Enhancement of AUV Autonomy Using Backseat Driver Control Architecture

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Abstract—**The Deepwater Horizon oil spill accident (April 2010) in the Gulf of Mexico released an unprecedented amount of crude oil, much of which was trapped around 1000m below the surface. The accident has attracted worldwide attention and promoted many autonomous underwater vehicles (AUV) projects. The principal objective of our project is to establish a Backseat Driver control architecture for an AUV to monitor undissolvable marine pollutants. Our scope of work focuses on validating a new method to manoeuvre and control an AUV by implementing the Missions Oriented Operating Suite (MOOS-IvP) Backseat Driver system that was newly integrated on the *Memorial University of Newfoundland (MUN) Explorer* AUV. A *Ping360* scanning sonar, as the main in-situ sensor, was integrated with the vehicle. This enabled a capability to survey horizontal sectors up to 360° and ranges up-to 50m from the AUV in real-time to evaluate information of sonar reflections from objects surrounding the vehicle without a human-operator-in-the-loop. We validated the capability of this intelligent Backseat Driving control through three sets of field experiments that were conducted in October – November 2020 in Newfoundland, Canada.**

Index Terms—**autonomous underwater vehicle, marine pollutants, oil plume delineation, underwater acoustic detection, backseat driver control, MOOS-IvP**

I. Introduction

This planet survives on the balance of the oceans. However, the balance of aquatic ecosystems has been broken down by environmental pollution caused by various human activities; some are occasional but lethal such as oil spill accidents while others are more chronic, but cumulative, such as increasingly abandoned plastic debris. Every year, millions of tonnes of rubbish and other pollutants enter the ocean. Nature can heal itself using its intrinsic restorative capacity if we give it the urgent attention it requires [1].

The release of a liquid petroleum hydrocarbon, namely an oil spill, is one of the four major categories of ocean pollution: heavy metals (arsenic, mercury, lead, copper, nickel, zinc and cadmium), inorganic compounds (fluoride and nitrates), organic contaminants (carbon-molecules-contained materials) and pathogens (bacteria, protozoa or viruses) [2]. In general, hydrogen bonds between organic compounds and water molecules produce compounds that have a relatively high ability to dissolve in water, such as alcohols, phenols, aldehydes, ketones and acids. On the other hand, C-H bonds (carbon – hydrogen) are not sufficiently polarised to make hydrogen bonds [3]. As a result, the hydrocarbon part of a molecule does not support dissolution in water. Hence, alkane and alkyne components of petroleum hydrocarbons are not soluble in water due to weak polarisation and weak intermolecular forces with water molecules [4], [5]. The water-soluble hydrocarbon components of oil slicks with lighter fractions, such as gases, usually evaporate in the first few days after a spill; what remains are the relatively more viscous components with heavier fractions of oil masses. The undissolved remaining oil, referred to collectively as micro-droplets, have a range of droplet sizes from micrometre to millimetre diameters [6]. At higher exposures, these undissolved oil droplets or films result in physical-mechanical effects that suffocate marine organisms [7]. Therefore, large-scale oil spills often cause death of marine mammals, birds and fish [8]-[10]. To offset this, an initial oil spill response often involves the release of dispersants on a surface oil slick such that the oil can be broken down into smaller droplets, which are more readily dissolved in the water. In practice, however, it is not always possible to access the centre of an accident site. Therefore, ever since the *Deepwater Horizon* oil spill accident, there have been a number of studies on the efficacy of various dispersants [11]-[14] as well as utilisation of autonomous underwater vehicles (AUVs) for reconnaissance purposes [15]-[18].

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The principal objective of our project is to establish a robust control architecture for an AUV to monitor and delineate undissolvable marine pollutants. Unlike continuous dissolved plumes containing a series of iso-density contours throughout their structure, which are a common target for gradient-following methods [18], [19]; we aimed to model a discontinuous and patchy plume emulating a realistic petroleum plume composed of countless undissolved droplets mixed into seawater and representing the coalescent and clustering features of oil. Our scope of work in this paper primarily focuses on validating a newly designed control method to manoeuvre and control an underwater vehicle by implementing the Backseat Driver system integrated on the *Memorial University of Newfoundland (MUN) Explorer* AUV.

II. Background

A. Principal of Backseat Driver Control

The AUV community uses the basic distinction between a Frontseat Driver and a Backseat Driver [15], [20]. The Frontseat Driver follows a set of pre-defined instructions and directly controls the vehicle motion, such as heading and depth; whereas the Backseat Driver makes independent decisions about the vehicle motions, sent as commands to the Frontseat Driver, which the Frontseat Driver may or may not follow. Making this distinction between the control (i.e. Frontseat Driver) and command (i.e. Backseat Driver) provides several merits and the benefit of adopting a Backseat Driver system in marine vehicles have been addressed as follows [21]:

- To allow various levels of real-time requirements via the decoupling of part of the system.
- To provide flexibility in implementing the software.
- To ease the addition and modification of sub-modules at each level since an independent data process mechanism is allowed.

