A Review of Hazard Identification Techniques for Autonomous Operations in Norwegian Aquaculture

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Abstract: There are tremendous needs in Norwegian aquaculture to apply automated and autonomous system to reduce the exposure of the workers to the harsh environment, increase the weather window for operations and reduce cost. Ensuring safe and reliable autonomous operations is important to personal safety and fish welfare. This paper uses an inspection-class Remotely Operated Vehicle (ROV) that has three operation modes (i.e., manual control, Dynamic Positioning, net pen tracking) at different levels of autonomy as a case. The objective is to assess how have hazard identification methods been applied to systems with adaptive Levels of Autonomy and identify the needs for improvement. The literature review shows that limited research examines the risk issues related to ROV and Autonomous Underwater Vehicle operations, and the focus has been mainly on technical hazards. The paper recommends that the hazard identification should consider different control architectures and possible human error modes accordingly for functionalities at different levels of autonomy. Environmental interactions in addition to environmental features should also be emphasized in the hazard identification.

Keywords: Hazard identification, Level of Autonomy, ROV, Control architecture

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1. INTRODUCTION

The Norwegian aquaculture has tremendous growth in recent years and has a potential for a three-fold increase of production over the next 35years to meet increasing global fish consumption [1]. The industry is, however, facing the challenge of operating at the edge of safety limits [2]. The less available sheltered coastal environment, increased negative ecological consequence due to sea lice, fish escape and farm waste on the seabed push the Atlantic salmon fish farms further into exposed locations. The severe wave and current conditions, irregular wind, and sheer remoteness may amplify the risk to personnel, the fish and the environment (e.g., fish escape) in most fish farming operations. There are strong motivations to apply automated and autonomous systems in Norwegian aquaculture to ensure increased regularity, reduce exposure of the workers to the harsh environment and increase the weather window for operations (e.g., delousing, net cleaning).

In some sites, feeding operations are entirely remotely controlled from a feeding barge. The operators manage the feeding time and feeding speed (kg/s) by monitoring the behaviour of the salmon via underwater cameras. The feed is automatically distributed to cages, periodically. Remotely Operated Vehicles (ROV) are increasingly used within aquaculture to replace divers to inspect nets and moorings [3]. Service companies started to use Remotely Operated Net Cleaner (RONC) to clean the net, instead of using cleaning discs that have to be lifted up and down by cranes on the vessels. The experimental offshore cage farm Ocean Farm 1, which is equipped with 20,000 sensors, has achieved complete automation in monitoring, feeding for 1 million salmon[4].

Ensuring safe and reliable autonomous operations is critical to personal safety and fish welfare. Potential hazards arise not only from mechanical failures but also complex interactions among human operators, machines and rapidly changing current and weather conditions. These hazards may lead to accidents if not recognized and controlled well. This paper focuses on hazard identification for different Levels of Autonomy (LoA) in aquaculture operations. Specifically, inspection-class ROVs with different LoAs is used as a case study. Industrial [5] and research [6] efforts focus on developing higher-level autonomous ROV systems due to challenge of manual maneuvering around flexible structures of the fish cages in wave zones. At present, much research into safe ROV operations focuses on improving collision avoidance, or fault detection and tolerance systems. Limited attention has been paid to risk analysis of the ROV itself for operations in aquaculture. This paper is concerned with the initial identification of hazards as the first step of risk analysis. The objective is to assess how have hazard identification methods been applied to systems with adaptive Levels of Autonomy and identify the needs for improvement. The application area is limited to aquaculture, but the results may be relevant for for similar autonomous operations in other industries as well.

The rest of the paper is organized as follows: Section 2 explains the adopted definitions of autonomy and LoAs in this paper. The control architectures of inspection-class ROV at different operation modes are presented in Section 3. Section 4 discusses the different focus of hazard identification at various LoAs, and presents hazard identification techniques that are used today for underwater vehicles by a literature review. The implications for the improvement of hazard identification process in light of ROV operations at different LoAs are also discussed. Section 5 concludes the work.

