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The Role of Simulation as an Integral Element of Risk Reduction for Autonomous Underwater Vehicle Operations

Achille Martin, Francesco Fanelli, Davide Fenucci, Rachel Marlow, Robert Templeton, Edward Chaney, James Burris, Georgios Salavasidis, and Alexander B. Phillips

***Abstract*—Autonomous underwater vehicles (AUVs) are enabling the collection of unique oceanographic data sets and are playing an increasingly important role in the exploration and monitoring of the global ocean. However, AUV operations inherently involve significant risk due to the complexity of the vehicles, the limited opportunities for operator intervention, as well as the dynamic and often poorly characterized environments in which they take place. To improve operational reliability, we present a practical approach for integrating high-fidelity simulation into the operational risk management workflow of long-range AUV campaigns. Using Autosub Long Range, an ultra-long-endurance AUV designed for over-the-horizon operations, we demonstrate how high-fidelity physics-informed simulation can be systematically employed to support mission rehearsal, software validation, navigation assessment, and contingency evaluation both before and during field operations. The approach is applied across three complex real-world campaigns: extended unaccompanied operations in the Southwest Approaches, low-altitude surveys near decommissioned oil and gas infrastructure in the North Sea, and multiday under-ice operations in the Amundsen Sea. The results indicate that high-fidelity simulation can play a significant role in reducing operational risk, improving mission preparedness, and increasing confidence in autonomous system behavior.**

***Index Terms*—Autonomous underwater vehicles (AUV), autonomous operations, robot simulation.**

I. Introduction

THE ability of autonomous underwater vehicles (AUVs) to acquire high-quality spatial and temporal measurements throughout the water column, as well as to map and image the benthic environment in deep water and under ice, has driven the oceanographic science community to be early and enthusiastic adopters of marine autonomy [1]. Yet, AUVs are complex mechatronic systems in which the failure of any component, including the pilot, can lead to undesirable consequences, such as degraded mission performance, complete mission failure, costly premature vehicle recovery interventions, or even total vehicle loss [2]. The resulting operational cost of failure is a strong driver to both quantify the risk and implement mitigations to derisk AUV operations. We define "risk" as a situation in which an asset (i.e., the AUV and its operators) is exposed to harm, damage, or even loss [3], and "derisking" as the process of reducing the risk associated with AUV operations. In our case, "AUV operations" encompass three phases: the AUV preparation before deployment; the in-water deployment with associated data collection; and the review of collected data and AUV performance.

The loss of Autosub-2, under the Fimbulisen in Antarctica in 2005, is perhaps the most high-profile example of AUV loss. The subsequent investigation concluded that the incident was most likely due to a fault originating from the manufacturing/assembly stage or from maintenance activities. However, the root cause could have also been related to design error, operations, or even external factors, with a compound likelihood equal to that of the maintenance activities [4]. The lasting outcome of the Autosub-2 incident and the resulting investigation initiated the development of a structured approach for assessing the risk of AUV loss [5] and evaluating existing risk management processes [6].

Assessing risk in AUV operations is challenging due to the complexity of the systems involved and the dynamic nature of the ocean environment. A "risk assessment" process can help evaluate, in terms of levels of criticality, the probability of occurrence and severity of identified "hazards" (i.e., potential sources of risk) [7]. Within this process, "risk analysis" forms a major part and encompasses both qualitative methods (e.g., expert knowledge) and quantitative methods (e.g., Bayesian Belief Networks [8]). These methods further help classify operational risks into three main categories: technical, human, and environmental [2]. However, established risk assessment methodologies often rely on abstract representations of the system and struggle to capture complex interactions between the vehicle, operators, and the environment at sufficient fidelity [7], potentially limiting the identification of relevant risks. Furthermore, many analytical approaches heavily depend on theoretical assumptions and expert judgement rather than empirical operational data, limiting their ability to reliably predict AUV failures [9].

The use of simulation can help address the limitations of current risk assessment methodologies. We define "simulation"

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as the high-fidelity representation of both the AUV and its operating environment. In this context, "high fidelity" denotes a high degree of realism in vehicle dynamics (i.e., how the AUV behaves), sensing (i.e., how the AUV perceives its surroundings), and environmental representation (i.e., how the environment is displayed to the operator). High fidelity is usually achieved through the integration of a physics engine, sensor and actuator models, communication modules, and a rendering engine [10], which makes simulation particularly valuable to help identify risks originating from and happening between the three main risk categories.

Although simulation appears well suited to complement existing risk assessment methods, the use of high-fidelity simulation for this purpose remains limited, particularly in the underwater domain. For example, simulated methods, mentioned as part of major AUV reliability analysis methods [9], are typically numerical and do not involve high-fidelity representations. Similarly, surrogate modeling methods primarily focus on creating simpler models of existing systems for machine learning applications. The limited adoption can be explained mainly by the absence of common standards for simulation evaluation [11], the lack of realistic models [7], and the high computational cost and significant time investment required to run simulations with accurate dynamics [7].

While there has been growing interest in applying high-fidelity simulation to the underwater domain [12] in the last five years, contributions mainly focus on sharing new features and capabilities, rather than highlighting applications in challenging real-world scenarios involving complex AUV operations. Notable examples include HoloOcean [13], the uncrewed underwater vehicle (UUV) Simulator [14], DAVE Simulator [15], Stonefish [16], and SMaRCSim [17]. Only a limited number of contributions have attempted to use high-fidelity simulation to derisk operations in the underwater domain, and even then, their results are limited or restricted to a single aspect of operations and do not target AUVs exclusively. For instance, in [18], the path planning of an AUV inspecting underwater tanks is derisked through simulation, using UUV Simulator as simulation back-end; however, there is no evidence that the trajectory planned in simulation was used in a real-life scenario. In [19], a simulation-in-the-loop methodology, involving the use of UUV Simulator, enables robust testing of software modules of a remotely operated vehicle (ROV); however, the planning aspect of operations is not mentioned. In [20], archaeological mission planning with an ROV is derisked via simulation based on Blender; however, there is no emphasis on the software aspect of operations.

