

In the simulator, several obstacles were modeled. To get a visual representation of the collision detection module during testing in the simulator, a visual representation of the envelope in the simulation was added. This representation is shown in Figure 12. The visualization shows all octants in the envelope. When no collision is detected in an octant, the octant is represented with a green shade. When a collision is detected, the octant color changes to red.

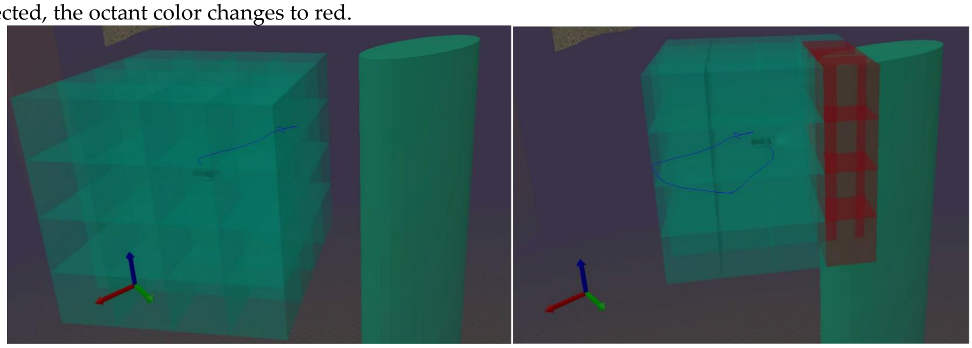

Figure 12. Underwater CAS in the underwater MORSE simulator.

3.2 Setup in the Ocean Laboratory

Figure 13 illustrates the overall laboratory setup. The AROV supervisor area consisted of a human-machine interface in the form of a joystick and two visualization screens (the live video feed from AROV and the virtual representation of the safety envelope). The safety envelope and traffic rules are two aspects of the CAS. The Qualisys motion sensor system relayed the current position and orientation of the AROV and the AROV panel.

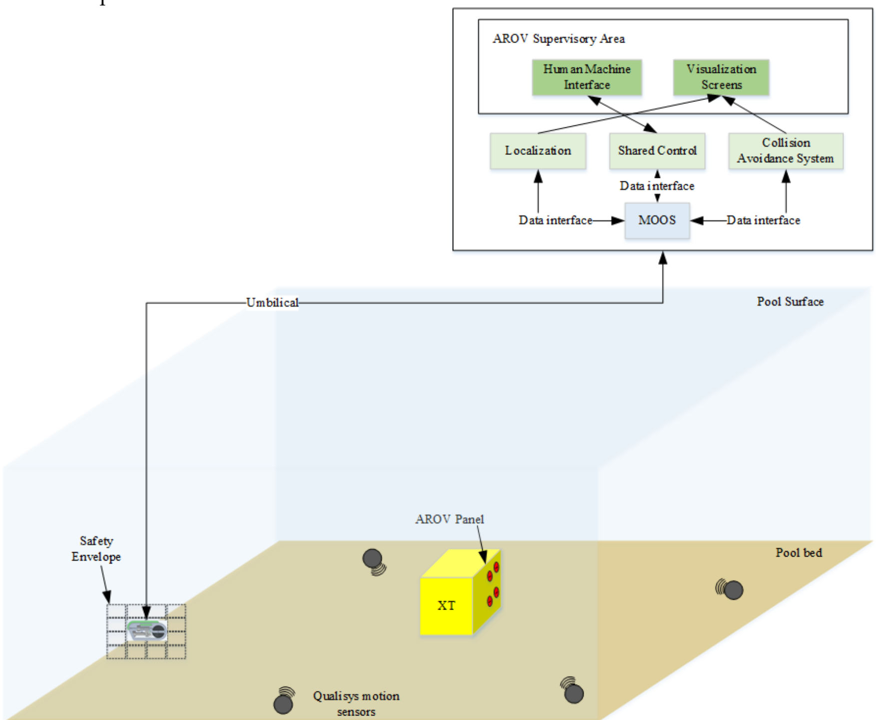

Figure 13. MOOS interface to gather position data of obstacle and the AROV during laboratory tests.