2. AUTONOMY AND LEVELS OF AUTONOMY

Autonomy in engineering systems is the ability of a system to be independent of an outside supervisor - another engineering system or a human [7]. Independence means that the system has the "ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making and acting to achieve the goals assigned by human operators through designed human-machine interface" [8]. There are different classifications of LoAs. In this paper, we adopt the definition from [9] and [10], which classify autonomous operations into four levels: automatic operation, management by consent, semi-autonomous or management by exception, and highly autonomous. For more details, see [9] and [10].

1. **Automatic operation (remote control):** the human operator directs and controls all high-level mission planning. The environmental conditions and sensor data are presented to the operator through a human-machine-interface (HMI).
2. **Management by consent:** the system automatically makes recommendations for missions or actions related to specific functions. The system can perform some functions independently of human control when delegated to.
3. **Semi-autonomous operation (management by exception)**: The system automatically executes mission-related functions. The human may override or change parameters and cancel or redirect actions with defined timelines. The operators' attention is only brought to exceptions for certain decisions.
4. **Highly autonomous operation**: the system automatically executes mission or process related functions in an unstructured environment with the ability to plan and replan the mission. The system is independent and intelligent.

ROVs in aquaculture need to handle flexible structures, demanding environments with currents and large waves, and changing geometry in an undetermined pattern [3]. This paper investigates three operation modes: manual control mode that represents the ROV operation today; Dynamic Positioning (DP) control mode and net pen tracking mode that are desirable from the industry´s point of view and under research [11]. Even though it is challenging to make a single and exact LoA scale that suits the above three modes of ROV operations, they are still representatives for LoA 1, 2 and 3. LoA 4 would correspond to Autonomous Underwater Vehicles (AUVs) stationed in garages on the seabed operating without a tether and interference with human operation. This is currently too advanced with respect to ROV operations, so it is out of the scope of this paper.

3. ROV OPERATION MODES AND CONTROL ARCHITECTURE

ROVs range in shape, size, depth capabilities, control method and architecture, available power and power supply (electric or electro-hydraulic power) [12]. The main modules of a general control system for ROVs can be divided into the Mission Planning Module, the Guidance System Module, the Navigation System Module, and the Control System Module. These modules contain sub-modules depending on the LoA. The explicit modularity has the benefit of physically and logically separating the main modules of the software so that new add-on features can be efficiently designed. The above-mentioned modules form the basis for the evaluations of the hazard identification for different LoAs of ROV. Note that we keep the same names of the modules for all three operation mode for the sake of comparison. However, the functions and complexity of the module may vary and are subject to the operation mode and LoA.

3.1 Manual control mode – autonomy level 1

In this mode (Figure 1), the ROV-pilot has direct control of each Thruster via Operation control (e.g., joysticks or control console). The ROV-pilot has visual feedback on the Display from Cameras, data from Sensors (e.g., depth sensor, compass) to steer the ROV by sending control forces to the Thrust Allocation Module. The raw data from the sensors are processed in the Signal Process Module to remove noises. Desired RPM (revolutions per minute) is allocated to each thruster, accordingly. A rough heading and depth indication, together with the visual feedback, and regular positions fixes are sufficient for the pilot to control the ROV. The manual control mode is the most common operation mode in today's inspection class ROVs. It takes much effort from the ROV pilot to control position and orientation of the ROV to compensate ROV dynamics and environmental disturbances (i.e., wind, waves and current) [12]. Preventing entanglement is subject to the skill of the ROV pilot.