We aim to address the gap in literature by presenting a practical approach for integrating high-fidelity simulation into the operational risk management workflow of long-range AUV operations. Using three real-world campaigns of Autosub Long Range (ALR), we demonstrate how simulation can be systematically employed to mitigate mission-planning, navigation, and software-related risks both before and during field operations. The rest of this article is organized as follows. Section II outlines the campaign risk management process, the ALR platform, and the simulation solution developed at the National Oceanography Centre (NOC). Section III presents three case studies illustrating how simulation was used to support the derisking of complex long-range AUV operations. Finally, Section IV summarizes the key findings and discusses areas for future development.

II. Methodology

A. Campaign Risk Management

NOC operates a fleet of Marine Autonomous and Robotic Systems (MARS) as part of the National Marine Equipment Pool (NMEP), on behalf of the U.K.'s Natural Environment Research Council (NERC), to provide advanced ocean robot access to the broader marine science community. Through scientific grant applications submitted to NERC, principal investigators are able to request support from MARS to undertake data gathering campaigns. These requests range from low-risk routine activities with a research vessel on standby to high-risk under-ice deployments.

To ensure the long-term sustainability of the NMEP, the risk associated with each campaign needs to be reviewed and managed. The workflow for managing community requests is shown in Fig. 1 and represents an operationalized version of the approach introduced in [6]. The workflow can be decomposed into two primary phases. First, the outline request stage which encompasses the left half of the figure and focuses on ensuring that the proposed campaign is within the risk limit set by the operator. This phase is qualitatively approached through a standardized hazard identification (HAZID) process, which identifies required mitigations varying from changing the operating area and reducing campaign duration to requiring procurement of additional vehicles in higher risk campaigns. In this phase, the use of high-fidelity simulation (introduced in Section II-C) can be agreed as a mitigation tool. Second, the preparation and implementation phase, on the right half of the diagram, focuses on the management and implementation of any mitigations along with a more detailed analysis of the risks. In this phase, high-fidelity simulation is a useful tool to both derisk and quantify campaign risk, as it helps reduce the probability of occurrence of some high-criticality risks by addressing them directly in the simulated environment.

B. Autosub Long Range

1) Hardware Description: ALR is an ultra-long-endurance AUV developed for over-the-horizon operations (i.e., without an operator or support ship nearby) spanning weeks to months. NOC currently operates two ALR variants, a 1500 m depth-rated variant (ALR1500) [21] and a 6000 m depth-rated variant (ALR6000) [22]. The standard ALR vehicles are 3.6 m long, 0.8 m in diameter, have a dry mass of 750 kg, and displace 1.3 m^3 submerged. ALR1500 has a cruise speed of 0.45 m/s (0.9 m/s for ALR6000) and uses up to 30 kWh of energy on board (95 kWh for ALR6000). They both rely on the same communication technologies (Iridium Short Burst Data and WiFi), and they are both equipped with core navigation sensors (CTD, DVL/ADCP, six-axis compass, GPS). Their standard configuration is shown

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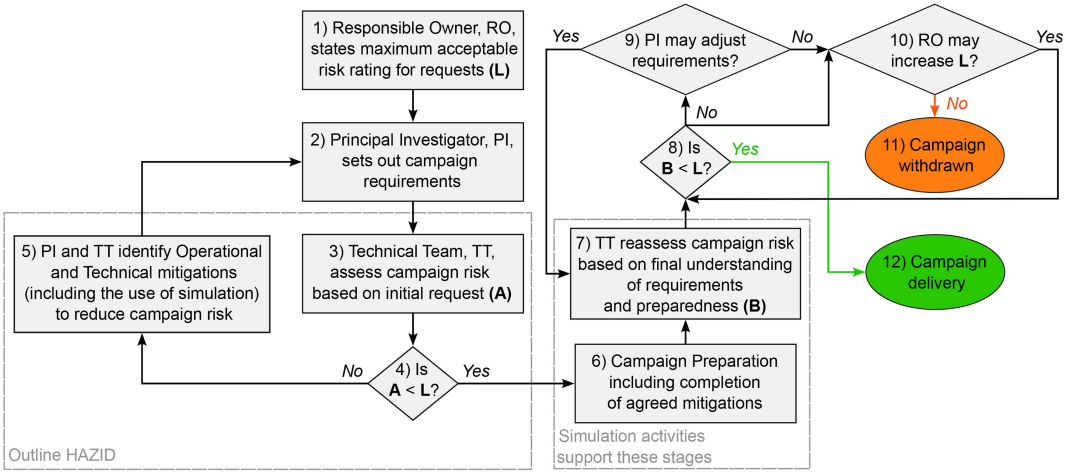

Fig. 1. Campaign risk management process (adapted and operationalized from [6]).

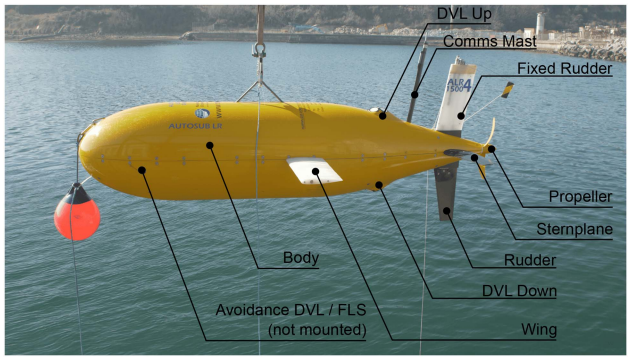

Fig. 2. ALR suspended on a crane with a float attached at the front.

in Fig. 2. For a better understanding of the internal components of ALR vehicles, refer to [21].