The Mission Orientated Operating Suite (MOOS) middleware was used to pass information between the Qualisys motion sensor systems, onboard vehicle sensors, guidance and control functions for the vehicle, and the CAS. This was done in MOOS in the form of a publish-subscribe pattern [44]. The localization module publishes the orientation and position of the AROV. The umbilical provides a communication link to the AROV. To verify the real-time feasibility of the proposed safety envelopes and subsea traffic rules, laboratory tests were performed. The aim was to verify whether the suggested traffic rules matched the proposed traffic rules.

4. Results

In Figure 13, as the AROV flies around the Christmas tree (XT), the collision detection algorithm provides a continuous update on corresponding colliding octants. The colliding octants are linked to the octant numbers, as described in Section 2.3.3 to derive the appropriate safe traffic rule. Table 6 lists the different data points collected during laboratory tests. The column "Collision Detected in Octant" lists the octants, which have detected a collision with the obstacle. The octants, which are detected as colliding with the obstacle are compared with the proposed ruleset. After the scoring algorithm evaluates and selects the optimal traffic rule, the traffic rule is displayed in the user interface as shown in Figure 14.

Table 6. Verification of proposed traffic rules during laboratory tests.

Data Point	Collision Detected in Octant	Proposed Traffic Rule	Traffic Rule Suggested in Lab Tests
1	43	Stop-Collision alert	Stop-Collision alert
2	61	Stop-Collision alert	Stop-Collision alert
3	63	Turn left and climb	Turn left
4	43 61	Stop-Collision alert	Stop-Collision alert
5	61, 63	Stop-Collision alert	Stop-Collision alert
6	27, 61, 63	Stop-Collision alert	Stop-Collision alert
7	25, 43, 61	Stop-Collision alert	Stop-Collision alert
8	7, 25, 43	Stop-Collision alert	Stop-Collision alert
9	43, 52, 61, 70	Stop-Collision alert	Stop-Collision alert
10	34, 70, 7, 43, 16, 52, 25, 61	Stop-Collision alert	Stop-Collision alert

Data Point 2 in Table 6 shows that the CAS also suggests the "Stop-Collision alert" traffic rule. The traffic rule suggested in the lab test for Data point 3 in Table 6 is limited to only horizontal separation (turn left) because, during the implementation of CAS in the lab, the minimum depth constraint to maneuver the vehicle was 0.5 m from the pool surface. Therefore, the vertical separation logic is annulled and the suggested rule only considers the horizontal separation rule. The traffic rules suggested for the other eight data points correctly correspond to the proposed traffic rules from Table 4 in addition to detecting obstacles and suggesting subsea traffic rules, the user interface also displays the operations to be performed in the lower left corner.

Figure 14 illustrates the user interface developed to demonstrate the proposed underwater CAS. The illustration to the left shows the AROV in the center of the screen with octants in green, when no obstacles are detected. In the figure to the right, the AROV moves toward the AROV panel, and the AROV panel is detected as an obstacle in Octant 61, which relates to the traffic rule "Stop-Collision alert."

The level of autonomy in the shared control system is also highlighted in the display. When the human operator takes over control of the AROV, the control is displayed as human control. In Figure 14, the control mode is displayed as semi-autonomous, which refers to limited intervention from the human operator. The safety envelope and the AROV in the user interface mimic real-life orientation and rotational movement of the AROV during the laboratory test.

