LUPINE PUBLISHERS

Advances in Robotics & Mechanical Engineering

DOI: 10.32474/ARME.2023.04.000178

ISSN: 2643-6736

Research Article

An Autonomous Underwater Vehicle (AUV) Dual Driver System for Subsurface Hydrocarbon Plume Survey

Jimin Hwang[1]*, Neil Bose[2], Gina Millar[3], Ginelle Nazareth[4] and Craig Bulger[5]

[1]*Faculty of Engineering and Applied Science, Memorial University of Newfoundland, Canada*

[2]*Office of the President, Memorial University of Newfoundland, Canada*

[3]*Autonomous Ocean Systems Centre, Memorial University of Newfoundland, Canada*

[4]*Faculty of Engineering and Applied Science, Memorial University of Newfoundland, Canada*

[5]*Centre for Applied Ocean Technology, Fisheries and Marine Institute of Memorial University of Newfoundland, Canada*

***Corresponding author:** Jimin Hwang, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, Canada

Received: June 20, 2023 **Published:** June 26, 2023

Abstract

Autonomous Underwater Vehicles (AUVs) are a highly suitable platform to investigate subsurface oil spills in the ocean. Adopting a dual driver system (sometimes known as a backseat driver) is now becoming almost standard practice since it enhances autonomy in the operation of the vehicle, thus increasing the achievement of successful mission goals. The objective of our project was to develop an autonomous system to effectively search and survey a petroleum hydrocarbon plume in the ocean using a single AUV. This paper introduces the developed dual driver system for the Memorial Explorer AUV. A modular control architecture for the backseat driver was designed. Our developed system was successfully validated through MOOS-IvP simulations and open water field trials. The field experiment results verified that the autonomy has been enhanced by separation of the dual drivers, while ensuring safety of operation of the vehicle.

Keywords: Autonomous Underwater Vehicle (AUV); dual-driver system; adaptive sampling; AUV autonomy; subsurface oil search design; in-situ oil sensors; oil-in-water detection

Introduction

The ocean is the largest water body on Earth, covering three quarters of the planet's surface. It makes our planet habitable by providing 97% of the water supply for all life [1]. However, the oceans are under rapidly increasing stress due to pollution [2]. The Industrial Revolution in the mid-19th century brought us material affluence, but it also brought about the beginning of global water pollution [3]. The Second World War was followed by the post-war baby boom until the 1960s resulting in a significant population growth [4]. The combination of those two events has led to population pressure and the current climate change crisis at levels that humans have never had to face before. One of the most serious adverse effects is the limitation of the oceans to slow down climate change by absorbing increasing levels of anthropogenic CO_2 from the atmosphere, which presently accounts for one quarter of total CO_2 emissions (about 10-20 billion tones'annually) [5]. In principle, cold water is better at dissolving greenhouse gasses compared with warmer water [6]. With continuously increasing sea surface temperatures, the oceans role as the biggest carbon sink becomes less efficient, and the absorbed gas can even be released back into the atmosphere more rapidly than it is absorbed. This affects not just the countless fish and other ocean creatures, but also all living creatures on the planet; consequently, the need for unpolluted oceans is more important now than ever. The fundamental concept underlying the implementation of dual drivers in AUVs involves the separation of the primary vehicle propulsion unit and the decision-making unit, thus establishing

Copyright © All rights are reserved by Jimin Hwang.

the significance of a backseat driver in the context of adaptive sampling during AUV missions. The integration of a backseat driver enhances the AUV's ability to achieve targeted sampling objectives and supports monitoring efforts in various disciplines, including oceanography, marine biology, and environmental studies. Several studies have examined the application of this approach in the realm of AUVs. Petillo et al. [7] proposed an average gradient method that utilized temperature profiles to determine depth bins and identify thermoclines. Zhang et al. [8] focused on tracking thermoclines by detecting maximum vertical temperature gradients, while Woithe and Kremer [9] introduced a dichotomous triggering method based on temperature and depth thresholds. Das et al. [10] introduced a hierarchical probabilistic regression to achieve targeted sampling by considering environmental parameters and organism abundance. Smith et al. [11] employed data assimilation and model-based trajectory design to define sampling waypoints, and Ferri et al. [12] utilized a triggered spiral prospecting strategy for adaptive surveying. Farrell et al. [13] developed a behavior-based plan for tracking chemical plumes, and Zhang et al. [14] modified an adaptive triggering algorithm for oil detection.

Each approach showcases different data-driven methods implemented through the utilization of a separate data processing unit in AUV missions. Compared to previous works, our project stands out by addressing the specific objective of searching and surveying suspended targets in an unknown georeferenced location. Our team focuses on discrete small-sized pollutant particles that are not completely dissolvable in seawater such as petroleum hydrocarbons. Our work was inspired by the 2010 Deepwater Horizon explosion that led to the largest oil spill incident in history [14,15]. To facilitate the autonomy of the vehicle during a mission, we employed a dual driver system for our AUV and human intervention to minimize mission length and time to achieve a given outcome. We introduced a modular control architecture to accommodate an agile AUV operation supporting in-situ target detection, real-time analysis, and an adaptive decision-making process. This strategy is not only a cost-effective way of managing the mission by maximizing the limited resources, but it also provides flexibility in delineating an inadequately defined target in the water column. The developed system, which was simulated and validated via field trials in the ocean, is described.

Modular control architecture of the AUV

Modularity is generally a vital element in robotics since it preserves the coherence with both hardware and software architecture [16]. Having more than one vehicle driver (meaning a controller in this context) allows the allocation of distributed mission tasks to each driver; hence, decreasing the possibility of failure of a mission or compromised commands. Our AUV has been equipped with two drivers: a frontseat driver (also known as the Vehicle Control Computer or VCC) which is the vehicle's dynamic control processor and a backseat driver which is the intelligent control processor. Typically, the VCC controls the dynamic motions of the AUV to maintain the desired vehicle state (course, speed and depth). Having dual vehicle drivers is extremely beneficial in conducting underwater missions especially in the case where the area of operation is unstructured or prior knowledge of the target of interest is insufficient. For example, if the target of interest is at an unknown location, the vehicle must first survey the area to locate it. If the vehicle is to continue from this point without human intervention these situations demand the vehicle to autonomously decide the next move itself. Furlong et al. [17] highlighted that one of the significant advantages of having a modular control architecture is the increased portability of software from detachment autonomy system from the vehicle details. This type of approach contributes to bringing marine robotics one step closer to full autonomy. There are a few software systems available to support the dual driver mode for marine vehicles - not just for AUVs, but also for Autonomous Surface Vehicles (ASV) - these include the Robot Operating System (ROS), Lightweight Communications and Marshalling (LCM), Teleo - Reactive Executive (T-REX), and the Mission Oriented Operating Suite - Interval Programming (MOOS-IvP). In the common acceptance of the word, these are called Backseat Driver (BD) controllers. However, the control architecture proposed in this paper will be referred to as Dual Driver control because it is more culturally sensitive and a more accurate description of our application.

Dual driver system

We enhanced the autonomy of our AUV by integrating an additional payload computer in which MOOS-IvP was installed, making it dedicated to collecting and processing in-situ data from a suite of scientific sensors. The payload computer (the second AUV driver) connected with various scientific sensors can collect and process in-situ sensor data in real time. It can also use the analysis of this data to autonomously make important decisions without a human in the decision-making loop to accomplish the mission goals. The developed dual driver system for AUV maneuvering and mission accomplishment is shown in Figure 1. Basically, the front seat driver oversees the thruster and planes to directly control the motion of the vehicle (e.g., location and heading) to follow the given path by the operator prior to the mission. The backseat driver, on the other hand, makes independent decisions on which tasks to perform via reasoning (or logical processes) based on the (near) real time information about the surrounding environment in which the vehicle operates. That information is based on onboard in-situ sensor data and the backseat driver computer performs real-time analysis. When an AUV is deployed, the front seat driver assumes control and monitors the vehicle's state, position, faults, and surrounding hazards. Upon reaching the designated start location, the front seat driver transfers control to the backseat driver, which determines the next target location (x, y, z). The front seat driver accepts the backseat driver's decisions unless there are reported hazards, or the decisions exceed pre-set limits on operation. Throughout the mission, the front seat driver continues to perform functions such as hazard monitoring, vehicle state monitoring, and obstacle avoidance, regardless of the driver in control. At mission

completion, the front seat driver resumes control and returns to the base. If the vehicle or mission deviates from safety criteria or pre-set limits (e.g., spatial, temporal, and state), the front seat driver overrides the backseat driver's commands. This dual driver system enhances AUV autonomy while ensuring mission safety is not compromised. It should be also noted that the ` operations are crucial. Therefore, balancing the power requirements for both drivers and optimizing energy efficiency become vital considerations to maintain the AUV's endurance.