2) On-Board Control System (OCS): The OCS [23] is the unified software architecture which drives the ALR vehicles. It is a distributed system based on the robot operating system (ROS) middleware [24] and can be split into the following three layers.

a) The supervisory layer, which undertakes high-level decision making and system monitoring. This layer coordinates all interactions with the pilot and incorporates the mission executive (Helm), the vehicle health monitoring system (NHS), on-board data logging, and data telemetry management.
b) The mission layer, which includes the guidance, navigation, and control (GNC) subsystems [25], [26], [27], as well as the management of power for on-board devices.
c) The vehicle layer, which is responsible for the lower-level control of devices (e.g., sending inputs to the actuators and handling on-board sensor data collection) and provides interfaces abstracting the underlying hardware.

3) Piloting Toolchain: The NOC C2 project [28] defined a unified web-based infrastructure for piloting, monitoring and managing the data of long-range Marine Autonomous Systems during operations. The C2 system mainly provides the following capabilities.

a) An intuitive process for creating missions, defined as a sequence of maneuvers (e.g., dive, follow a straight line, and loiter) and commands (e.g., switch payload ON or OFF). The missions can then be sent to deployed vehicles via over-the-horizon communication channels.
b) The monitoring of the deployed AUV state by visualizing the content of telemetry reports received.
c) The review of critical data during a mission to inform subsequent mission planning without the need to recover the vehicle.

C. High-Fidelity Physics-Based Simulation

The need for simulation emerged from a desire to strengthen operational derisking methodologies at NOC. The candidate simulation framework was required to support ROS for ease of integration with the existing OCS architecture, provide high-fidelity representations of the vehicle and its environment for enhanced risk identification, as well as remain open and extensible to be relevant in a research context.

Based on these requirements, UUV Simulator [14], a Gazebo-based underwater simulation framework [29], was selected. The simulator was then integrated with the existing ALR software ecosystem while minimising modifications to the OCS architecture. This enabled mission planning, navigation, and autonomy behaviors to be exercised in a realistic virtual environment. The resulting simulation solution, named the NOC Gazebo Simulator (NGS), mirrors the structure of the operational software stack and relies on ROS interfaces to exchange information between simulated and operational components.

At the system level, the NGS components are fully integrated into the OCS architecture and are presented in Fig. 3, which highlights the components associated with the AUV, the NGS, and those shared between both. The core NGS components include the following.

a) The virtual vehicle configuration module, which instantiates the virtual vehicle with the desired components provided by UUV Simulator. The virtual vehicle is described through a Unified Robot Description Format file,

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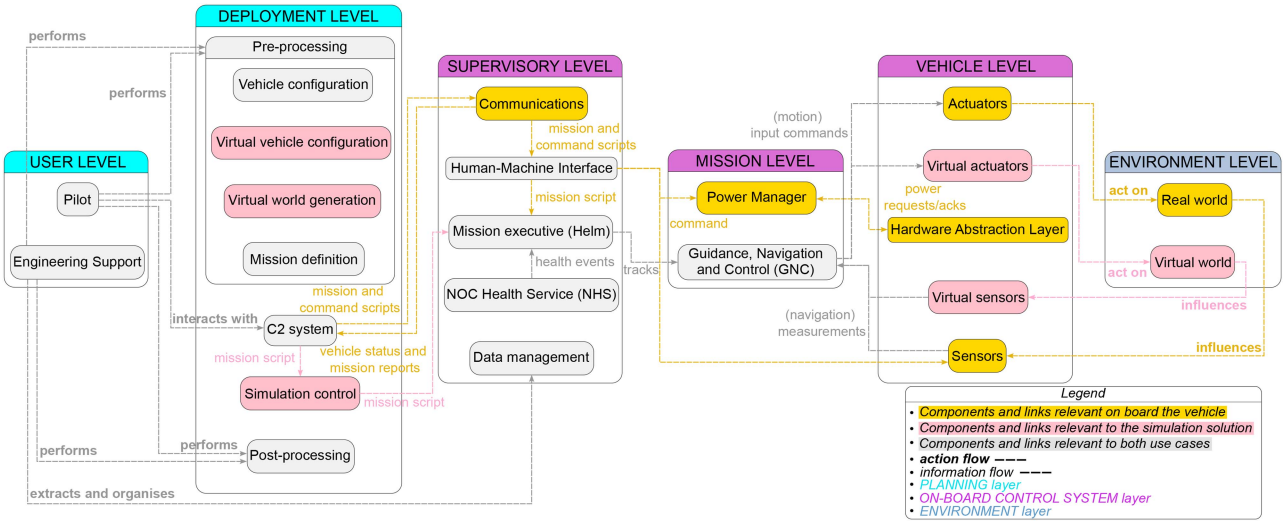

Fig. 3. Simulation solution integrated into the ALR system architecture.

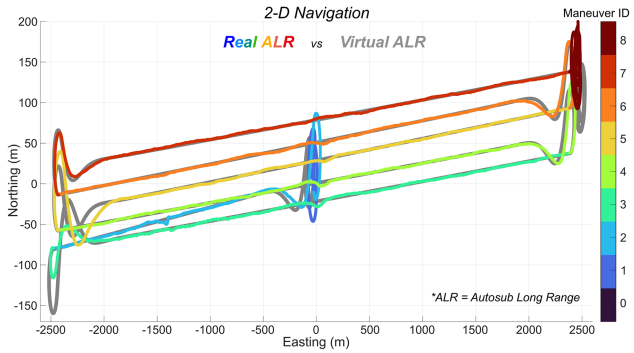

Fig. 4. 2-D navigation comparison between real (colorful) and virtual (gray) ALR for a lawnmower-style survey at depth during AT-SEA deployment.