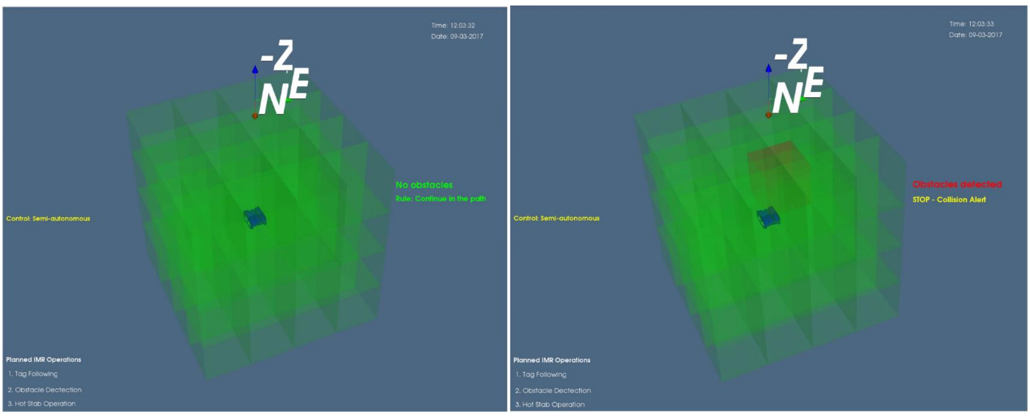

Figure 14. User display of the underwater CAS during live pool demonstration.

5. Discussion

The following observations were made during the development and testing phase of the proposed underwater CAS and require further discussion:

- Advantages of the proposed underwater CAS
- Vehicle-specific traffic rules and safety envelopes
- Application of CAS to static and moving underwater obstacles
- Proposed underwater CAS is dependent on reliable sensor inputs
- From suggesting to executing the traffic rule

5.1 Advantages of the Proposed Underwater CAS

From Goodwin [13], it can be observed that ship domains were developed based on lessons learned from the safety envelopes in the aviation industry. The maritime industry in the 1970s was in need to ensure safety of ships and the crew. The current need for AROV safety envelopes can be compared to the need of ship domains in the 1970s. It can also be noted that the properties of ship domains have changed and improved continuously to this day. The properties of the proposed safety envelopes for AROVs, such as shape, size and logic may also be changed and improved with future research work.

By providing the AROV with both vertical and horizontal separation traffic rules, the proposed subsea traffic rules are conservative. When the scores are tied, the scoring algorithm chooses either vertical or horizontal separation rule. For example, the suggested rule in Data point 3 of Table 6: if the suggested rules by the CAS in Data point 3 of Table 6 was "turn left and climb", the AROV would have to rise to the pool surface. Instead, the scoring algorithm sonly choses the horizontal separation rule "turn left". This heuristic scoring has two advantages: first, the minimum and maximum vertical depth and horizontal travels can be defined. Second, the suggested rule will always ensure separation from the obstacle in at least one of the two axis.

Traditional ROV information screens display the live video feed from the ROV, the relative location of the ship, the relative heading of the AROV, and the thruster allocation. During operation, the human operator must rely on his/her expertise to detect obstacles and avoid them. To ascertain the depth in a 2D screen is a challenge. Human operators have a more supervisory role when operating ROVs with some degree of autonomy (AROVs). The operator would have to rely on the information screens to make an informed decision to override the autonomous control. The use of safety envelopes and proposed subsea traffic rules may promote situation awareness of the human supervisor and AROV by making the choice of rules more transparent to the human supervisor (i.e., showing the traffic rule suggested and/or executed by the AROV in real time).

5.2 Vehicle Specific Traffic Rules and Safety Envelopes

In this article, the safety envelopes and the traffic rules have been developed to suit an AROV application. However, if the safety envelopes and traffic rules need to be applied to other underwater vehicles, such as AUVs or gliders, the properties of the safety envelopes and the traffic rules will be different, as these vehicles differ in size and thruster allocation. Therefore, both safety envelope properties and traffic rules must be adapted to suit the type of vehicle being considered.

Consider a scenario where an AROV and an underwater glider detect each other as obstacles. The underwater glider may have limited propulsion abilities to avoid a collision. In such circumstances, it is expected that the traffic rules governing the two vehicles will consider the vehicles' size and propulsion limitations and consider the functional limitations before suggesting a safe traffic rule.

5.3 Application of CAS to Static and Moving Underwater Obstacle

In the given examples, it must be noted that the proposed safety envelopes and traffic rules are limited to known subsea static obstacles and therefore do not extend to moving obstacles, as shown in Figure 1.

Adaptations are necessary if the proposed CAS is to be extended to known and unknown moving obstacles. For unknown static obstacles, sensors and the sensing module must be reliable and accurate to detect never-before-seen obstacles.

