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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 loss of subsea assets and the AROV 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; loss prevention; safety envelopes; collision avoidance; subsea IMR

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 (Uyiomendo and Markeset, 2010). 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 (Ramberg et al., 2013; Ruud et al., 2015). Robust IMR techniques and development of autonomous underwater vehicles is needed to maintain these future subsea factories (Radicioni and Fontolan, 2016). 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 (Schjølberg et al., 2016).

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 (Hegde et al., 2015). 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, (2017) suggests 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, (2015), 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. Impact energies of vehicular collision with sensitive equipment of the SPS may lead to structural damage and, in worst case, to hydrocarbon release. Lack of consideration of novel marine systems during risk assessments has also been observed, which may increase uncertainties during operations (Vinnem, 2014). 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 (Germanischer Lloyd Aktiengesellschaft, 2009).

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 (Erlien et al., 2016; Suh et al., 2016). In the maritime industry, ship domains are used to identify safe areas around the ship (Davis et al., 1980; Fujii and Tanaka, 1971; Goodwin, 1975). In the aviation industry and space industry, safety envelopes are also used to avoid midair collisions and collisions with space debris, respectively (Kuchar and Drumm, 2007; NASA, 2002; US Department of Transportation and Federal Aviation Administration, 2011). 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 (Huffman, 2015, Germanischer Lloyd Aktiengesellschaft, 2009**)**. 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 novelty of this article is related to researching and combining safety envelope approaches from other industries, and to the derivation, implementation and testing of safety envelopes and subsea traffic rules for safe AROV operations. Safety envelopes and subsea traffic rules allow introduction of rule based underwater collision avoidance systems. 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 extends the work by Candeloro et al., (2016) in which simple traffic rules applied to AUVs are proposed by combining collision regulations from the aviation and marine industries.

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 Figure 1.

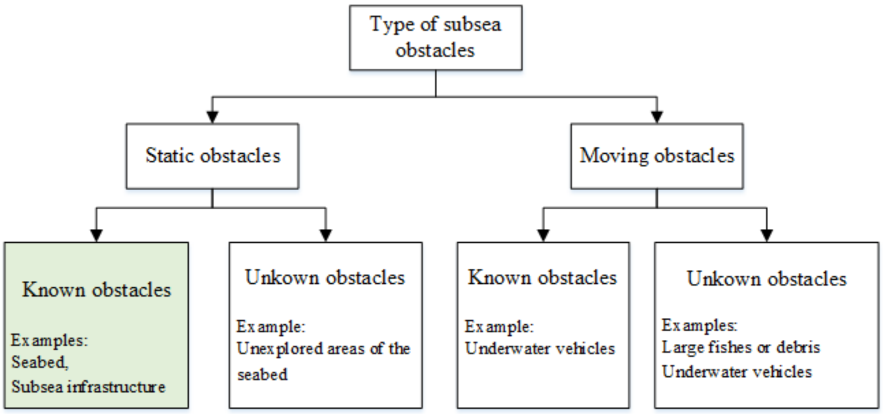

Figure 1 Scope of the article

1.2 List of abbreviations

AROV	Autonomous remotely operated vehicle
AIS	Automatic identification system
AUV	Autonomous underwater vehicle
CAS	Collision avoidance system
COLREGs	Collision regulations
EUC	Equipment under control
IMR	Inspection, maintenance and repair
MOOS	Mission orientated operating suite
MORSE	Modular open robots simulation engine
PST	Process safety time
ROV	Remotely operated vehicle
SIF	Safety instrumented function
SLAM	Simultaneous localization and mapping
SMT	Safety margin time
SPS	Subsea production system
SRT	Safety instrumented function response time
SSN	Space surveillance network
TCAS	Traffic collision avoidance system
TTT	Time to trip
XT	Christmas tree