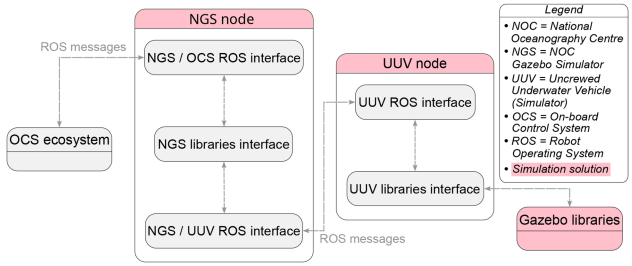

Fig. 5. Simulation solution ROS node architecture.

matching the real vehicle configuration (shown in Fig. 2 as an example). To ensure a realistic vehicle behavior in water, the NGS relies on a hydrodynamic model provided by UUV Simulator and based on [30]. The hydrodynamic coefficients were initially derived from hydrodynamic testing of an AUV scale model and progressively refined through engineering trials, while control parameters were first identified using a MATLAB (R2020a) model and later updated through trials. Simulation fidelity is assessed in Fig. 4, which compares a lawnmower-style survey at depth, extracted from the AT-SEA deployment (introduced in Section III-B), with its simulated counterpart. During the mission, ALR dived via maneuver #1 and surfaced via maneuver #8. The 2-D root-mean-square error (RMSE), representing the 2-D navigation error between the real and virtual ALR, is 131 m for the survey (excluding unimportant loiter phases). The 3-D RMSE (including depth data) is identical, confirming the confidence in the depth component. The moderate RMSE value however highlights limitations with the physics of the virtual vehicle, especially during turns involving coupled hydrodynamic effects. When taking into account only the straight tracks of the survey, the RMSE value drops to 19.9 m, comparable to the 15 m spatial resolution of high-accuracy bathymetric surveys.

b) The virtual world generation module, which instantiates the whole virtual environment with the desired bathymetry and features. The environment is described in a Gazebo world file and loads various objects and meshes. The bathymetry data originates from various sources, such as high-accuracy scans and surveys, General Bathymetric Chart of the Oceans (GEBCO) data sets [31] which use a 15 arc-s interval grid, or BedMachine Antarctica v2 [32] data sets with a spatial resolution of 500 m.

c) The simulation control module, which is a local control interface simplifying interactions with the NGS.

d) The virtual actuator and virtual sensor interfaces, which convert the OCS inputs into inputs for the virtual devices and convert the measurements from virtual sensors into navigation measurements for the OCS. The sensor and actuator models have been adjusted from models provided by UUV Simulator.

At the component level, ROS interfaces are leveraged to ensure communication between components of the software architecture, as shown in Fig. 5: ROS interfaces are used between the NGS node and the rest of the OCS ecosystem, as well as between the NGS node and UUV node, while UUV node uses its library interface to access Gazebo models and functions.

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TABLE I
SUMMARY OF HAZID ACTIVITY FOR LDPT DEPLOYMENT (COLORED TEXT HIGHLIGHTS MITIGATIONS RELATED TO SIMULATION)

Identified Risk	Potential Consequence	Risk Mitigation
Incorrect handling of primary lithium batteries	Damage to vehicle or equipment and/or injury to operators or personnel	Use UN38.3 certified batteries, in accordance with the United Nations Manual of Tests and Standards for the Transport of Dangerous Goods. Vacuum-seal the pressure vessel rather than use bolts to eliminate explosion risk. Internally monitor the temperature, humidity, and pressure of the pressure vessel containing the batteries.
Incorrect assembly of main pressure vessel	Flooding resulting in loss of AUV due to sinking	Proof-test pressure vessels to ensure resistance to hydrostatic loading. Assemble pressure vessels in a clean environment on site to avoid transport-related issues.
Incorrect ballasting of the AUV	AUV loss due to sinking	Follow standard operating procedures (SOPs) related to ballasting. Confirm the final weight and floating attitude on site to ensure reliable values. Define software behaviors to identify and remedy unexpected submergence. Fit an abort weight for emergencies.
Logistically-inadequate transport to launch site	Damage to AUV or sensors, leading to delays or cancellation of deployment	Follow SOPs related to shipping. Cover sensitive instruments for transport. Ensure AUV suitably tied down during transport.
Inadequate towing of AUV during launch and recovery	Collision leading to damage or loss of AUV	Use a suitable vessel with an experienced crew. Organise informal safety talks before AUV launch (toolbox talks). Follow SOPs related to towing.
Interruption of piloting toolchain (C2 fault)	Loss of communication with the AUV, leading to incident or AUV loss	Perform long-duration end-to-end testing of full operational toolchain. Provide alternative piloting toolchain. Fit secondary Iridium beacon for redundancy. **Exercise the C2 with simulated AUVs.**
Pilot error	Loss of useful science data or AUV loss due to collision with shore	Pilot in pairs. Pre-plan and independently review mission plans. **Rehearse pre-planned mission plans in simulation.**
OCS failure (OCS fault)	Loss of control of AUV, leading to incident or loss of AUV	Perform long-duration hardware and software testing. Rely on the on-board system watchdog to help detect and recover from OCS malfunctions. **Exercise the OCS in simulation**.
AUV hardware failure	Inability to collect science data, early recovery of AUV, or AUV loss	Test the system extensively in water to benchmark system performance. Extend end-to-end quayside testing to identify faults prior to deployment.
Inadequate navigational awareness near shipping lanes	Ship strike leading to damage or loss of AUV	Fit flashing strobe light. Send notice to Mariners. Plan missions to avoid or limit operation in shipping areas. Request pilots to monitor the automatic identification system to identify other vessels early.
Improper interaction with moving parts of the AUV	Injury to operator or personnel	Select the recovery vessel and crew carefully. Ensure propeller stopped before approaching the AUV. Organise toolbox talks.