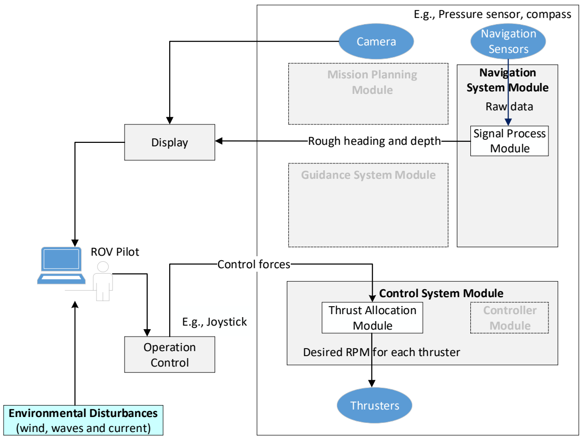

Figure 1 Control architecture of the manual control mode

3.2 Dynamic Positioning (DP) control mode – autonomy level 2

DP control modes (Figure 2) could be auto-heading, auto-depth and auto-altitude. DP system keeps position (and heading) within certain excursion limits [13]. The motion control system compensates for environmental disturbance and ROV dynamics.

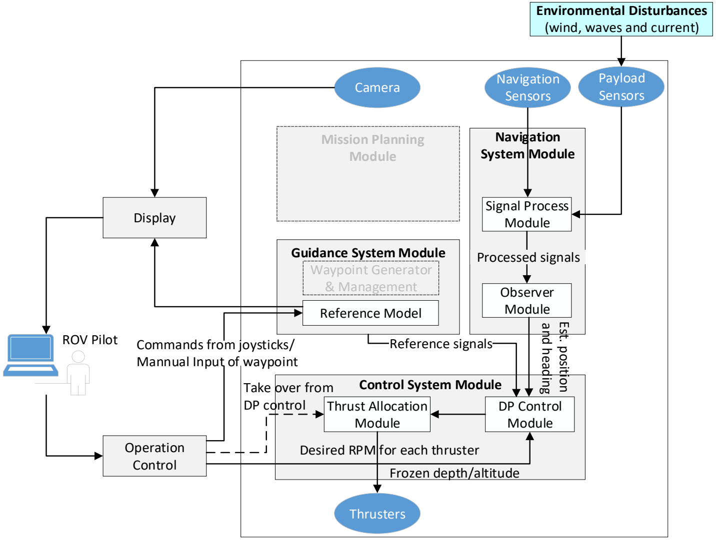

Figure 2 Control architecture of the DP control mode

The Navigation System Module is responsible for finding the position, velocity, and attitude (PVA) of an ROV in a given reference system. The navigation sensors may contain a compass, pressure gauge, a transponder which is part of acoustic positioning system (APS), DVL (Doppler Velocity Logs), sonar, gyroscopes and accelerometers [14]. There could be other payload sensors, such as ADCP (Acoustic Doppler Current Profiler) to measure the velocity of the currents. The Signal Process Module is more complex in the DP control mode. It is responsible for treating the redundant measurement and generating a combined signal based on a signal weighting and voting system. The module also detects sensor failure or signal freeze and reports it to the rest of the system. The Observer Module takes in processed measurements (even if the signals are flawed or missing) and outputs smooth estimated position and heading to the DP Control Module. The task of the DP Control Module is to calculate the difference between the estimated and desired states to produce control force to the Thrust Allocation Module. The Guidance System Module is the highest level in the control structure to interface with the ROV pilot. The pilot can set up a fixed depth/altitude to the DP Control Module, or manually enter waypoints to the Reference Model. The ROV pilot also has the authority to take over control from the DP control to send directly control forces to the Thrust Allocation Module.

3.3 Net pen tracking – autonomy level 3

Net pen tracking is a desired ROV function within aquaculture, but currently under research. In this mode, the ROV follows the shape of the net to do the inspection autonomously. The ROV determines its position and senses the environment to inspect and react appropriately to changing circumstances. Obtaining the relative position of the net pen is challenging. The net pen deforms by current induced drag forces which makes it an undetermined shape [15]. [15] report 20% reduced net pen volume when it is exposed to a current velocity of 0.5m/s.