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

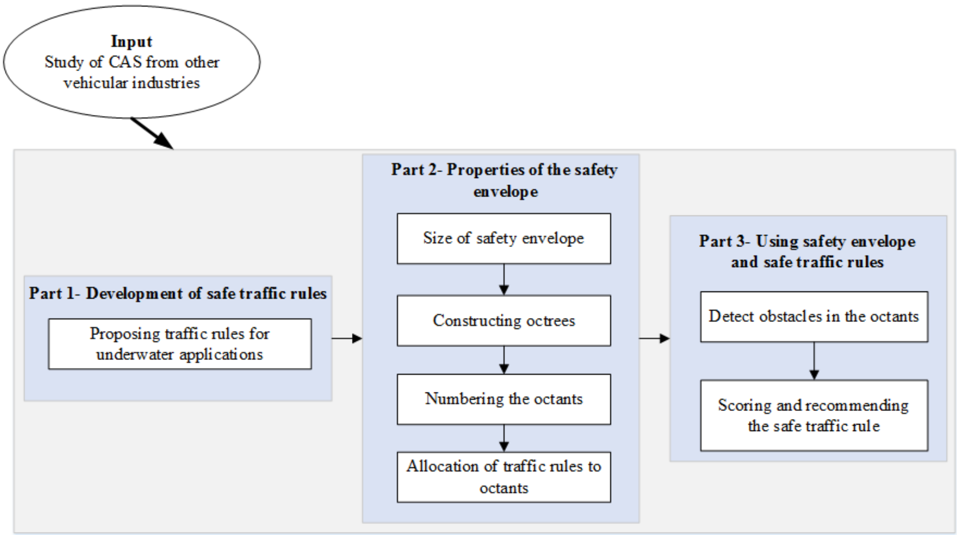

Figure 2. Developing safe underwater traffic rules and safety envelopes and application during IMR operation. CAS is collision avoidance system

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

Fujii and Tanaka, (1971) present the concept of ship domain to aid marine traffic modelling. Goodwin, (1975) 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, (1975) 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., (1980) 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, (1975) match the area covered by the three zones from Davis et al., (1980). This simplification is used to allow for practical ship domain calculations (Tam et al., 2009).

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 (Fujii and Tanaka, 1971; Lewison, 1978). Tam et al., (2009) review various methods proposed to determine the optimal ship domain and collision avoidance using statistical, analytical and artificial intelligence (AI) methods. According to Pietrzykowski and Uriasz, (2009), 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.

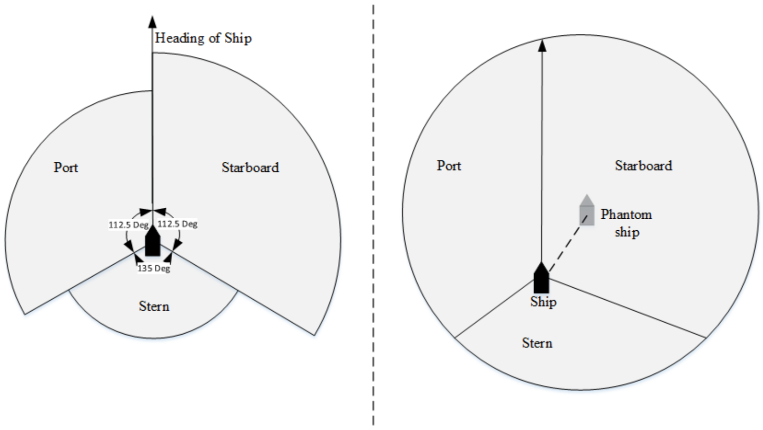

Figure 3 Examples of a ship domain as described by Goodwin, (1975) and Davis et al., (1980)

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 provides rules to avoid collisions between two or more maritime vessels at sea (International Maritime Organization, 2005) . 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, (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 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.