III. RESULTS AND DISCUSSION

A. Long-Distance Proving Trial (LDPT): Southwest Approaches

1) Campaign Rationale: The LDPT took place in the Southwest Approaches in Spring 2022. The main goal of the deployment was to demonstrate the robustness and the capabilities of the ALR platform through a multiweek unaccompanied deployment [21]. The key objectives of the deployment included the demonstration of mission planning and over-the-horizon piloting through the NOC C2 system, the demonstration of the ability to perform various mission types with the vehicle in order to increase the range of available scientific data collection methods, and the demonstration of the long-term stability of the OCS. Missions were defined as a combination of simpler maneuvers to further demonstrate the flexibility and adaptability of the whole system to changing requirements.

2) Key Risks: Prior to the deployment, a HAZID activity was conducted as part of the campaign risk assessment process, introduced in Section II-A. The risks with the highest criticality, after mitigation, are highlighted in Table I.

3) Simulation Activity: The simulation solution, introduced in Section II-C, helped reduce the criticality of 3 out of the 11 risks listed in Table I: pilot error; C2 fault; and OCS fault. Mission rehearsals were performed in simulation to exercise the system components associated with these investigated risks.

In total, before the deployment, 43 missions were simulated (out of the 55 effectively run during the deployment), as they represented a wide range of mission archetypes, such as calibration missions, transits toward areas of scientific interest, and sampling missions. The virtual environment for the simulation was created using bathymetry information of the Celtic Sea, extracted from the GEBCO data set since high resolution was not required for the LDPT campaign.

The main issues identified in simulation, along with the updated risk mitigations, are summarized in Table II. There was no undesirable behavior observed with the C2 system.

4) Campaign Outcomes: On 10 May 2022, ALR-4 was towed south of the Plymouth Breakwater and released to mission. The ALR transited independently in a southwest direction, from Plymouth coastal waters, past the continental shelf into open ocean, and back (see Fig. 6). The ALR was recovered in Plymouth on 13 June 2022. The deployment consisted of dives lasting roughly 4–24 h. After each dive, the ALR telemetered back decimated data and received updated piloting instructions.

During the deployment, two main issues were identified, which however did not jeopardize the main goal. The first issue involved a compass calibration mission which did not end properly, resulting in poor calibration coefficients being used by the OCS. The second issue involved an increased biological productivity in the upper layers of the water column which caused false returns on the downward-looking DVL, preventing

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TABLE II
SUMMARY OF SIMULATION RESULTS FOR LDPT DEPLOYMENT

Investigated Risk	Undesirable Behavior Discovered	Updated Risk Mitigation
Pilot error	Insufficient or incorrect mission timeouts were set for 8 mission plans created by pilots, resulting in contingency behaviors being triggered at unexpected times, even when the vehicle was not stuck and still responsive	The timeouts were set to a higher/safer value in updated missions to prevent early trigger of contingency behaviors.
Pilot error	The virtual vehicle reported the inability to descend to deeper depths (i.e., descent velocity below threshold) during a transit mission planned by pilots	This issue seemed to only affect the simulation solution because of the hydrodynamic coefficients selected for the virtual AUV: the turning and diving motion affected the angle of descent and velocities just enough to cause the issue.
Pilot error	One mission was pointing toward the opposite direction of the intended trajectory	The waypoints in the mission were adjusted to correctly orient the trajectory.
OCS failure (OCS fault)	On simulation startup, the ALR vehicle configuration failed to load in the OCS	The vehicle configuration was fixed.
OCS failure (OCS fault)	The on-board logger exhibited data gaps when periodically creating new log files	It was commonly agreed to limit the creation of new files.
OCS failure (OCS fault)	Speed over ground demand was incorrectly rounded	The precision of fields used to store speed demands within each manoeuvre was increased.

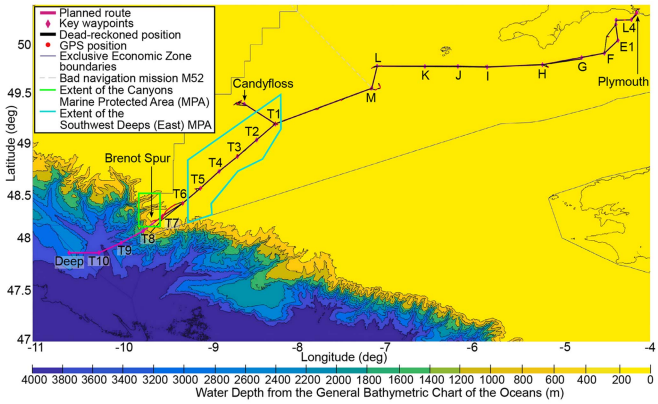

Fig. 6. LDPT Route (extracted from [21] under https://creativecommons.org/licenses/by/4.0/ CC BY licence and then enhanced for clarity).

the vehicle from diving (i.e., the AUV thought it was too close to the seabed).

The first issue could have been observed in simulation if a compass emulator had been available. The second issue could not have been anticipated through simulation before the deployment, as it was very specific to the hardware, the environment, and the specific time of the year. Even though a mitigation could have been tested against random false returns in simulation, the vehicle was not accessible during the deployment to implement the mitigation.

Apart from the two issues identified above, the deployment was an overall success, as the simulation solution contributed to mitigate behaviors that could have resulted in costly mistakes during the deployment. Notably, the detection of undesirable behaviors in simulation prevented the loss of up to 88 h during an 821-h deployment, representing 11% of potential data collection time. To understand the hours lost, consider the wrongly oriented mission: it would have cost 15 h to execute the mission, 1 h to realize the mistake, 15 h to come back on track and then execute the corrected mission. Similarly, incorrect timeouts in mission could have triggered contingency behaviors leading to a minimum of 1 h of remote debugging while trying to get the vehicle back on track.