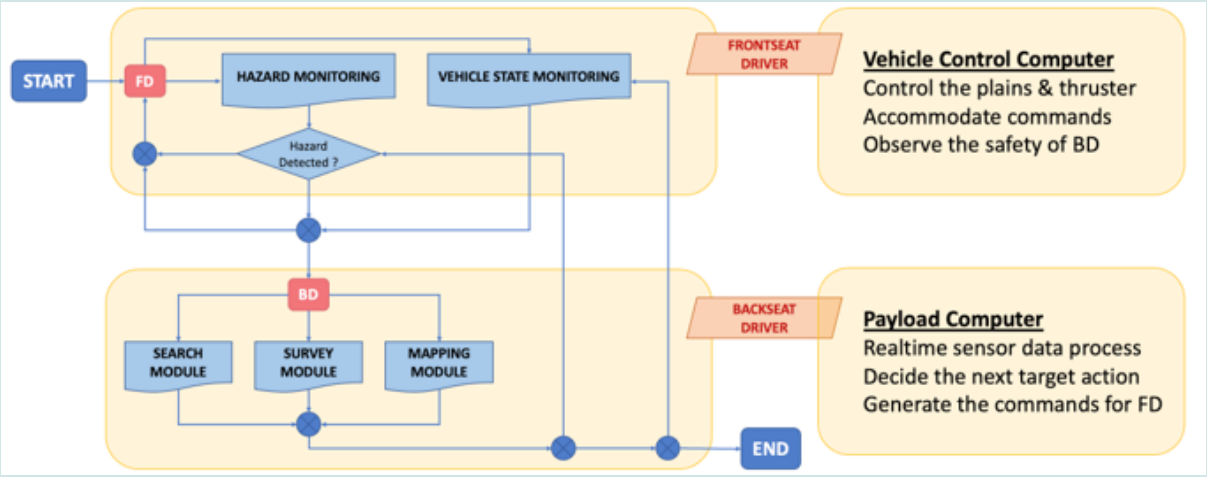


Figure 1: Flowchart describing the separated dual driver control units developed for AUV mission.

Oil Dynamics in Ocean

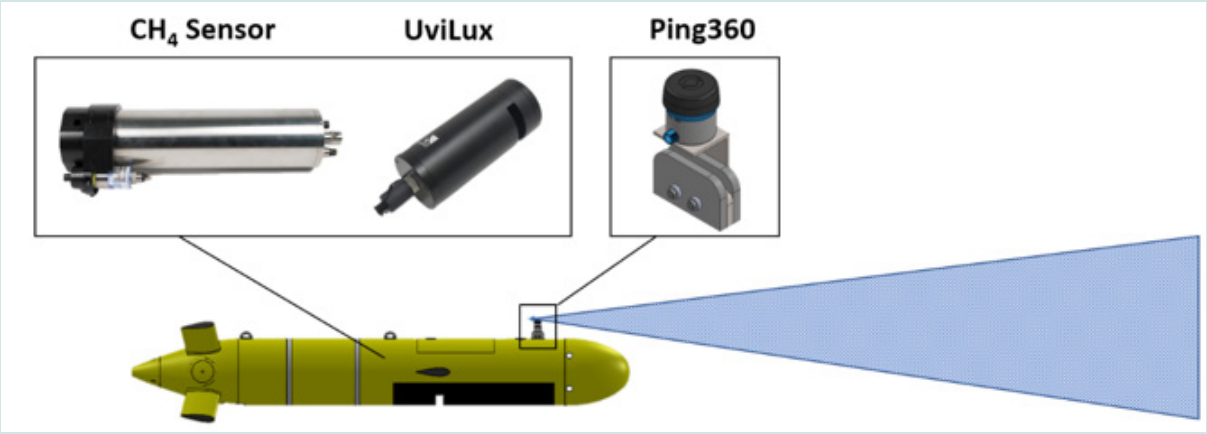


Figure 2: Sensors on board the MUN Explorer AUV for detecting and mapping an oil plume.

To further our missions, it is essential to understand the dynamic attributes of an oil spill in seawater. Once released into the ocean, oil is subjected to a variety of external influences, and undergoes numerous physical, chemical, and biological processes. For example, it is transported away from the source of the spill by ambient currents, and extensively distributed vertically by waves. The impacts of those external forces on spilled oil are explained and tested [18,19]. After some time, oil in sea water also goes through oxidization by sunlight (on the surface) and marine organisms (in the water column), respectively. This implies two things: firstly, a rapid investigation is required for oil spill response purposes; secondly, those variables must be taken into consideration when planning AUV missions. Oil is a complex mixture of molecular compounds although crude oils are primarily composed of Hydrogen (H) and Carbon (C) known as hydrocarbons. Petroleum hydrocarbons include one of two types, aromatics (the atomic bond is based on a 6-carbon benzene ring) or alkanes (the carbon atoms are connected by a straight-chain). Different compounds of oil present different characteristics in sensing perspectives. Therefore, to maximize the location of a plume, we aim to target various aspects of a plume by utilizing several oil sensors. Through field tests in the past few years, we have developed multi survey modules that can be run independently and sequentially [20,21]. We also designed several combinations of those modules. In this

paper, we will introduce one of those combinations that is designed to specifically investigate "a mixed phased oil plume consisting of oil droplets and gas bubbles". We have selected and integrated three types of oil detecting sensors: a Ping360 sonar, UviLux fluorometer, and CH4 sensor (See Figure 2). The Ping360 is a mechanically scanning sonar which senses acoustic scattering of a target in the water column; the UviLux is a fluorometer which measures fluorescence (or emission of light) of a specific wavelength by objects; the CH4 sensor is a laser-based methane sniffer that can detect straight-chain hydrocarbons. Although the UviLux and CH4 sensors are operated conjointly, it is unlikely for both units to detect the same compound because their detection ranges of hydrocarbon do not overlap. For example, the CH4 sensor does not respond to benzene ring-chained structured hydrocarbons (e.g., PAH).

Three Modules: Search, Survey, and Mapping

The developed oil investigation model consists of Search, Survey and Mapping modules; and they all run simultaneously over the entire course of mission. The Search module connected with the Ping360 is responsible for remotely locating a plume at a distance in an efficient and effective way in terms of balancing cost and safety. Therefore, a (non-point-based) remote sensing method was adopted. The Ping360 has a scanning range up to 50m, horizontal azimuth angle of 360 degrees with a vertical coverage of 25 degrees. The collected acoustic data is processed in real-time by the Search module. If the analyzed information satisfies the set criteria, a 'white flag' is planted on the empty map in the Mapping module. Then the survey zone #N is created with the 'white flag' as the center. The AUV then conducts a thorough survey using two independent sub-modules of the Survey module to pick oil sensor readings of the hydrocarbon plume. At the end of the survey, the area is declared as either a 'green flag' or 'red flag' to confirm the presence of an oil plume; then the Search module is continued until the next 'white flag' is declared. Figure 3 presents a diagram showing the detailed layout of each module.