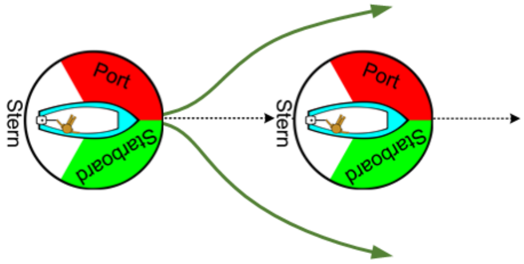

Figure 4. Rule 13 of COLREGS

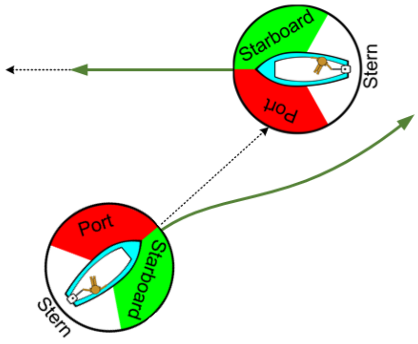

Figure 5. Rules 15, 16, and 17 of COLREGS

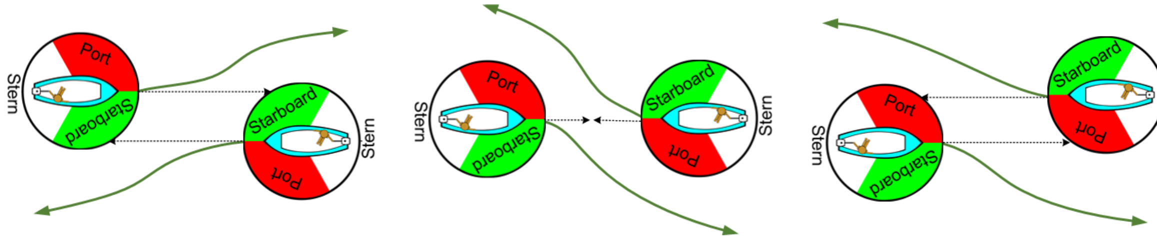

Figure 6. Rule 14 of COLREGs (International Maritime Organization, 2005)

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 (Kuchar and Drumm, 2007; US Department of Transportation and Federal Aviation Administration, 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 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 (US Department of Transportation and Federal Aviation Administration, 2011). 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.

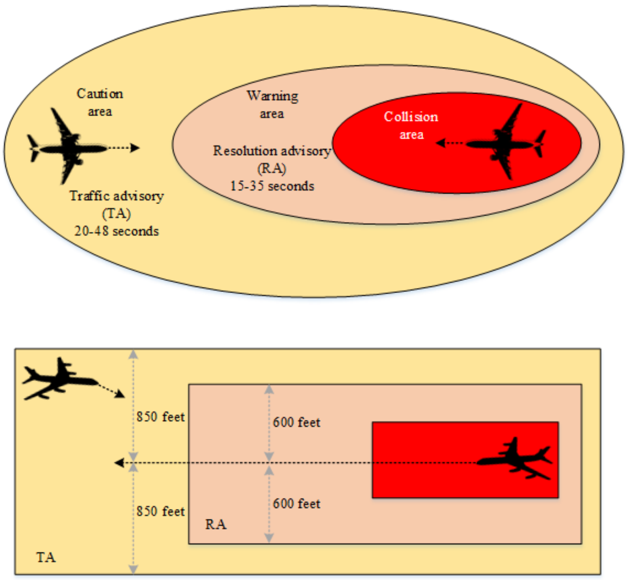

Figure 7. Safety envelopes in aviation traffic collision avoidance systems (TCAS- II) (US Department of Transportation and Federal Aviation Administration, 2011)

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 (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 probability of collision in the red threshold is set to greater than 10^{-4} (NASA, 2002).