B. Over-the-Horizon Camera Surveys Near Decommissioned Oil and Gas Infrastructure in the North Sea

1) Campaign Rationale: Decommissioned offshore infrastructure requires thorough environmental assessment and monitoring to understand ecological changes and mitigate any unexpected impacts. Advances in autonomous monitoring of the marine environment around offshore installations offer the potential for significant improvements in monitoring efficiency [33], yet these approaches remain largely untested. The main goal of the Autonomous Techniques for anthropogenic Structure Ecological Assessment (AT-SEA) project was to undertake the first shore-launch environmental survey of decommissioned offshore infrastructure in the North Sea [34]. The key objectives of the deployment included the execution of survey missions near infrastructure with limited knowledge of the terrain prior to the deployment, as well as the demonstration of accurate navigation to travel from shore to the areas of interest while avoiding busy areas of marine traffic and scattered "restricted areas" in which private business operations were being carried out.

2) Key Risks: Prior to the deployment, a HAZID activity was conducted. The risks listed in Table I for LDPT were relevant for AT-SEA, even though some of them were less critical for AT-SEA mainly due to the difference in environments. Furthermore, the risk associated with end-to-end system testing involving OCS and C2 was already mitigated by previous deployments (LDPT included). The HAZID activity helped identify complementary risks for AT-SEA with high criticality after mitigation. These complementary risks are highlighted in Table III.

3) Simulation Activity: The simulation solution helped reduce the criticality of 1 out of the 2 risks exclusively relevant to AT-SEA and listed in Table III: inadequate navigational awareness near subsea infrastructure. The simulation solution also addressed 1 recurrent risk previously identified for LDPT deployment as listed in Table I: pilot error. Mission rehearsals were performed in simulation to exercise the system components associated with these investigated risks.

In total, before the deployment, 25 missions were simulated (out of the 35 effectively run during the deployment). The missions were split over two legs: 17 missions (out of 20) were simulated for the northern leg from Lerwick to Northwest

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TABLE III
SUMMARY OF HAZID ACTIVITY FOR AT-SEA DEPLOYMENT (COMPLEMENTS THE SUMMARY PROVIDED IN TABLE I)

Identified Risk	Potential Consequence	Risk Mitigation
Inadequate navigational awareness near subsea infrastructure	Damage or loss of AUV, trapped in subsea infrastructure	Plan missions away from known submerged objects whenever possible. Fly at a sensible altitude (> 30 m) during transit missions to give enough time to the AUV to react. Run low-altitude missions at a higher altitude first to confirm obstruction-free path. Fit a forward-looking collision avoidance system. **Rehearse missions near infrastructures in simulation.**
Inadequate handling of class 4 lasers (part of the sensors)	Injury to eyes or skin	Train operators and define suitable SOPs. Fit a hydrostatic isolation switch to prevent lasers being operable in air or on the surface. Use software interlock to further prevent operation of lasers in air or on the surface.

TABLE IV
SUMMARY OF SIMULATION RESULTS FOR AT-SEA DEPLOYMENT

Investigated Risk	Undesirable Behavior Discovered	Updated Risk Mitigation
Pilot error	Insufficient or incorrect mission timeouts were set for 6 mission plans, causing the AUV to try to surface earlier than expected and to start surveys before reaching the desired depth	The timeouts were set to a higher/safer value in updated missions to ensure complete underwater surveys.
Inadequate navigational awareness near subsea infrastructure	The on-board avoidance system prevented the virtual vehicle from diving because of insufficient water depth during a mission	This issue only affected the simulation solution due to the inaccuracy of the GEBCO map near the shore: the virtual vehicle ended up too close to the seabed while on surface.
Inadequate navigational awareness near subsea infrastructure	Relatively large surfacing errors were observed in simulation (around 2% of the distance travelled), despite not simulating sea currents	This issue was traced back to the different world models used by the virtual GPS sensor provided by Gazebo (based on the WGS84 Earth model) and UUV Simulator requiring a projected flat world. Navigation accuracy was increased locally in simulation by creating a number of smaller virtual environments near each modelled infrastructure.

Hutton; and only 8 missions (out of 15) were simulated for the southern leg from Lerwick to Miller and Braemar Pockmarks. The southern leg had effectively less priority than its northern counterpart and the missions were still being planned at the time of testing. The simulated missions were run with virtual ALR-3, in a virtual representation of the North Sea created with GEBCO bathymetry combined with limited high-accuracy survey data and enhanced with true-scale infrastructure models (i.e., meshes represented as a hollow rectangular footprint with a circular shape at each corner) positioned according to locations reported in available sources.

The main issues identified in simulation, along with the updated risk mitigations, are summarized in Table IV.

4) Campaign Outcomes: Over 21 days, starting from 19 September 2022, ALR-3 conducted two deployments from Lerwick out into the North Sea, traveling more than 1000 km. The ALR collected millions of seabed images and detailed environmental data at the decommissioned Northwest Hutton and Miller platforms, as well as across the Braemar Pockmarks Special Area of Conservation.

Only one major issue was identified during the deployment: the vehicle reported being unable to descend fast enough during one mission. The issue arose because ALR was asked to dive at low speed and was already close to the destination waypoint. This situation created a hydrodynamic effect that considerably slowed the downward progression of the vehicle. On the second attempt at running the mission, the ALR successfully dived because it started further away from the target waypoint. The issue could have been identified in simulation if the descent velocity threshold had not been modified for the NGS following an edge-case behavior reported in Table II.

Apart from the issue identified above, the navigation error was evaluated at a staggering 0.66% of the distance traveled, thanks to bottom-lock navigation (i.e., constant flying of the AUV close to the seabed). The deployment outcomes confirmed once more that the derisking exercise with the simulation solution helped significantly reduce the occurrence of navigation and planning issues. Notably, simulation prevented the loss of up to 47 h during a 517-h deployment, representing 9.1% of potential data collection time.