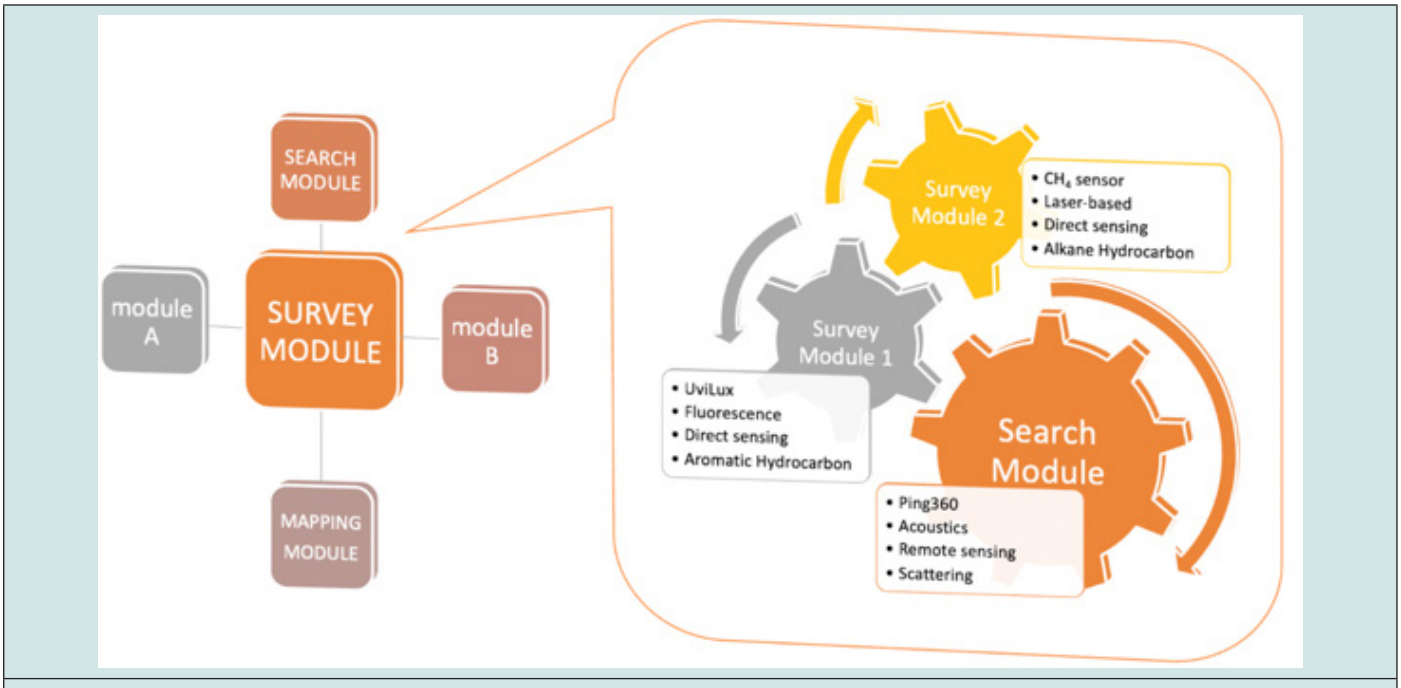


Figure 3: A schematic of the Search, Survey and Mapping modules and their details.

Simulation

Three categories of missions (Search missions; Survey missions; Depth-varying missions) were planned for field trials. They were simulated in MOOS-IvP software prior to the field trials.

Search Missions (Alpha)

Previously, we developed a biomimetic search method [21] to design an efficient and effective way of locating a single oil plume within a given unknown search area. However, in this work, we extended the approach to find a number of plumes over a range of locations within a given search area. Therefore, evenly distributed waypoints were allocated to maximize the areal coverage. Two search missions (named alpha missions in our programming terms) were simulated: one with a checkerboard path (named alpha-1), and the other with a fishbone shape (named alpha-2). A list of waypoints was given to each mission (20 and 17, respectively) as shown in Figure 4, to test the dual driver operation in the absence of sensor inputs, and the AUV performed line-following between those waypoints. A tolerance of 1.0 meter was given to approve the valid arrival at each waypoint.

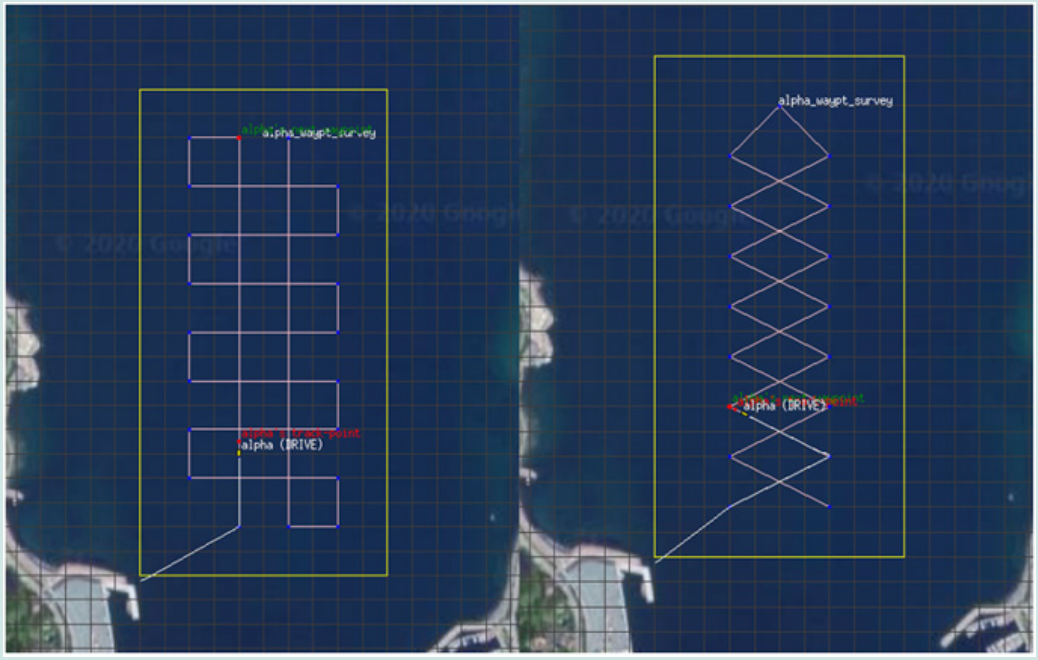


Figure 4: Search missions: alpha-1 and alpha-2 in MOOS-IvP simulation.

Survey Missions (Beta)

The survey missions (named beta missions) were to verify the dual driver's capability of making decisions based on external information (navigational data) that was received by the driver. Since the second aim of this simulation was to determine the survey pattern (in a horizontal plane), we simplified the required conditions to provoke the survey to 'arrival at waypoints' instead of 'found the plume'. The first pattern was a bowtie shape (named beta-1) and the second one (named beta-2) was a circular shape as shown in Figure 5. Both surveying behaviors were controlled by the developed MOOS BHV codes: BHV_Loitering and BHV_Turning, respectively. Our developed MOOS application Search keeps updating the goal achievement status. Once the status is "achieved", the vehicle is triggered to perform surveying. In the simulation, the AUV performs surveying on the spot, this can also be flexibly adjusted to "Go to flag" and then perform surveying in a real oil spill situation.