The ROV pilot is more like a supervisor, who has the authority to intervene in case of emergency or change of mission plan by overriding waypoints (i.e., switch to DP control mode) or directly control thrusters using joysticks (i.e., switch to manual control mode). One possible control structure is shown in Figure 3. The Mission Planning Module interfaces with the ROV pilot. The pilot provides a mission (e.g., clean along half of the net pen wall (0°–180°)) to the Mission Planning Module, which is responsible for path planning and re-planning. The Obstacle Avoidance Module may contain certain safe navigation rules in the presence of moving or static obstacles as an input to path re-planning.

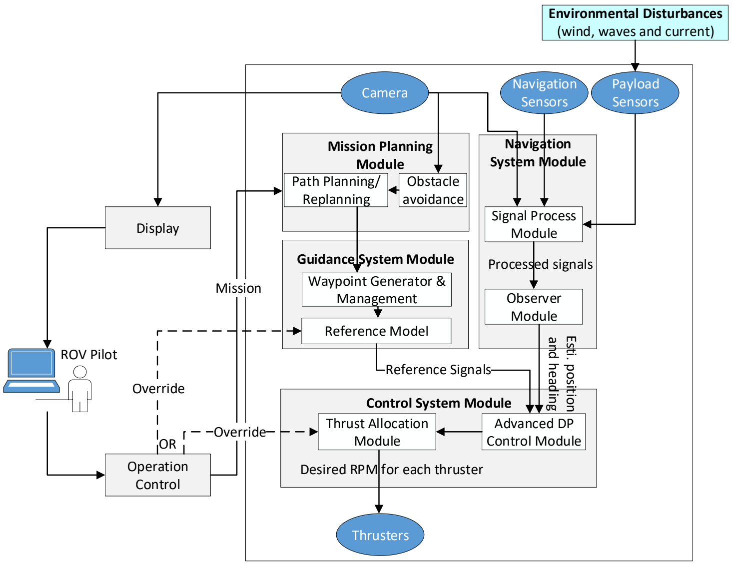

Figure 3 Control architecture of the net pen tracking mode

The generated plan is passed to Waypoint Generator in the Guidance System Module, which establishes a set of waypoints according to the mission plan, the weather, the operation and so on. The waypoints are updated based on the current position of the vehicle by the Waypoint Management Module. A smooth feasible trajectory is generated based on the Reference Model, the actual vehicle position, and the active waypoints, as an output of the Guidance System Module (i.e., providing reference signals) to the Advanced DP Control Module. The raw data from the Sensors, including images from the camera are processed in the Signal Process Module to give position, velocity and heading estimates to the Advanced DP Control Module. The controller calculates the forces and moments needed to minimize the error between the desired and estimated state and sends them to the Thrust Allocation Module.

4. HAZARDS AND HAZARD IDENTIFICATION FOR DIFFERENT LEVELS OF AUTONOMY

Inspection ROVs can reduce exposure of personnel to severe wave and current conditions. However, it poses the risk of fish escape if the holes in the net are not detected, if the ROV collides and damages the cage structure, or the net. Fish escape is the most severe risk to the environment that the authorities in Norway pay much attention to its prevention. If the ROVs lose control and start running wildly inside the cage, the fish can become frightened and stressed. Sustainable aquaculture requires that the risk to the environment, risk to fish welfare and risk to marine assets are the other four dimensions of risk that should be considered together with risk to personnel [8, 16].

A hazard is either a property, a situation, or a state that is a prerequisite for the occurrence of a hazardous event that may cause harm [17]. The hazard identification, therefore, is a process of "identifying and describing all the significant hazards, threats, and hazardous events associated with a system" [17]. In this section, we start the discussion by illustrating what could be the different focus of hazard identification at different LoA, and proceed with how hazard identification are carried out for underwater vehicles today. The implications are reflected to explore what could be potential hazard identification methods that are applicable for functionalities at different LoAs.