For known moving obstacles, the sensing module needs to relay the position of vehicles to each other. This way, both vehicles know the state and thrust capabilities of each other. When the vehicles have limited moving abilities (for example an AUV), the vehicle with a higher degree of freedom should execute the evasive maneuver. This is the same logic used in the COLREGs, when a powered vessel encounters a sailing vessel, the powered vessel needs to initiate the evasive maneuver. This is because the sailing boat has limited capability to change its heading. The traffic rules to be developed for known moving obstacles should consider such limitations.

For the unknown moving obstacle, the surveillance module of the CAS in the future will need to be able to continuously track the obstacle position, size, and velocity. Since unknown obstacles are not previously registered by the AROV, avoiding these types of obstacles can be a challenge, and techniques to track and avoid such obstacles need to be a focus in future research.

5.4 Proposed Underwater CAS is Dependent on Reliable Sensor Inputs

Fundamentally, the CAS consists of surveillance, threat detection, and threat resolution modules to avoid collision with underwater obstacles. Sensing the obstacle is the primary and key step. In this article, it was assumed that the position of the obstacle and the AROV are known deterministically during tests in the simulator. During ocean laboratory tests, the optical sensors from Qualisys motion systems were assumed to provide accurate data of obstacle and AROV positions. However, it must be noted that, during a real-life implementation of the proposed CAS, the effect of unreliable sensor inputs may provide incorrect situation awareness and may even hinder the collision avoidance capability of the AROV.

5.5 From Suggesting to Executing the Traffic Rule

Through the application of proposed underwater CAS in a simulator and via lab tests, a suggestion of movement to the AROV is provided (e.g., "Turn right and climb"). This is a suggestion given to the AROV or the human supervisor and is not a concrete action taken by the AROVs flight control system. In the future, the traffic rules suggested by the underwater CAS need to be executed by the AROV either with or without the approval of the human supervisor. This requires additional development of combining the rule base with the control system of the AROV, which is outside the scope of this article. However, the execution of the traffic rule by the AROV will depend on the agreed level of autonomy; the higher the level of autonomy, the higher the need to execute the traffic rule without human intervention.

6. Conclusions

This article proposes a novel approach to develop safety envelopes and subsea traffic rules for underwater vehicles by transferring knowledge from the maritime and aviation industries. The proposed safety envelopes and subsea traffic rules aim to avoid damage and loss of functions in the underwater vehicle and the subsea infrastructure. Safety envelopes and subsea traffic rules could be essential for future applications of autonomous remotely operated vehicles (AROVs) in subsea inspection, maintenance and repair operations.

The proposed safety envelope around the AROV is developed by the Octree method and is realized in a cuboidal shape. The recommended safe navigation rules from the maritime and the aviation industries are combined to suggest novel subsea traffic rules. The feasibility of the proposed safety envelopes and subsea traffic rules are tested by developing an underwater collision avoidance system (CAS) user interface in an in-house simulator and during laboratory tests. The results show that the proposed CAS recommends rules that match the proposed subsea traffic ruleset. Three-dimensional visualization may provide valuable information to human supervisors by visualizing the orientation of the AROV and the location of the obstacle in relation to the AROV. Both human supervisors, as well as decision makers, can benefit from knowing the possible actions the AROV can take when a random collision scenario occurs in the subsea environment.

Further research can improve the underwater CAS to not only suggest a subsea traffic rule but also to execute an evasive maneuver autonomously. Extending the proposed CAS to include unknown static, known and unknown moving obstacles (Figure 1) can also be further investigated by installing sensors on the AROV to actively detect obstacles.

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Article 6

A 3D dynamic voronoi diagram-based path-planning system for UUVs

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UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)

UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)
UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension Floating Body. (Dr.Ing. Thesis)
UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
MTA-89-63	Chang Li, MH	Force Coefficients of Spheres and Cubes in Oscillatory Flow with and without Current. (Dr.Ing. Thesis
MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
MTA-89-65	Arild Jæger, MH	Seakeeping, Dynamic Stability and Performance of a Wedge Shaped Planing Hull. (Dr.Ing. Thesis)
MTA-89-66	Chan Siu Hung, MM	The dynamic characteristics of tilting-pad bearings
MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
MTA-89-68	Jiao Guoyang, MK	Reliability Analysis of Crack Growth under Random Loading, considering Model