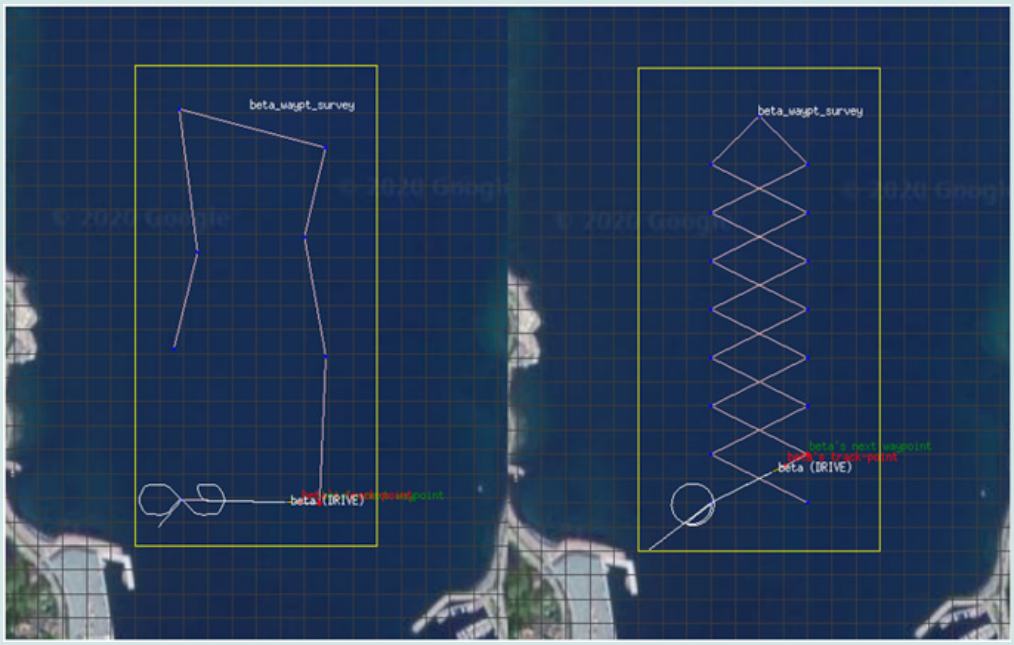


Figure 5: Survey missions: beta-1 and beta-2 in MOOS-IvP simulation.

Depth Varying Missions (Delta)

We also simulated three depth-varying scenarios (named delta, delta_psurf, and delta_gdep, respectively) to extend the vertical coverage for the Survey modules. See Figures 6-8. Depth varying missions were generated in two ways. The first way was to define a series of target depths and the BHV_GoToDepth function coupled with a timer function can be utilized to determine how long the vehicle is to remain at each depth. This depth can also be set as a dynamic variable: target depth is determined and autonomously modified by the analyzed data of real-time sensors while AUV passes through an oil plume. The second way is to set a surfacing behavior which periodically forces the vehicle to go to the surface (depth = 0) after remaining at a constant depth for a set desired time using the functions called BHV_PeriodicSurface and BHV_ConstantDepth. In the first depth-varying mission (delta), we tested the MOOS behavior function: BHV_GoToDepth with the set target depth 3m, 8m, and 13m repeatedly. This was also to visualize the vertical turning (yo-yo path) and to confirm maneuverability of our Explorer class AUV. During the simulation the vehicle went around the octagon (Figure 6) while changing depth along the way. It successfully reached each target depth as instructed. In the second (delta_psurf) and the third (delta_gdep) mission, different MOOS behavior functions were utilized. For delta_gdep, BHV_GoToDepth was used as with the first mission, while a combination of BHV_ConstantDepth (15m) and BHV_PeriodicSurface were used for delta_psurf. The absence of intermediate target depths in the delta_psurf mission resulted in a much sharper pitch angle in a vertical yo-yo path compared with the delta_gdep mission. Hence the approach used in the second mission can provide a more thorough vertical surveying and mapping and can be advantageous within the allowed maximum pitch angle for the vehicle. However, as shown in Figure 7, when the given period (10 seconds in this case) is set to be insufficiently short, the vehicle is unable to reach the target depth (15m in this case) before surfacing behavior kicks in. By contrast, the outcome of delta_gdep presents a more effective survey trajectory; in short, BHV_GoToDepth controls depth more effectively than BHV_PeriodicSurface. Since the intermediate target depths were always aimed for on each leg, they ensured the full vertical coverage of the given survey area. In addition, the number of target depths, the length of time at each depth (3 seconds in this simulation), conditions to trigger a depth change, and others can be set as variables that the vehicle can decide autonomously during the mission. This higher flexibility enables the mission to be more adaptive.

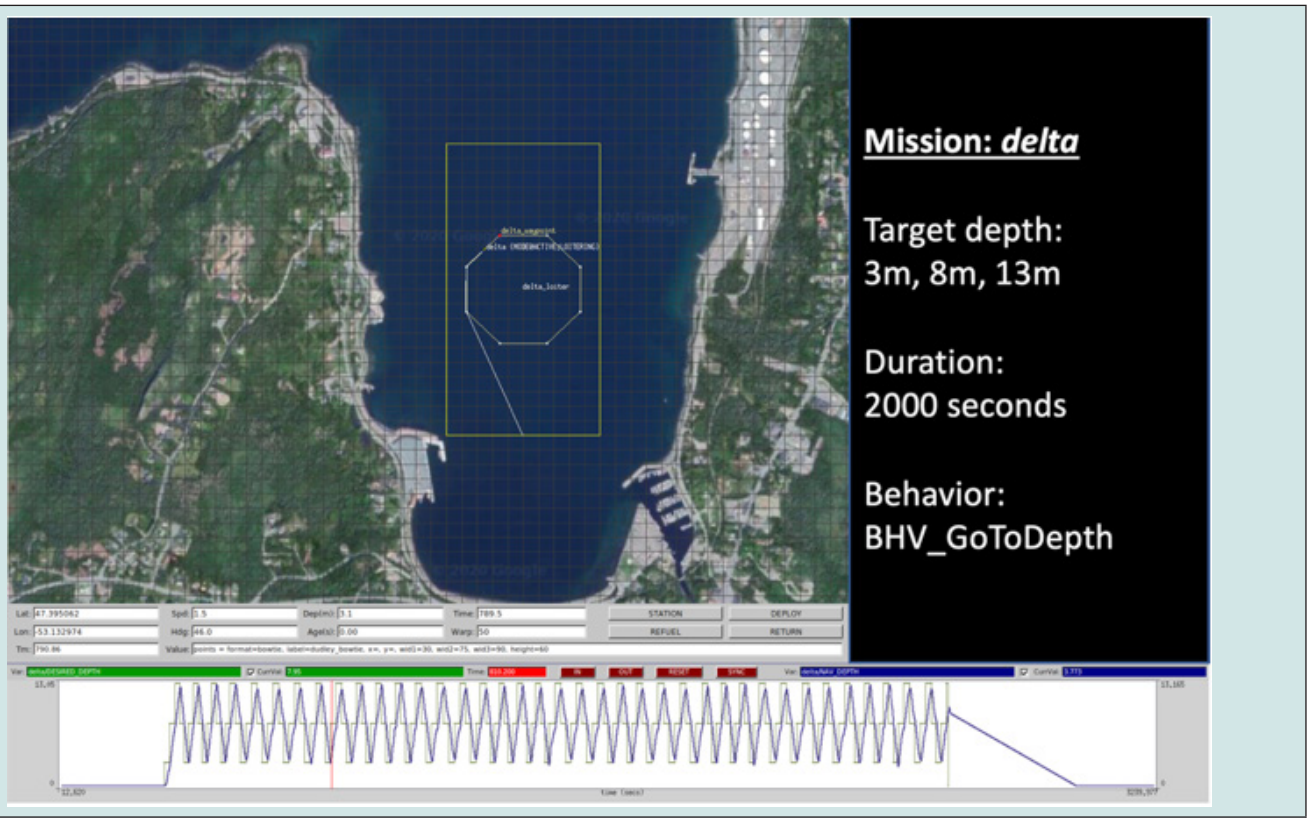


Figure 6: delta mission with a target depth of 13m conducted in MOOS-IvP simulation.