4.1 Different focus of hazard identification at different LoA

The hazards in ROV operation may arise from engineering system (i.e., the ROV being designed), human interaction errors, and environment [18]. The environmental hazards faced by ROV are the same under all operation modes. Technical hazards include mechanical failures (e.g., loose parts, faulty electronics), software failures (e.g., faulty algorithm design) and software-hardware interaction failures (e.g., opposite signal sent from software to the hardware) [19]. The hardware configurations and the software complexity of the operation modes at different LoAs are rather different (cf. Figures 1-3). The causes for hazardous events (e.g., ROV fail to stop, accelerate suddenly) are subject to the various modules and their interactions. These hazards may be unanticipated or predicted by the ROV operator.

Human-machine cooperation (co-agency) specifically needs to be emphasized with a sound underlying model of the processes [20]. We need to understand the construct of autonomy (at different levels) to comprehend how the cooperation proceeds, in turn, to identify how the cooperation can fail. Merely pointing out human errors as hazards is not sufficient to understand how to mitigate the risk. From Figures 1-3, we can understand that there is a shift of roles to perceive, comprehend, project, and cooperate between the human and the ROV. The manual control mode relies heavily on the skills and experience of the ROV pilot to manage the tether against entanglement and control its tautness while the ROV moves [12]. Long endurance and repetitive tasks (e.g., net inspection) exposes the operator to lose their vigilance. To keep it requires hard mental work [21]. Higher LoAs aim to reduce human maneuvering errors, however, issues of unbalanced workload and low Situation Awareness (SA) during supervisory control may arise [22]. SA and mental workload both influence human performance and change with LoA [23]. SA is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [24]. Mental workload is "the relation between the function relating the mental resources demanded by a task and those resources available to be supplied by the human operator". The high mental workload at low LoAs leads to low operator SA; while low mental workload at high LoAs may lead to boredom [25]. Also, high LoA may result in an "out of the loop" operator who may be unable to diagnose the problem and intervene promptly [25, 26]. Table 1 summarizes the changes in ROV pilot authority and workload, ROV autonomy, and situation awareness along with changes of LoA.

Table 1 Examples of hazards for different operation modes at different LoAs concerning ROV operation for net inspection; + new hazards in DP control mode, ++ new hazards in net Pen control mode

Operation mode	LoA	ROV pilot authority	ROV pilot workload	ROV autonomy	Situation awareness			Examples of Technical hazards	Examples of Human-system interaction hazards	Examples of System-environment hazards
					Perception	Comprehension	Projection			
Manual control mode	1	Full	High	None	ROV pilot	ROV pilot	ROV pilot	Hardware component failures (e.g., camera, GPS, sensors, thruster, joysticks, tether) Flaws in signal process module Flaws in thrust allocation module Failures in sending/receiving signals	Maneuvering errors (due to e.g., long endurance and repetitive tasks, strong waves splashing over the side of the vessel) Poor tether management Slips and lapses (e.g., not detect obstacles) Pilot-induced oscillation	Swimming fish Obstructions Water current flow exceeding the performance capabilities of the vehicle[27] Bad weather [28] Water leakage[12] Foreign objects (that may ingest to thrusters) Chemicals [12] Thermal shock [12] Water optical condition (poor visibility)
DP control mode	2	Full	Medium	Advise only if requested	Sensors Observer module Reference model	DP control module	ROV pilot	+Flaws in reference model +Flaws in navigation system module (e.g., Fail to accept input from sensors [29], Flaws in observer module) +Flaws in DP control +Failures in interfaces among GNC	Erroneous input (e.g., waypoints, auto depth, auto heading) Erroneous interpretation of the situation Wrong interference Too early/ too late to take over from DP control	
Net pen tracking	3	Revoke/ Override action	Low	Advise and action unless revoked/overridden	Sensors Observer module Waypoint generator and management model Reference model	Advanced DP control module	Obstacle avoidance Path planning/re-planning	++Flaws in path planning ++Flaws in Waypoint generator and reference model ++Failures to detect obstacle[30] ++Failure to avoid obstacle ++Failure to re-plan the path +False alarm [30] ++Failures in interfaces among MGNC Communication failures[31] Unplanned behaviour during mission [28]	Wrong mission parameters are implemented during preparation [28] Wrong configuration setting [29] Erroneous interpretation of the situation [32] Erroneous override Failure to detect and react to emergent situations Failure to diagnose the problem Failure to intervene in a timely manner	