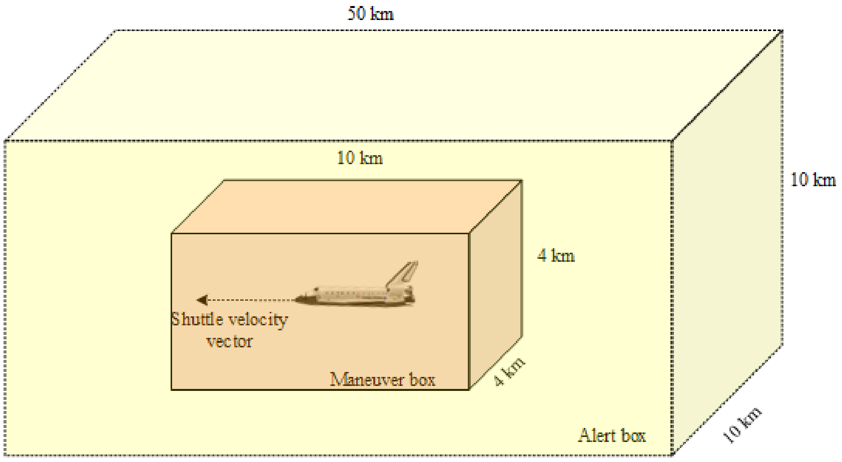

Figure 8. Shuttle alert and maneuver boxes adapted from National Research Council, (1997)

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 (Candeloro et al., 2016), as previously mentioned. Table 1 suggests that in current underwater collision avoidance literature, *there is a gap with respect to the safe action an underwater vehicle can take after detecting an obstacle.* The survey indicates that there is a need for simple, yet robust underwater CAS, which can be used during autonomous subsea IMR operations.

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., (2016), 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., (2007)	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., (2009)	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, (2013)	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., (2014)	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., (2015)	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., (2016)	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., (2016)	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., (2016)	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., (2000)	Present a grid occupancy search method to detect obstacles underwater when using a forward-looking sonar.	No	No
	Jakuba and Yoerger, (2008)	Present a method to identify hydrothermal vents using hydrothermal tracer data collected by an AUV using occupancy grid mapping.	No	No
	Hernández et al., (2009)	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., (2015, 2014)	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

Figure 4, 5, and 6 illustrate how the marine vessels avoid collisions by controlling the horizontal distances from potential obstacles. Figure 7 shows how aircrafts avoid collisions by maintaining a minimum vertical distance between two aircrafts. 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 (IEC 61508, 2009). 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 (IEC 61511, 2016). 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 instrumented 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 (IEC 61511, 2016).

Figure 9, based on Knight, (2016), 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. Simulation results from Candeloro et al. [20] show that a replanning system of the underwater vehicle can plan a new safe path within 2.5 s. To account for sensor data latency and availability, an additional 2.5 s is added as a safety factor resulting in a total PST of 5 s. The SRT starts when the process is at the trip point and ends when the final elements reach safe state and prevent the hazard (IEC 61511, 2016). A trip point represents the start of the SIF response time (Knight, 2016). 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 CAS**	**Allocated Time Budgets (s)**
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.

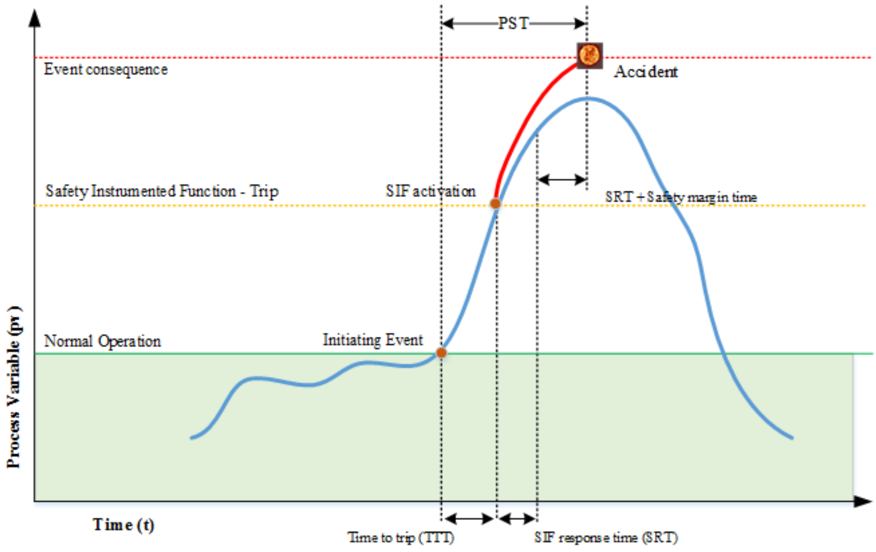

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Figure 9. Time budgets for the process safety time, as defined by Knight, (2016)

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., (2013), 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.