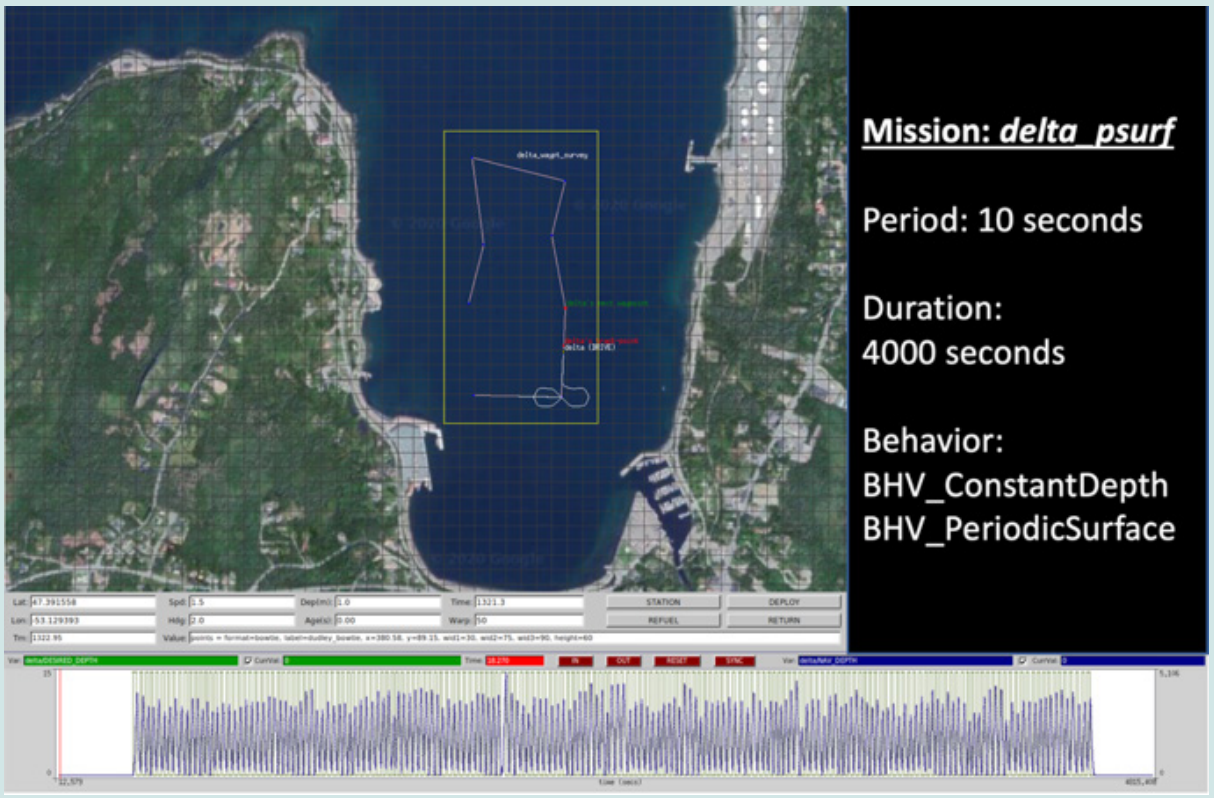


Figure 7: delta_psurf conducted in MOOS-IvP simulation.

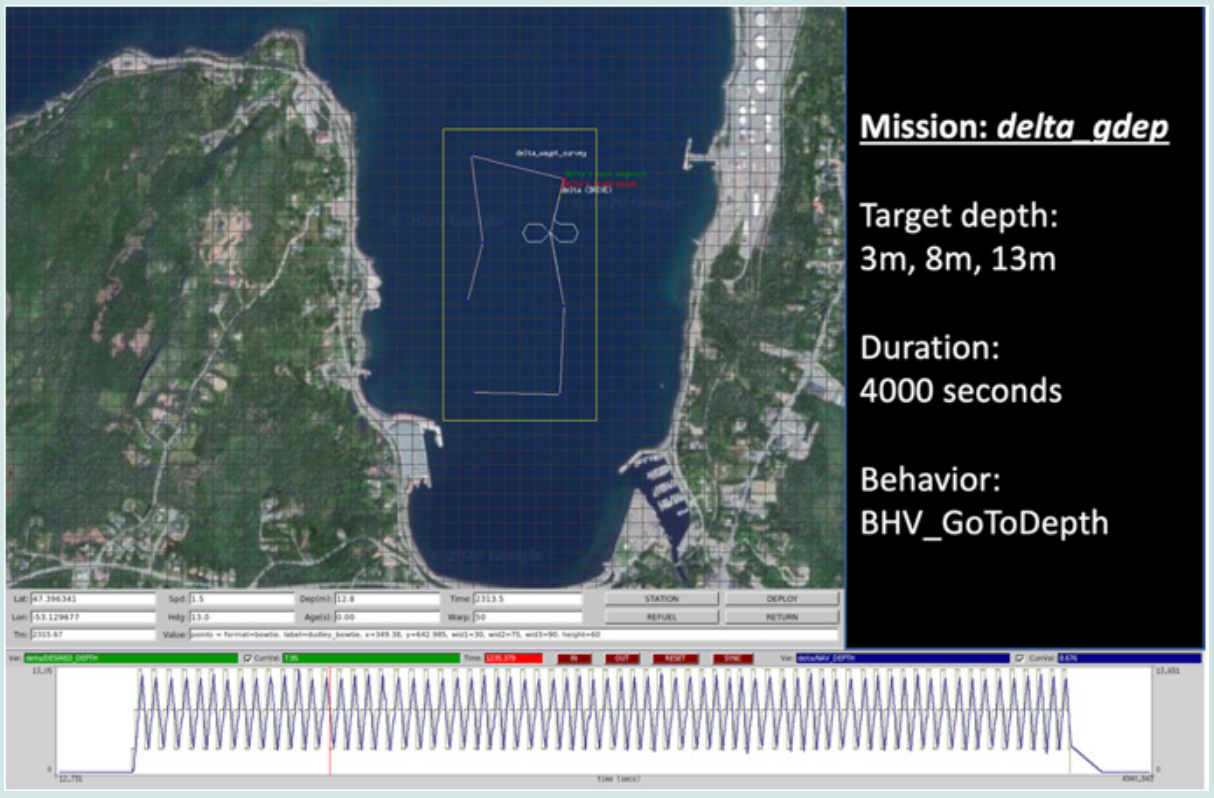


Figure 8: delta_gdep conducted in MOOS-IvP simulation.