The roles of situation awareness are described in the form of modules from the control architectures to illustrate what could lead to failures of perception, comprehension, and projection during operation. The impacts of these failures on risk need to be further analyzed. From the examples of hazards that could arise during operation, we can see that the focus of hazard identification is different for various operation modes at different LoAs for technical hazards and human-system interaction hazards, even if the modes are integrated into one system. In the column "Example of technical hazards", in addition to the possible hazards under manual control mode, more types of hazards present in DP control mode, such as failures in interfaces among GNC (Guidance, Navigation and Control) that request ROV pilot's intervene. The "+" in the cell means the hazards that need to be considered in addition to the ones in manual control mode. Similarly for net pen tracking mode, several hazards need attention in addition, such as false alarm, the flaws in path planning and obstacle avoidance modules, and failures in interfaces among MGNC ("++"). The human-system interaction hazards are somewhat different in the three operation modes, due to different ways of cooperation. In manual control mode, the human error modes might be the maneuvering errors due to long endurance and repetitive tasks, poor tether management skills, and slips and lapses that lead to undetected obstacles. The ROV is expected to respond quickly to commands. If the lag is too long, the ROV pilot can experience a loss of control and keeps giving commands that the ROV cannot follow. This can cause Pilot-induced oscillation (PIO), which is also a possible human error mode [33]. In DP control mode, the possible human error modes change to the erroneous input of depth or waypoints, wrong interference, or take over from DP control too early or too late. While in net pen tracking mode, giving the wrong mission, erroneous override, and failure to detect and react to emergent situations or failure to intervene in a timely manner are the possible human error modes.

4.2 Hazard identification for underwater vehicles from the literature

The literature review[1] shows that a certain number of publications integrate risk in AUV path planning and navigation [27, 34]. However, the research covering risk management and risk assessment of ROV and AUV operations is limited. This is also pointed out by [35]. Several studies use fault tree analysis [36-38] and FMEA [39, 40] to analyse reliability of AUV. [41] applied Bow-tie technique to analyse the causes of AUV collision and corresponding consequences. A series of risk analyses has been carried out for AUVs based on fault logs [29, 42-46]. In the absence of objective data, the risk analyses uses expert subjective judgment to predict the survival of Autosub3 AUV under four different environments. Fault history provides critical information for hazard identification but it is also rather model-specific and unavailable in literature. [32] proposed a hazard taxonomy for AUVs operated in arctic areas for hazard identification, which emphasis more on natural events and technical events. Human behaviour events such as negligent and inexperience are listed as hazards due to e.g., operation outside the design envelope, and limited situation awareness and training. [35] concludes from his experience with AUV control failures that technical failures are not dominant in the operation but the operational failures (e.g., user errors) are. There is little research examining human-associated risk issues related to operating underwater marine vehicles [47, 48]. [49] uses the Bond graph language to model and simulate the energy flow in ROV operations and determine consequences of deviations on the system and operation. The operator interaction and control becomes "visible" by showing how signals are transmitted through the system. [28] identified 37 hazardous events for various phases of AUV operation (i.e., storage and maintenance, preparation and deployment, mission start and mission, retrieval and post-dive activity) from checklists. FTA and ETA analysis are carried out for "AUV is deployed with compromised watertightness", "AUV is deployed with wrong setup for target area" and "Internal faults of the AUV during mission". They further build up a risk model for AUVs focusing on human-autonomy collaboration using Bayesian Belief Network (BBN). The nodes in the BBN describe the factors that influence the human performance, and level of autonomy is regarded as one of the factors. Environmental hazards are considered for AUVs in terms of weather conditions, oceanography, and geological hazards [28, 32]. Environmental uncertainties associated with predictive models of ocean currents [27] and disagreement between forecasts [50] are investigated to predict the risk of mission failures and risk of collision. Traffic density map [50] and dynamic obstacles [51] are considered to help in deciding a course of action that allows safer operation.