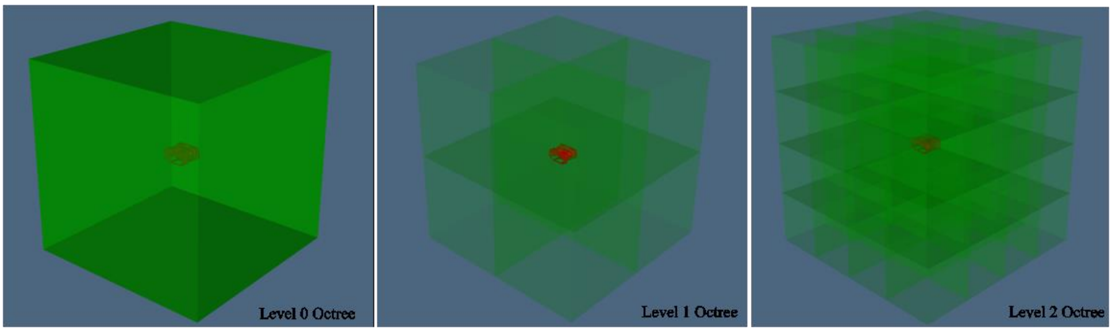


Figure 10. Construction of octree level 0, level 1, and level 2 with AROV positioned in the center

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. As observed in Figure 10, the size and shape of the AROV covers a small area within octants 25, 34, 07, 16, 61, 43, 70 and 52. 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.

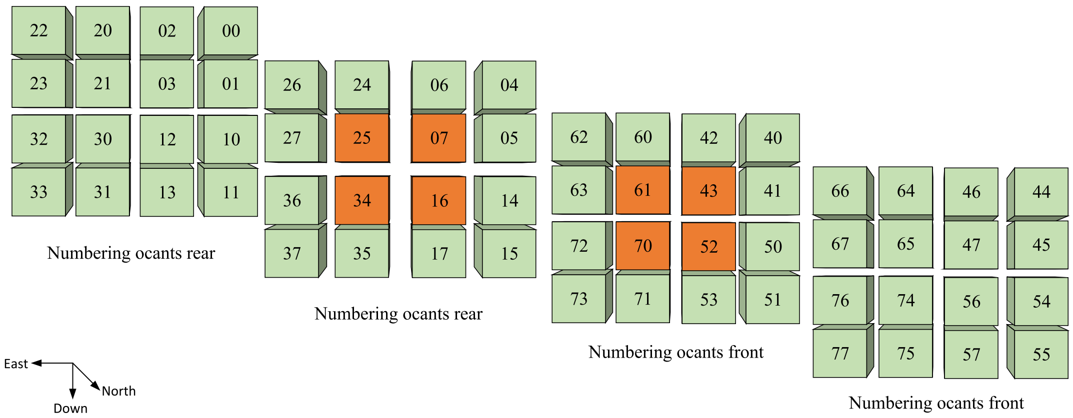


Figure 11. Construction of octree level 0, level 1, and level 2 with AROV positioned in the center

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 11 Octant 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 (Pan et al., 2012). 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. The hypothesis was 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 (Henriksen et al., 2016). 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. The blue line represents the path traced by the AROV.