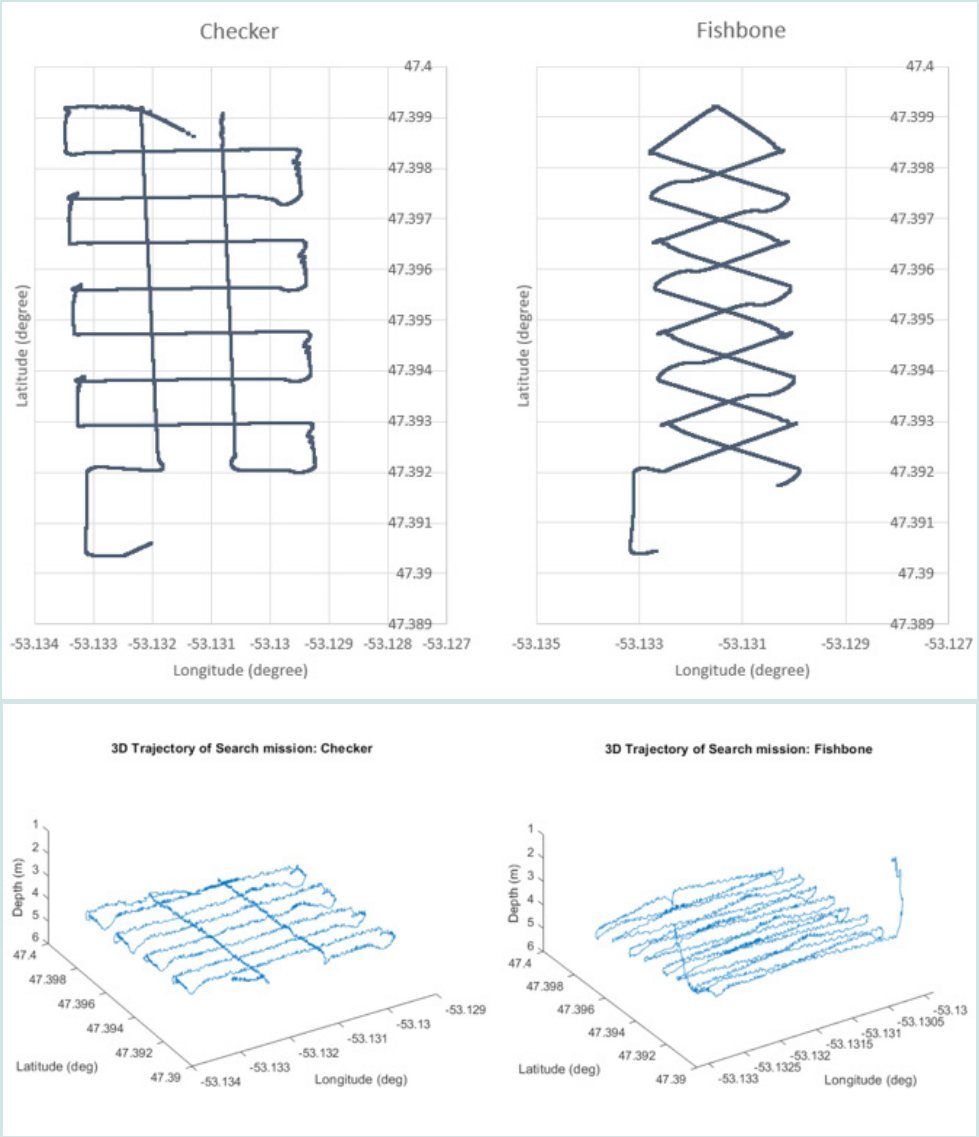
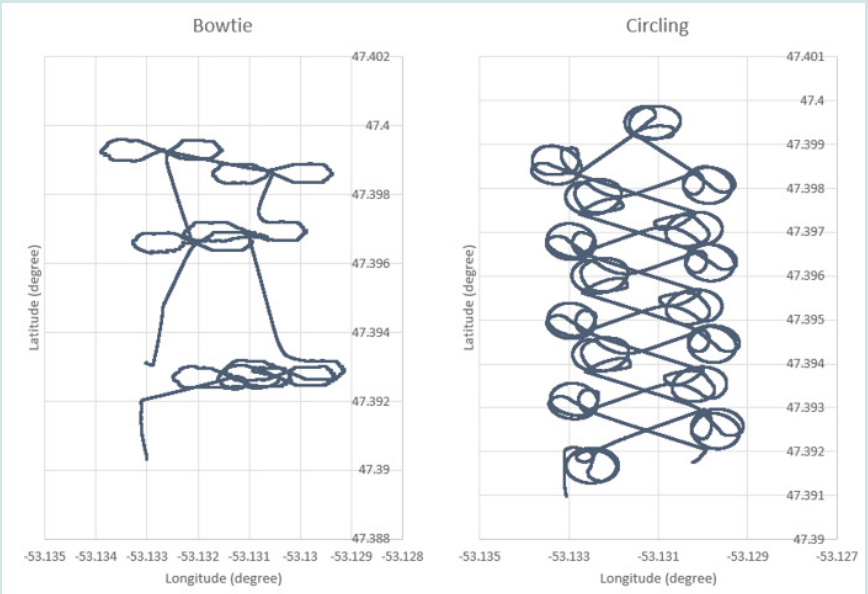


Figure 9: Search missions: Checker (alpha-1) and Fishbone (alpha-2) during Holyrood field trials.



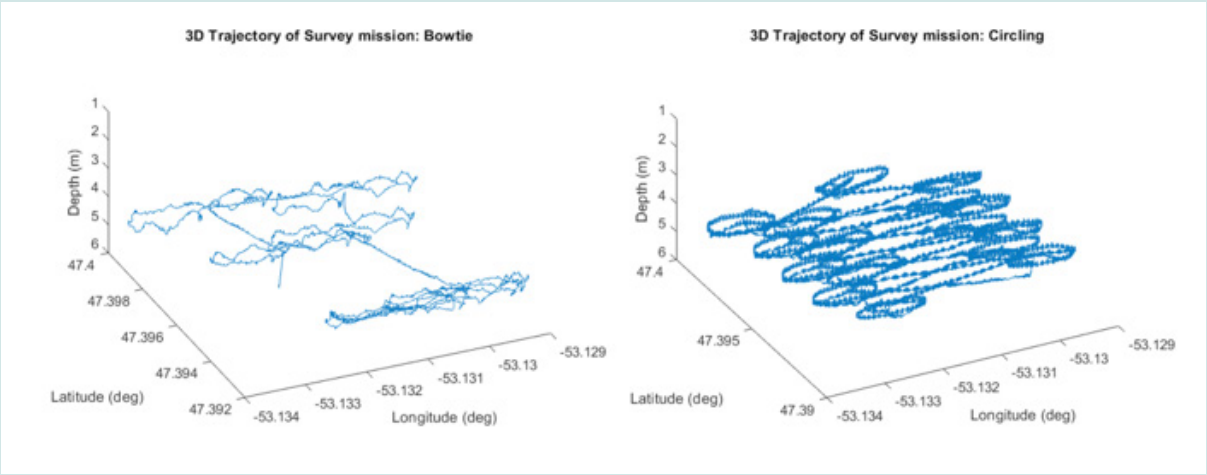
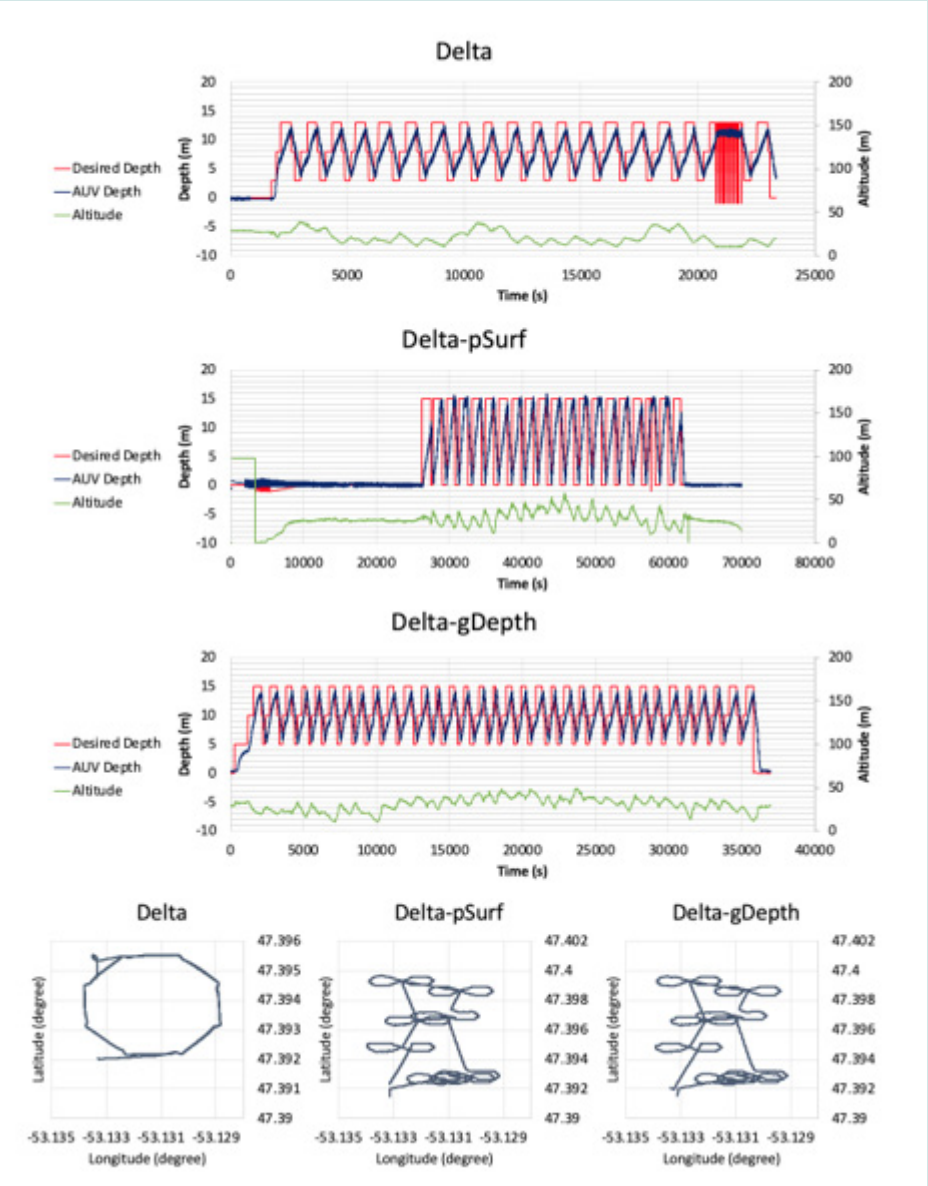


Figure 10: Survey missions: Bowtie (beta-1) and Circling (beta-2) in Holyrood.