C. Under-Ice Operations in the Amundsen Sea

1) Campaign Rationale: Due to their nature, polar operations are particularly high-risk for AUV operations, yet they have the potential to provide unique measurements beneath the ice. As part of the Thwaites-Amundsen Regional Survey and Network Integrating Atmosphere-Ice-Ocean Processes (TARSAN) project [35], ALR was deployed in the Amundsen Sea at the beginning of 2022. The main goal of the deployment was to collect physical oceanography data to help explain the drivers for the unexplained and worryingly fast rate of Thwaites Glacier melting. The key objectives of the deployment focused on a set of required new engineering developments [36], such as new collision avoidance features, new under-ice maneuvers with emergency countermeasures, as well as colocated C2 (i.e., at the same physical location) since over-the-horizon piloting in such complex and changing environment would not have been suitable.

2) Key Risks: The HAZID activity for TARSAN shared many risks with the LDPT assessment, although differences in deployment duration and environment altered their criticality. Additional high-criticality risks specific to TARSAN are listed in Table V.

3) Simulation Activity: The simulation solution helped reduce the criticality of 4 out the 5 risks exclusively relevant to TARSAN deployment and listed in Table V: incorrect under-ice mission design (correlated with pilot error); inadequate

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TABLE V
SUMMARY OF HAZID ACTIVITY FOR TARSAN DEPLOYMENT (COMPLEMENTS THE SUMMARY PROVIDED IN TABLE I)

Identified Risk	Potential Consequence	Risk Mitigation
Incorrect under-ice mission design	Loss of ALR due to highly unpredictable behavior	Design simple missions. Ensure independent review of missions. **Rehearse under-ice missions in simulation.**
Inadequate navigational awareness near variable sea ice	Loss of AUV, unable to surface or be acoustically guided to surface	Reduce length of missions to build confidence in successful recoveries. Ensure ability to retask AUV at depth via acoustic communications. Design missions with final surfacing location defined well clear of ice-covered regions.
Inadequate navigational awareness over highly complex terrain	Loss of AUV, unable to self-localize or navigate over obstacles	Fly AUV at high altitudes ($\sim$ 100 m) over moderate features. Rely on forward-looking collision avoidance system for rough terrain. **Exercise navigation in challenging virtual environment.**
Inadequate navigational awareness below complex ice shelf morphology	Loss of AUV, unable to get out of crevasses	Rely on upward-looking DVL to ensure sufficient spacing with ice keel. Set a minimum depth in missions to fly below the expected ice keel. **Exercise navigation in noisy virtual environment.**
Incorrect contingency behavior design	Loss of AUV, affected by a system failure preventing it from exiting under-ice cavities	Follow pre-deployment SOPs before every launch to verify integrity of system. Increase confidence in the system following extensive trials before the deployment. **Exercise contingency behaviors in simulation.**

TABLE VI
SUMMARY OF SIMULATION RESULTS FOR TARSAN DEPLOYMENT

Investigated Risk	Undesirable Behavior Discovered	Updated Risk Mitigation
Incorrect under-ice mission design	Insufficient timeouts were set on some mission legs, causing the virtual AUV to skip the end parts of affected legs and severely altering the intended trajectory	The timeouts were set to a higher/safer value in updated missions to ensure intended trajectories.
Inadequate navigational awareness over highly complex terrain	In the virtual under-ice playground (see Fig. 7), the altitude dropped rapidly when the virtual AUV tried to retreat, especially while attempting a U-turn on a steep slope	The minimum altitude above the seabed was increased and higher/safer thresholds related to the triggering of an event leading to a retreat were defined, as the issue was representative of a potential real-world scenario.
Inadequate navigational awareness over highly complex terrain	The virtual AUV was able to fly up steep slopes, even up to 75 degrees, thanks to the forward-looking avoidance sensor; however, after flying down even steeper slopes, the virtual AUV ended up stuck during a retreat in the "consecutive slopes" lane of the virtual under-ice playground	Downward steep slopes were avoided as much as possible at the planning stage, as the issue was representative of a potential real-world scenario.
Inadequate navigational awareness over highly complex terrain	In the noisy virtual under-ice environment (refer to Section III-C3), even though the virtual AUV was able to navigate in and out of the under-ice cavities, oscillations in depth control were spotted because of spurious detection of seabed features and slopes	A potential need for altitude filtering was identified but not implemented because the reason for the oscillations was attributed to the highly noisy geometry of the environment.
Inadequate navigational awareness below complex ice shelf morphology	The AUV did not respect the minimum depth set in a mission and went directly to the shallower target depth, which is unsafe when trying to avoid the ice keel	This edge-case issue in the mission executive (Helm) was analysed and fixed.
Incorrect contingency behavior design	The Helm did not trigger a retreat in a tight under-ice cavity when it was supposed to	This issue in the Helm was analysed and fixed.

navigational awareness over highly complex terrain and below complex ice shelf morphology; and incorrect contingency behavior design. The simulation solution focused on mission rehearsal and OCS robustness validation in various virtual environments, so that the system components involved with these investigated risks were exercised.

Surprisingly, none of the 12 missions run during the deployment were directly simulated ahead of the expedition because the location of the deployment changed from Thwaites to the Dotson Ice Shelf due to adverse sea ice conditions. These 12 missions were in fact derisked during the deployment itself, thanks to a portable version of the simulation solution which enabled the field team to fully test each mission right before launching the vehicle. This versatile approach represents the campaign risk management process (see Fig. 1) applied to individual missions.

Prior to the deployment, the simulation solution focused on general under-ice features as well as occasional Thwaites features. The simulated missions were run with virtual ALR-1, in a virtual environment created from BedMachine Antarctica v2 representing both the seabed and the continental ice derived from water column thickness provided with the model.