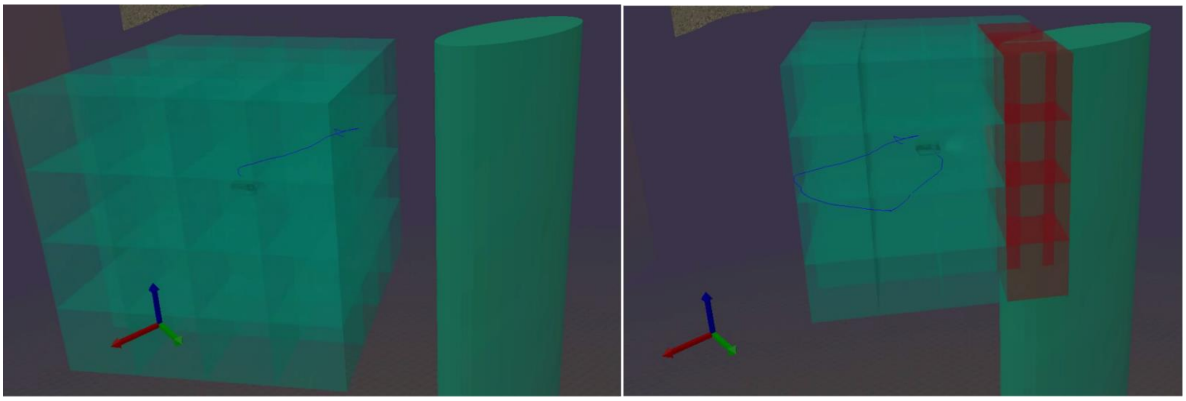


Figure 12. Underwater CAS in the underwater MORSE simulator

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. 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 (Newman, 2006). 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 of the test was to verify whether the suggested traffic rules matched the proposed traffic rules.