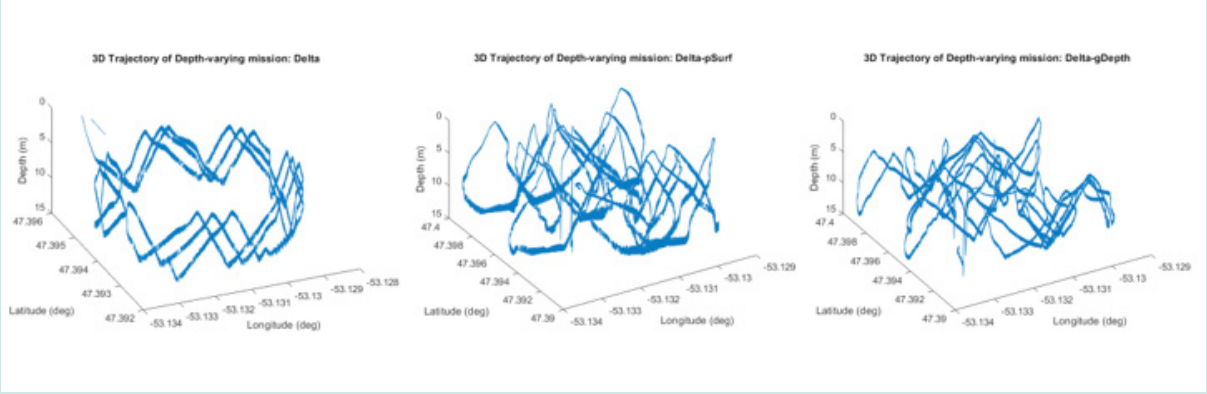


Figure 11: Depth-varying missions: delta, delta_psurf, and delta_gdep in Holyrood.

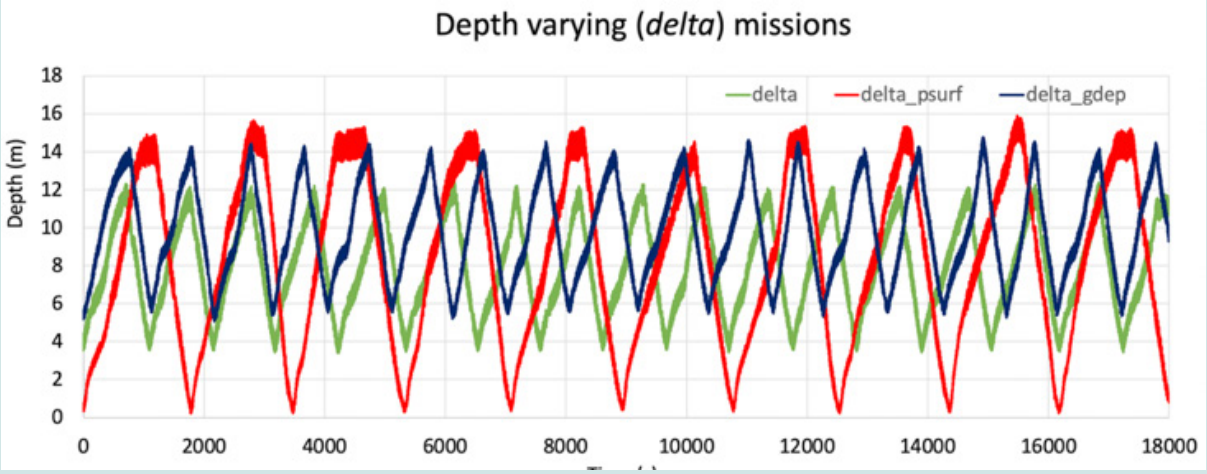


Figure 12: Comparison of delta missions in Holyrood.

Table 1: Field trial conditions for the delta missions.

Detail	delta	delta_psurf	delta_gdep
Horizontal	Octagon	Bowtie	Bowtie
MOOS behavior	BHV_GoToDepth	BHV_PeriodicSurface	BHV_GoToDepth
Target depth	3m, 8m, 13m	0 – 15m	5m, 10m, 15m
Number of yo-yos	16.5	10	18.7

Field Trials

The missions designed and simulated in the MOOS-IvP software were implemented on the Memorial Explorer AUV's second dual driver computer and the field tests were carried out in the ocean adjacent to Memorial's Holyrood marine base, NL, Canada for validation. The field experimental results of the search missions (alpha-1, alpha-2) and the survey missions (beta-1, beta-2) are presented in Figure 9 and Figure 10, respectively. Both missions were conducted at 5m depth. Once below the surface, the vehicle cannot update its georeferenced information and hence is subject to path variation from the ambient currents. Therefore, a drift in real AUV trajectory was confirmed owing to the growing positional error, when compared with the planned path (Figures 4 & 5). This drift resulted in reduction of efficiency in terms of the horizontal survey coverage, especially in the beta-1 mission; and the accumulated error led to an overlapped survey path (see Figure 10). Unlike the simulated result (Figure 5) (which only shows one active bowtie survey), there was a transition when the circling behavior was triggered in the beta-2 mission. This meant that the vehicle performed a smaller circle before it performed its planned full-sized circling behaviour. This is due to the Explorer AUV's limited turning radius. This unintentionally resulted in a more thorough survey inside each circle during this field trial. An override behavior was observed between the time stamp 20,000 and 22,000 during the delta mission (see Figure 11). This was

caused by the AUV getting too close to the sea bottom (closer than the allowed altimeter setting) and the first driver overruled the mission for safety reasons. This was not intentionally designed into the mission. However, it verified the strengthened safety function by using the dual driver mode; the first driver lets the second driver take control only while the vehicle remains in a safe region of operation. We extracted some vertical yo-yo sections from all three delta missions and superimposed these on the same time stamp as shown in Figure 12. While the octagon shape was given as the search pattern (in the horizontal plane) for the delta mission, a bowtie shape was used for the delta_psurf and delta_gdep missions. BHV_PeriodicSurface was used for the delta_psurf mission, while BHV_GoToDepth behavior was used for the delta mission (with target depth 3m, 8m, and 13m) and delta_gdep (with target depth 5m, 10m, and 15m) mission. See the field trial conditions in Table 1. All three delta missions showed successful achievement of the planned depth-varying performance as controlled by the second driver of the vehicle within an error band of 1m. We also observed that different shapes and target depths affected the number of the yo-yo performances within a given time: 18 yo-yos were performed during the delta_gdep mission and 16 yo-yos were performed during the delta mission.

Discussion

While the field trial results demonstrated successful dual driver operation of our AUV, they also revealed unexpected challenges and points for improvement. Firstly, the AUV trajectory at depth is not as straight as the planned path when the simulated and experimental results are compared. This is due to strong currents that occur in Holyrood Bay on the trial days, and limits in the accuracy of the vehicle positioning system underwater. These must be improved by further calibrating the vehicle's navigation system before utilizing the oil sensor data as the main variable for driving the AUV. When location of either the AUV or a detected plume (relative to the vehicle) is inaccurate, the sensed data results cannot be accurately positioned. Therefore, this was an important check point to validate our developed system. Secondly, there was an exchange of control between the drivers during the delta mission when the set lower limit of AUV altitude, which was 10m, was violated. While the vehicle was under the control of the second driver, the vehicle reached the set lower limit of altitude, and the first driver immediately and automatically retrieved the control; then, the control was returned to the second driver when the vehicle was considered safe. The field experiments confirmed the strong advantages of appointing the first driver to oversee the mission under the control of the second driver: this allowed the autonomous mission to be done with reduced chance of crash or the vehicle departing from a given area of operation. Learning from these trials and taking the next steps, we plan to conduct a field experiment in the ocean where natural oil seeps exist.