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[1] Search criteria in Scopus: TITLE-ABS-KEY ("underwater vehicle" OR "underwater robot" OR "ROV" OR "AUV") *AND* TITLE-ABS-KEY ("hazard identification" OR "risk analysis" OR "risk assessment")

The methods for hazard identification of underwater vehicles are summarized in Table 2. From the limited relevant publications, we can conclude that the focus of risk assessment of underwater vehicles is still on technical aspects. Few look into integrated software failure mechanisms, human behaviour and human errors during operation. How software and the human operator can fail under different LoAs, as was demonstrated in the examples in Table 1, have not been well captured during hazard identification.

Table 2 Hazard identification technique used in underwater vehicle operation from literature

Type of hazards	Hazard identification techniques	Reference	Risk
Technical hazards	Fault Tree Analysis and Event Tree Analysis	[28, 36, 38, 40, 52]	Loss of AUV
	Bow-tie Analysis	[41]	Risk of collision of AUV
	FMEA	[39, 40, 49]	Risk in general
	Hazard taxonomy	[32]	Risks to the environment, human and material assets
	Checklist	[28]	Loss of vehicle, Mission abort, External damage
	Fault history	[29, 46]	Loss of AUV
Human-system interaction hazards	Bond graph	[49]	ROV risk in general
	BBN	[48]	Loss of AUV
	SPAR-H	[28]	Loss of vehicle, Mission abort, External damage
Environmental hazards	Environmental uncertainty	[50]	Risk of underwater glider mission failure due to environmental conditions
	Uncertainty in predictive models of ocean currents	[27]	Risk of collision of AUV
	Dynamic obstacles identification	[51]	Risk of collision of AUV

4.3 Implications to hazard identification for ROVs

In this subsection, the techniques that have potential to be used for ROV operation modes at different LoAs are discussed in light of Table 1 and Table 2. First and foremost, the hazard identification process should consider different constructs of control structures of different operation modes (cf. Figures 2-4). The Systems-Theoretic Process Analysis (STPA) [53] can provide a structured and systematic view of ROV operation. The system is modelled as a controlled process, with sensors, automated and human controllers and actuators. Hazards arise from insufficient control actions: (i) not provide a necessary control action, (ii) provide unsafe control action, (iii) provide potential control action too late, too early or out of sequence, and (iv) provide safe control action too short or too long.

Secondly, the role of the software in the performance of the system safety needs to be emphasized more. Software FMEA, which builds on hardware FEMA [54], has been conducted for, e.g., on-board software [55], medical devices [56], and automation systems [57]. The Hazard and Operability (HAZOP) study technique has been used in many different application areas for studying how the effects of deviations create hazards for the system and operability problems [58]. Conventional HAZOP was adapted to computer-controlled plants to identify the new routes to failure and potential risk caused by using Programmable Electronic Systems (PES) and software [59]. [60] concluded that the guidewords for traditional HAZOP are adequate for the HAZOP of PES. [61] proposed and suggested hazard analysis methods for the design phase of software systems, addressing specifically the software requirements specification, software architecture, software code and detailed software design. [19] uses a known hazardous event and assesses how it can arise through dynamic flow graph methodology (DFM). DFM is a state-based modelling technique with a focus on information flow.