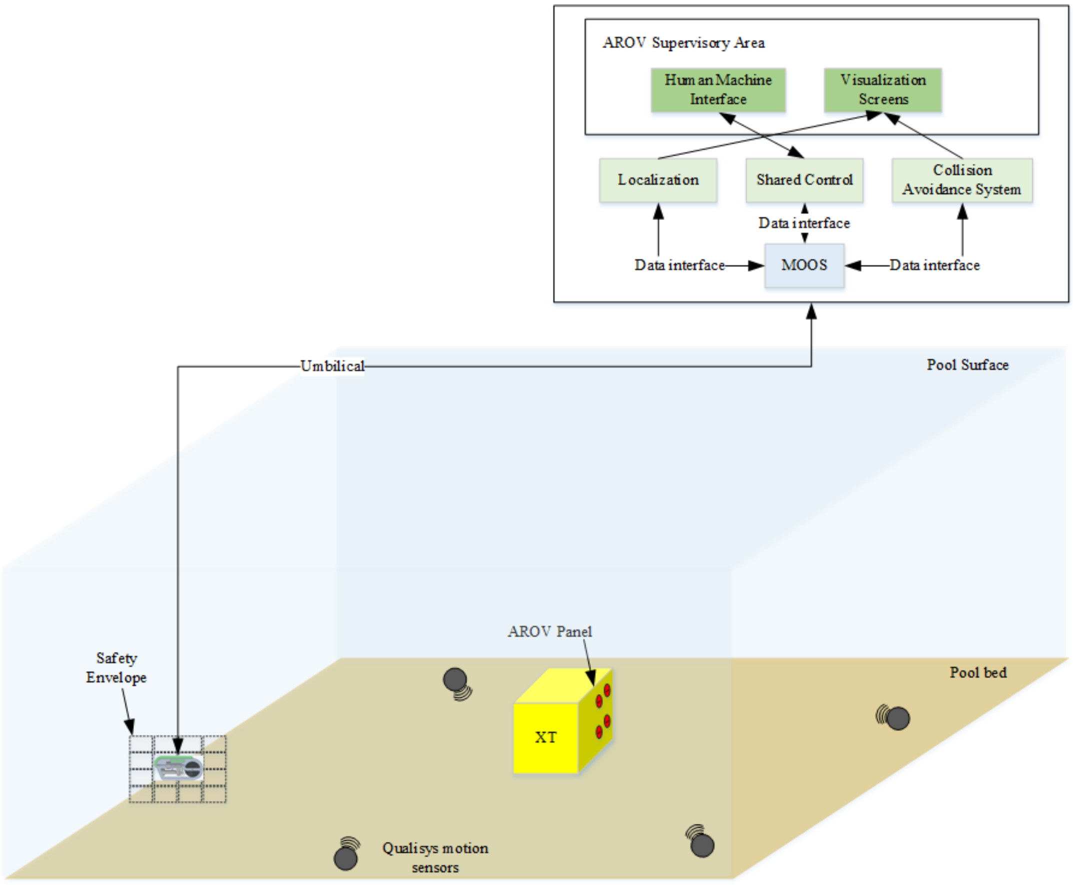


Figure 13. MOOS interface to gather position data of obstacle and the AROV during laboratory tests

During autonomous subsea IMR operations, the AROV will be required to approach subsea production systems to inspect, maintain or repair the SPS. If the approach is not planned and executed properly, the AROV can be exposed to collision scenarios with sensitive SPS equipment, which may be hazardous, for example, with respect to leakages and environmental impact. These collisions may also lead to unavailability of the AROV and SPS functions resulting in cost overruns. Figure 13 and Figure 14 illustrates one such hazardous scenario, which is the test setup utilized in this article.

In Figure 13 and Figure 14, 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 15.

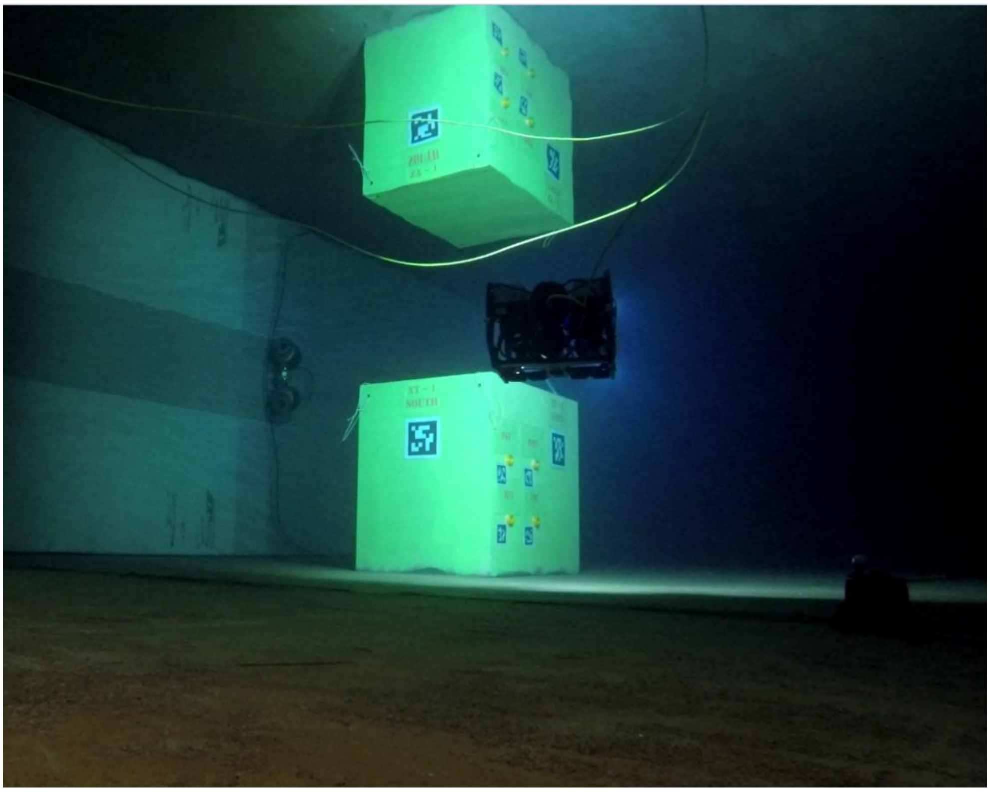


Figure 14. Image from laboratory test showing the AROV and the mock subsea production system