Assuming that an oil plume is detected by the search module, and it is too close to the AUV, the onboard oil sensors may be impaired even before the survey module is active. Then, it may produce inaccurate oil concentration data, since it becomes hard to distinguish whether the region is genuinely full of oil, or the sensor is contaminated by the sticky oil on the sensing window of the instrument. So, during the initial search phase, we will improve the module to avoid the plume and to direct the vehicle to remain a secure distance from the plume. Finally, we tested two survey paths: bowties and circles. However, the design can be further improved by maximizing the survey coverage and lessening overlapping areas. During the beta-1 mission, we observed overlapping areas by the extended survey trajectory (bowties), despite the distance set between the assigned waypoints. The waypoints were randomly and automatically set within the given search area; and they were intended to be distributed in a way that they were not too close. In this paper, we triggered the survey module from the navigational data, meaning that 'arrival at a waypoint' was the key condition for the survey module to begin. In the next phase of our work, this condition will be replaced by 'detection of oil'. So, it cannot be pre-known when and where this survey will kick in before the mission starts. To improve the efficiency of the survey module, we plan to build an add-on map that "crosses off" already surveyed sections. This will prevent the vehicle being trapped in the same patch of the plume during an adaptive mission.

Conclusion and Future Work

We have developed a dual driver system for an AUV to investigate subsurface patches of petroleum pollutants. A modular control architecture was designed; the framework of each module was constructed, simulated, and tested in open ocean trials. To verify the health of the modules, we simplified the missions by using navigational data as the main variables, rather than scientific data (oil sensor data). The field experiment results showed successful operation of the dual drivers, verifying that the autonomy has been enhanced by separation of the first driver (physical control) and second driver (intelligent command), but also ensuring safety of operation of the vehicle. Our future work will include testing a water sampling module with a multi water sample retrieving unit and adding sensor data analysis algorithms for each of the control modules tested in this paper.

Author Contributions

Conceptualization, J.H. and N.B.; methodology, J.H.; software, J.H. and G.N; validation, J.H., G.M. and G.N.; formal analysis, J.H.; investigation, J.H.; resources, G.M. and G.N; data curation, J.H.; writing-original draft preparation, J.H.; writing-review and editing, N.B.; visualization, J.H.; supervision, N.B.; project administration, N.B. and J.H; funding acquisition, N.B. All authors have read and agreed to the published version of the manuscript. Authorship must be limited to those who have contributed substantially to the work reported.

Funding

This work was funded by: Fisheries and Oceans Canada through the Multi-Partner Research Initiative (MPRI) 1.03: Oil Spill Reconnaissance and Delineation through Robotic Autonomous Underwater Vehicle Technology in Open and Iced Waters and MPRI 1.15: Inshore Trials of Robotic Autonomous Underwater

Vehicle Technology for Oil Spill Reconnaissance and Delineation using an Environmentally Friendly Proxy; the Natural Sciences And Engineering Research Council (NSERC) Alliance program: Characterization and delineation of oil-in-water at the Scott Inlet seeps through robotic autonomous underwater vehicle technology, in partnership with Fugro Canada and International Submarine Engineering, BC. Further financial support came from the NSERC Discovery Grant program to the second author: RGPIN-2021-02506 Advancing Autonomous Underwater Vehicle Capability for Assessment of Marine Pollution.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Vinogradova N (2016) Ocean water cycle: its recent amplification and impact on ocean circulation. In Proceedings of the EGU General Assembly Conference Abstracts pp. EPSC2016-10692.
2. Monteiro RC, do Sul JAI, Costa MF (2018) Plastic pollution in islands of the Atlantic Ocean. Environmental Pollution 238: 103-110.
3. Chaudhry FN, Malik M (2017) Factors affecting water pollution: a review. J Ecosyst Ecography 7: 225-231.
4. Coale AJ, Hoover EM (2015) Population growth and economic development. Princeton University Press, USA pp. 2319.
5. Bates N, Best M, Neely K, Garley R, Dickson A, et al. (2012) Detecting anthropogenic carbon dioxide uptake and ocean acidification in the North Atlantic Ocean. Biogeosciences 9(7): 2509-2522.
6. Easterbrook DJ (2016) Greenhouse gases. In Evidence-Based Climate Science; Elsevier pp. 163-173.
7. Petillo S, Balasuriya A, Schmidt H (2010) Autonomous adaptive environmental assessment and feature tracking via autonomous underwater vehicles. In Proceedings of the OCEANS'10 IEEE SYDNEY pp. 1-9.
8. Zhang Y, Bellingham JG, Godin MA, Ryan JP (2012) Using an autonomous underwater vehicle to track the thermocline based on peak-gradient detection. IEEE Journal of oceanic engineering 37: 544-553.
9. Woithe HC, Kremer U (2009) A programming architecture for smart autonomous underwater vehicles. In Proceedings of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems pp. 4433-4438.
10. Das J, Harvey J, Py F, Vathsangam H, Graham R, et al. (2013) Hierarchical probabilistic regression for AUV-based adaptive sampling of marine phenomena. In Proceedings of the 2013 IEEE International Conference on Robotics and Automation pp. 5571-5578.
11. Smith RN, Chao Y, Jones BH, Caron DA, Li PP, et al. (2010) Trajectory design for autonomous underwater vehicles based on ocean model predictions for feature tracking. In Proceedings of the Field and Service Robotics: Results of the 7th International Conference pp. 263-273.
12. Ferri G, Jakuba MV, Yoerger DR (2010) A novel trigger-based method for hydrothermal vents prospecting using an autonomous underwater robot. Autonomous Robots 29: 67-83.
13. Farrell JA, Pang S, Li W, Arrieta R (2003) Chemical plume tracing experimental results with a REMUS AUV. In Proceedings of the Oceans 2003. Celebrating the Past... Teaming Toward the Future (IEEE Cat. No. 03CH37492) pp. 962-968.
14. Zhang Y, McEwen RS, Ryan JP, Bellingham JG, Thomas H, et al. (2011) A peak-capture algorithm used on an autonomous underwater vehicle in the 2010 Gulf of Mexico oil spill response scientific survey. Journal of Field Robotics 28: 484-496.
15. Camilli R, Reddy CM, Yoerger DR, Van Mooy BA, Jakuba MV, et al. (2010) Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon. Science 330: 201-204.
16. Dashofy EM, Hoek Avd, Taylor RNA (2005) comprehensive approach for the development of modular software architecture description languages. ACM Transactions on Software Engineering and Methodology (TOSEM) 14: 199-245.
17. Furlong M, Marlow R, Munafo A, McPhail S, Pebody M, et al. (2018) OCEANIDS: Building next generation maritime autonomous systems. In Proceedings of the International Ship Control Systems Symposium (iSCSS) Glasgow.
18. Hwang J, Bose N, Fan S, Robinson B, Tenekedjiev K (2019) Complications of robotic delineation of oil spills at sea. In Proceedings of the Proceedings of the International Association of Maritime Universities (IAMU) Conference pp. 26-33.
19. Li Z, Lee K, King T, Boufadel MC, Venosa AD (2008) Assessment of chemical dispersant effectiveness in a wave tank under regular non-breaking and breaking wave conditions. Marine pollution bulletin 56: 903-912.
20. Hwang J, Bose N, Nguyen H, Williams G (2020) Auv adaptive sampling to delineate subsurface oil plumes. In Proceedings of the 2020 IEEE/OES Autonomous Underwater Vehicles Symposium (AUV) pp. 1-2.
21. Hwang J, Bose N, Nguyen HD, Williams G (2020) Acoustic search and detection of oil plumes using an autonomous underwater vehicle. Journal of Marine Science and Engineering 8: 618.

This work is licensed under Creative Commons Attribution 4.0 License

To Submit Your Article Click Here: Submit Article

DOI: 10.32474/ARME.2023.04.000178

Advances in Robotics & Mechanical Engineering

Assets of Publishing with us

- Global archiving of articles
- Immediate, unrestricted online access
- Rigorous Peer Review Process
- Authors Retain Copyrights
- Unique DOI for all articles