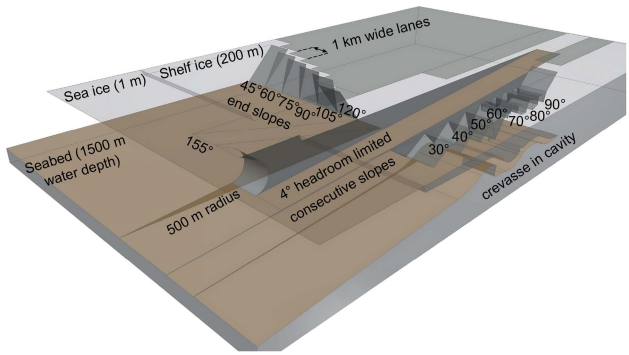

Fig. 7. Virtual under-ice playground specifications.

To further exercise the AUV capabilities, a challenging virtual environment was created. The environment was made more realistic by applying a noisy function to the depth element of the seabed, producing complex troughs and holes in the virtual terrain. In addition, to simulate compass and DVL noise near the poles and in under-ice environments, an artificial bias was introduced to the heading and velocity measurements. These values

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were estimated from data collected during previous Antarctic operations.

To specifically exercise the mission executive and avoidance system in a more controlled environment, a virtual under-ice playground was created (see Fig. 7). The playground was designed to contain multiple 1 km wide and 10 km long lanes with varying slopes and carefully selected under-ice features.

The main issues identified in simulation, along with the updated risk mitigations, are summarized in Table VI.

4) Campaign Outcomes: The TARSAN campaign was conducted on board the *Nathaniel B. Palmer* Research Vessel, supported by the United States National Science Foundation. The ship departed from Punta Arenas, Chile on 7 January 2022, but sea ice conditions prevented the ship from accessing the Thwaites Ice Shelf and forced it to navigate to the Dotson Ice Shelf which was comparatively accessible. The original mission plans were adapted and ALR-1 completed a total of 12 missions.

The campaign ended successfully at the beginning of March 2022. Even though a few issues were spotted during TARSAN, they did not jeopardize the objectives of the deployment. First, a small leak from a pressure relief valve adaptor was spotted during the first mission in open water, but the adaptor was promptly replaced. This was a purely mechanical fault and could not have been derisked with the simulation solution. Second, one timeout was set too short for the inward leg of a mission (DOT-4 18) [36]. This issue could have been spotted in simulation, but the mission had probably been changed at the last minute to adapt to changing ice conditions. Third, actual and false positive "actuator stuck" events were signaled during various missions. The events were indicating the fact that the actuator position did not match the demanded position within a certain threshold. The false positive events were traced back to hardware faults and communication delays between the software and the hardware, which could not have been spotted in simulation as they relied on hardware observations. Finally, spurious up-altitude measurements (i.e., distance between the ice shelf and the vehicle) triggered a retreat during a mission. These measurements were highly dependent on the hardware reacting to its environment. However, thanks to the portable simulation solution used during the deployment, the engineers were able to successfully design and test a filter to reject randomly generated false positive up-altitude measurements.

The deployment outcomes confirmed once again that the derisking exercise with the simulation solution helped significantly reduce the occurrence of critical issues linked to system behavior and planning, even in complex and unknown environments. Notably, the simulation solution helped prevent up to five potential scenarios that could have led to vehicle loss.

IV. Conclusion

Extending the operational envelope of AUVs to long-duration over-the-horizon operations introduces new hazards and often elevates the associated risk profile. To address this operational challenge, we demonstrated how high-fidelity physics-informed simulation can be systematically integrated into the risk management workflow of complex long-range AUV operations. Across three demanding ALR campaigns, simulation played a central role in validating mission plans, exercising software behaviors, as well as increasing operational confidence before and during deployment. The LDPT campaign marked the first unaccompanied multiweek deployment of an ALR and used simulation extensively to validate new mission concepts and assess the long-term stability of the software ecosystem, alongside quayside and in-water testing. The AT-SEA deployment involved complex low-altitude operations near decommissioned oil and gas infrastructure, where simulation was used to evaluate navigation performance and identify piloting and planning errors that could have resulted in collision or entanglement with subsea assets. The TARSAN campaign required the development and validation of new collision-avoidance and contingency behaviors for multiday under-ice missions in a highly uncertain environment. In this context, simulation served as a critical platform for validating operational logic, evaluating edge-case scenarios, and increasing confidence in the resilience of the autonomy stack both before and during field deployment.

Although simulation proved valuable in derisking AUV operations, it should be regarded as only one of the tools available to mitigate the risks associated with complex deployments. Regardless of the degree of fidelity of the simulation, real-world testing will generally reveal unexpected system behavior and even demonstrate the potential of the operator to command the AUV to perform injudicious actions.

Building on the positive outcomes achieved through simulation, ongoing development at NOC focuses on further integrating simulation into the operational lifecycle of long-range AUV deployments and expanding its role in system assurance and mission preparation. Current developments include the following.

a) The operationalization of the simulation solution within the C2 piloting toolchain, enabling pilots to routinely rehearse, validate, and assess missions directly within the operational environment.
b) The development of a Continuous Integration framework leveraging simulation to automate regression testing and behavioral validation of new OCS software releases prior to deployment.
c) The implementation of hardware-in-the-loop capabilities to enable the testing and validation of physical subsystems and interfaces within a controlled simulated environment.
d) The incorporation of a fault-injection system to evaluate system robustness against edge-case failures and abnormal operational scenarios that are difficult, unsafe, or impractical to reproduce in the field.
e) The investigation of complementary low-fidelity simulation approaches to support rapid mission iteration and early-stage operational assessment in time-constrained or dynamically changing deployment scenarios, as highlighted during the TARSAN campaign.

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