Thirdly, human-system interaction hazards need to be identified in connection with the control structure due to change of roles. The adopted method should couple cognitive models of individual operators into the analysis [62]. General human-machine system interactions have been the focus of Human Reliability

Assessment (HRA) and over 70 tools and techniques have been developed over the years, to assess the human contribution to risk [63]. In this paper, we are only interested in errors that can be committed by operators of ROV, to identify potential human error modes. It is necessary to have advanced knowledge of typical human behaviour under different LoAs to understand how cooperation can fail, to avoid accidents under various operation modes. The hazard identification process should look into actual mission execution and remote control. The three mostly used human error identification methods are Action error model analysis (AEMA), Human HAZOP and the systematic human error reduction and prediction approach (SHERPA) [17]. AEMA, which is similar to a FMEA, can be applied to most types of actions by using experience, guidewords, or brainstorming. Human HAZOP, which is derived from traditional HAZOP method, uses guidewords to identify all deviations from the intended performance of the various actions and their causes. SHERPA uses an error mode taxonomy, which can be used by the analyst to describe the form of the errors accordingly. One limitation of the above-mentioned methods is that they do not consider cognitive psychology components of the error mechanisms [17]. However, cognitive psychology is an important consideration behind SA and mental workload and the higher LoA requires better understanding of cognitive psychology.

Fourthly, environmental hazards should be identified in detail for a better understanding of operating environment. [64] point out that the existing hazard identification methods do not encourage the safety analyst to consider different types of environmental interaction as an input to ensure safe robot operations. The environmental hazards that are faced by the ROV can be largely divided into *environmental features* and *objects*. Environmental features are associated with the background environment, which covers weather conditions (e.g., sea state, strong wind, strong current and tides, visibility, salinity), oceanography (e.g., icebergs), and geological (e.g., earthquake, tsunamis) [65]. Other hazards under this category could be water current flow exceeding the performance capabilities of the vehicle, water leakage, chemical or radiological damage to electronic components, and thermal shock due to sharp temperature gradients [66]. Objects include *obstacles* and *agents*. Obstacles are obstructions to vehicle movement, such as fixed structure, surface floating obstructions (e.g., ships, buoys, anchor chains), objects suspended in the water column (e.g., fishing lines, loose netting) and bottom obstructions (e.g., subsurface structures, wrecks) [66]. Agents are the objects that are moving in the environment in a purposeful way. Four categories of agents are suggested to capture the full range of behaviour patterns that any agent may exhibit and need to be perceived by the robot [64]. They could be unintelligent (automatic systems), autonomous systems/other robots, animals and human.

Last but not the least, possible hazards arise from functional resonance among different operation modes need to be captured. The functional resonance analysis method (FRAM) focuses on the functional resonance among functions that are integrated into one system [67]. FRAM views a safe system as a system that can handle hazardous situations successfully. The method analyses the variability of functions in a system and how this variability might lead to system failure during normal operation.

5. CONCLUSION

At present, little attention has been paid to risk and safety analysis of ROV systems at the different level of autonomy (LoA) in aquaculture. This paper presents different control architectures for various operation modes (i.e., manual control mode, DP control mode and net pen tracking) for an inspection-class ROV. These operation modes are representatives for functionalities at LoA 1, 2 and 3, respectively. The different control structures and the ways that the ROV pilot and the ROV system cooperate under each operation mode promote a necessity to consider different sources of hazards while performing hazard identification. The paper also gives a preliminary overview of the potential hazard identification methods that can be applied to ROV operations at different LoAs. We recommend that the hazard identification should be carried out based on operation mode. The different control architecture and possible human error modes for each operation mode should be analysed independently. This can help operators to anticipate how things can go wrong in what manner under each operation mode. The operation modes should further be analysed together to identify the hazards that may arise from possible functional resonance and interaction failures. Our further work will investigate how to use existing hazard identification methods to identify hazards that considers the levels of autonomy.

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