		Updating. (Dr.Ing. Thesis)
MTA-89-69	Arnt Olufsen, MK	Uncertainty and Reliability Analysis of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-70	Wu Yu-Lin, MR	System Reliability Analyses of Offshore Structures using improved Truss and Beam Models. (Dr.Ing. Thesis)
MTA-90-71	Jan Roger Hoff, MH	Three-dimensional Green function of a vessel with forward speed in waves. (Dr.Ing. Thesis)
MTA-90-72	Rong Zhao, MH	Slow-Drift Motions of a Moored Two-Dimensional Body in Irregular Waves. (Dr.Ing. Thesis)
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MTA-91-79	Hoen, Christopher, MK	System Identification of Structures Excited by Stochastic Load Processes. (Dr.Ing. Thesis)
MTA-91-80	Haugen, Stein, MK	Probabilistic Evaluation of Frequency of Collision between Ships and Offshore Platforms. (Dr.Ing. Thesis)
MTA-91-81	Sødahl, Nils, MK	Methods for Design and Analysis of Flexible Risers. (Dr.Ing. Thesis)
MTA-91-82	Ormberg, Harald, MK	Non-linear Response Analysis of Floating Fish Farm Systems. (Dr.Ing. Thesis)
MTA-91-83	Marley, Mark J., MK	Time Variant Reliability under Fatigue Degradation. (Dr.Ing. Thesis)
MTA-91-84	Krokstad, Jørgen R., MH	Second-order Loads in Multidirectional Seas. (Dr.Ing. Thesis)
MTA-	Molteberg, Gunnar A., MM	The Application of System Identification

91-85		Techniques to Performance Monitoring of Four Stroke Turbocharged Diesel Engines. (Dr.Ing. Thesis)
MTA-92-86	Mørch, Hans Jørgen Bjelke, MH	Aspects of Hydrofoil Design: with Emphasis on Hydrofoil Interaction in Calm Water. (Dr.Ing. Thesis)
MTA-92-87	Chan Siu Hung, MM	Nonlinear Analysis of Rotordynamic Instabilities in Highspeed Turbomachinery. (Dr.Ing. Thesis)
MTA-92-88	Bessason, Bjarni, MK	Assessment of Earthquake Loading and Response of Seismically Isolated Bridges. (Dr.Ing. Thesis)
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MTA-92-91	Ask, Tor Ø., MM	Ignition and Flame Growth in Lean Gas-Air Mixtures. An Experimental Study with a Schlieren System. (Dr.Ing. Thesis)
MTA-86-92	Hessen, Gunnar, MK	Fracture Mechanics Analysis of Stiffened Tubular Members. (Dr.Ing. Thesis)
MTA-93-93	Steinebach, Christian, MM	Knowledge Based Systems for Diagnosis of Rotating Machinery. (Dr.Ing. Thesis)
MTA-93-94	Dalane, Jan Inge, MK	System Reliability in Design and Maintenance of Fixed Offshore Structures. (Dr.Ing. Thesis)
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MTA-93-96	Karunakaran, Daniel, MK	Nonlinear Dynamic Response and Reliability Analysis of Drag-dominated Offshore Platforms. (Dr.Ing. Thesis)
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MTA-93-98	Nordrik, Rune, MM	Investigation of Spark Ignition and Autoignition in Methane and Air Using Computational Fluid Dynamics and Chemical Reaction Kinetics. A Numerical Study of Ignition Processes in Internal Combustion Engines. (Dr.Ing. Thesis)
MTA-94-99	Passano, Elizabeth, MK	Efficient Analysis of Nonlinear Slender Marine Structures. (Dr.Ing. Thesis)
MTA-	Kvålsvold, Jan, MH	Hydroelastic Modelling of Wetdeck