4. Results

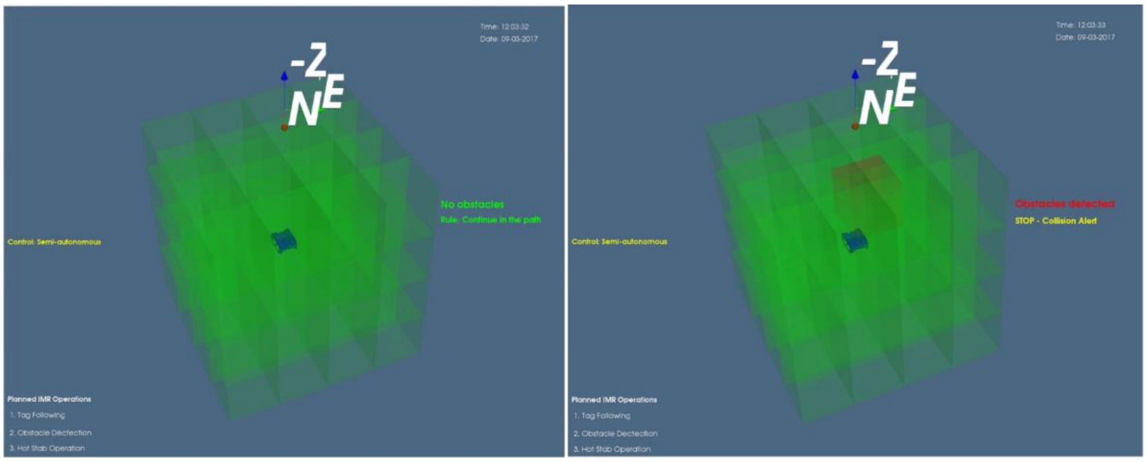
Data Point 2 in Table 6 shows that the CAS also suggests the “Stop-Collision alert” traffic rule. The traffic rule suggested in the lab test for Data point 3 in Table 6 is limited to only horizontal separation (turn left) because, during the implementation of CAS in the lab, the minimum depth constraint 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.

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

Figure 15 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 15**,** the control mode is displayed as semi-autonomous, which refers to limited intervention from the human operator. By using the orientation data from the Qualisys motion sensors, the safety envelopes in the user interface mimic real-life orientation and rotational movement of the AROV.



Time: 12:03:32
Date: 09-03-2017
No obstacles
Rule: Continue in the path
Control: Semi-autonomous
Planned IMR Operations
1. Tag Following
2. Obstacle Dectection
3. Hot Stab Operation

Time: 12:03:33
Date: 09-03-2017
Obstacles detected
STOP - Collision Alert
Control: Semi-autonomous
Planned IMR Operations
1. Tag Following
2. Obstacle Dectection
3. Hot Stab Operation

Figure 15. 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, (1975), 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 should 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 in this paper, such as shape, size and logic, may also be changed and improved with future research work. In addition, the proposed safety envelopes can also be related to the attenuation property of the inherent safety philosophy as suggested by Kletz, (1985). In this article, the attenuation property (safety envelopes) aims to provide a safe collision free area for the AROV.

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 a 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 only 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. Depending on the collision scenario, the proposed method in the article can choose to increase either the horizontal or vertical separation or both from the detected obstacle. This means the AROV does not have to travel longer distances than needed from the obstacle, thereby also decreasing propulsion power wastage.

Traditional ROV information screens display the live video feed from the ROV to the operator, as well as 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 by making the choice of decision rules used by the AROV 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. Such applications will require a set of hierarchical based rules depending on the vehicle functionalities.

The subsea traffic rules suggested in this article have not considered the effects of AROV umbilical entanglements. Underwater vehicles with umbilical and without umbilical may also mandate different set of subsea traffic rules due to the effects of an umbilical on the ability of the underwater vehicle to adhere to subsea traffic rules.

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. Error! Reference source not found. 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. Utilizing active sensors to detect and track known, and unknown obstacles will also be essential in the future.

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 c 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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