94-100		Slamming on Multihull Vessels. (Dr.Ing. Thesis)
MTA-94-102	Bech, Sidsel M., MK	Experimental and Numerical Determination of Stiffness and Strength of GRP/PVC Sandwich Structures. (Dr.Ing. Thesis)
MTA-95-103	Paulsen, Hallvard, MM	A Study of Transient Jet and Spray using a Schlieren Method and Digital Image Processing. (Dr.Ing. Thesis)
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MTA-95-105	Wang, Xiaozhi, MK	Reliability Analysis of Production Ships with Emphasis on Load Combination and Ultimate Strength. (Dr.Ing. Thesis)
MTA-95-106	Ulstein, Tore, MH	Nonlinear Effects of a Flexible Stern Seal Bag on Cobblestone Oscillations of an SES. (Dr.Ing. Thesis)
MTA-95-107	Solaas, Frøydis, MH	Analytical and Numerical Studies of Sloshing in Tanks. (Dr.Ing. Thesis)
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MTA-95-109	Hermundstad, Ole A., MK	Theoretical and Experimental Hydroelastic Analysis of High Speed Vessels. (Dr.Ing. Thesis)
MTA-96-110	Bratland, Anne K., MH	Wave-Current Interaction Effects on Large-Volume Bodies in Water of Finite Depth. (Dr.Ing. Thesis)
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MTA-96-112	Æsøy, Vilmar, MM	Hot Surface Assisted Compression Ignition in a Direct Injection Natural Gas Engine. (Dr.Ing. Thesis)
MTA-96-113	Eknes, Monika L., MK	Escalation Scenarios Initiated by Gas Explosions on Offshore Installations. (Dr.Ing. Thesis)
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		Thesis)
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MTA-97-118	Igland, Ragnar T., MK	Reliability Analysis of Pipelines during Laying, considering Ultimate Strength under Combined Loads. (Dr.Ing. Thesis)
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MTA-99-126	Mainçon, Philippe, MK	Fatigue Reliability of Long Welds Application to Titanium Risers. (Dr.Ing. Thesis)
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MTA-99-128	Langhelle, Nina K., MK	Experimental Validation and Calibration of Nonlinear Finite Element Models for Use in Design of Aluminium Structures Exposed to Fire. (Dr.Ing. Thesis)
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MTA-99-130	Andersen, Trond M., MM	Short Term Maintenance Planning. (Dr.Ing. Thesis)
MTA-99-131	Tveiten, Bård Wathne, MK	Fatigue Assessment of Welded Aluminium

		Ship Details. (Dr.Ing. Thesis)
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MTA-2001-144	Wang, Lihua, MK	Probabilistic Analysis of Nonlinear Wave-induced Loads on Ships. (Dr.Ing. Thesis)
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MTA-	Greco, Marilena, MH	A Two-Dimensional Study of Green-Water

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MTA-2001-147	Heggelund, Svein E., MK	Calculation of Global Design Loads and Load Effects in Large High Speed Catamarans. (Dr.Ing. Thesis)
MTA-2001-148	Babalola, Olusegun T., MK	Fatigue Strength of Titanium Risers – Defect Sensitivity. (Dr.Ing. Thesis)
MTA-2001-149	Mohammed, Abuu K., MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
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MTA-2002-157	Ge, Chunhua, MK	Global Hydroelastic Response of Catamarans due to Wet Deck Slamming. (Dr.Ing. Thesis)
MTA-2002-158	Byklum, Eirik, MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
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IMT-2003-2	Skaugset, Kjetil Bjørn, MK	On the Suppression of Vortex Induced Vibrations of Circular Cylinders by Radial Water Jets. (Dr.Ing. Thesis)
IMT-2003-3	Chezhian, Muthu	Three-Dimensional Analysis of Slamming. (Dr.Ing. Thesis)
IMT-2003-4	Buhaug, Øyvind	Deposit Formation on Cylinder Liner Surfaces in Medium Speed Engines. (Dr.Ing.

		Thesis)
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IMT-2007-22	Sun, Hui	A Boundary Element Method Applied to Strongly Nonlinear Wave-Body Interaction Problems. (PhD Thesis, CeSOS)
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		(Dr.ing.thesis, IMT)
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IMT-2008-44	Soni, Prashant Kumar	Hydrodynamic Coefficients for Vortex Induced Vibrations of Flexible Beams, PhD thesis, CeSOS
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IMT 2010-65	Seim, Knut Sponheim	Mixing Process in Dense Overflows with Emphasis on the Faroe Bank Channel Overflow. Ph.d.thesis, IMT
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		Ph.d.thesis, IMT.
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