B. MOOS-IvP Architecture

The Missions Oriented Operating Suite (MOOS-IvP) software is a well-known Open Source system that was developed specifically as a Backseat Driver system for marine vehicles. The software is comprised of two components: MOOS (*Subscribe – Publish* based middleware) and IvP-Helm (autonomy behaviour based architecture) [22]. MOOS and IvP-Helm support distinct modules to build the autonomy and sensing systems independently. In practice, the software runs from a payload computer that receives up-to-date vehicle position, heading and speed information from the main vehicle computer (*Subscribe*). Then, the payload computer sends desired vehicle heading, depth, and speed commands back to the main vehicle computer (*Publish*). The closed loop data flow system promotes a Backseat Driving capability with each autonomous decision made by the payload sensor data. The basic AUV control architecture including the two modules (Backseat Driver and Frontseat Driver) is shown in Fig. 1.

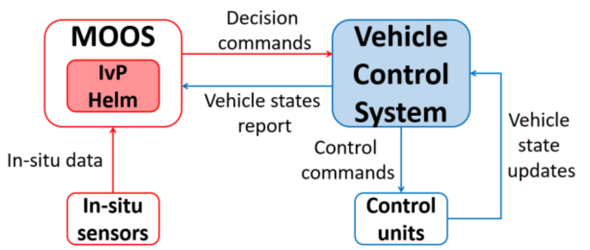

Figure 1. Designed AUV system architecture. The picture shows the connection between the Backseat Driver module (MOOS-IvP and in-situ sensors/ payload) and the Frontseat Driver module (vehicle control system and the control units).

C. Preliminary Work of the Project

We previously introduced two sets of adaptive sampling algorithms written in the MATLAB program. The first set of algorithms identified non-gradient marine pollutants utilising acoustic reflections and real-time analysis [23]; while the second set implemented a decision-making architecture for tracking the modelled pollutants [24]. The performance of the algorithms was evaluated in a simulation environment.

In this paper, we present a follow-up of the preliminary design work and describe how we implemented the algorithms on an actual AUV. We have validated the capability of the Backseat Driving control through both the MOOS simulation domain and a set of field experiments that were conducted in October – November 2020 in Newfoundland, Canada.

III. Proposed Method

A. Mission Descriptions

Three sets of missions were designed and set as shown in Table I. The *alpha-1* mission was to assess the assigned-waypoints-visiting capability by using the *'Waypoints behaviour'*; the *alpha-2* mission was to demonstrate loitering performance by following the vertices of a polygon around a region of particular interest for a desired period of time using the *'Loiter behaviour'*; and the *beta* mission was to conduct a conditional behaviour shift between the aforementioned two behaviours.

TABLE I. Mission Descriptions

Mission ID	Details	Required time
alpha-1	Visiting randomly generated waypoints sequentially.	2400 seconds
alpha-2	Loitering in a region of interest while following the vertices of a polygon.	1500 seconds
beta	Performing a combined *alpha-1* and *alpha-2* survey with a modified bow-tie form of loitering behaviour.	4600 seconds

B. Control Architecture

The primary objective in developing the application was to provide a suite of C++ based utilities and libraries to enhance modularity of the algorithm for rapid addition and removal of elements of code; support the ease of debugging, testing and modifying the code; and allow different level of requirements in the missions. Therefore, the control design was structured based on a multi-layered modular architecture, which reduced the complexity of the control algorithm. So, we constructed three layers of control hierarchy as shown in Table II.

TABLE II. HIERARCHICAL LAYERS OF CONTROL MODULE

Layer	Level of tasks in charge
Decision layer	Making high-level decisions after aggregating outputs from each module including: the monitored vehicle status, navigational reports and sensor measurements, e.g. *"Go to waypoint"* or *"Start search pattern manoeuvre"*.
Command layer	Converting the high-level decisions into lower-level commands to achieve the high-level decisions, e.g. heading, speed and depth.
Control layer	Performing the lowest level vehicle control. This is achieved through a closed-loop feedback between the onboard electronic systems and the sensor actuators. e.g. plane angles and thruster RPMs

C. *MOOS Application and IvP Behaviour Tree*

Three applications were supplementally created for AUV manoeuvring: *pWaypoints*, *pGenPath* and *pSearch*. *pWaypoints* generates a random set of waypoints within the boundary of the designated operational area for each mission. *pGenPath* calculates the most cost-effective trajectory (the one that requires the shortest path, hence travel time) to visit all the assigned waypoints. Finally, *pSearch* updates dynamic values of certain MOOS variables such as the reference location *(x, y)*.

pPingController was an additional MOOS application we created to control and log the Ping360 scanning sonar during missions. Each application consisted of virtual functions and they were sequentially and repetitively called. They perpetually handled a list of relevant variable-value pairs in real time. The layout of the virtual functions inside the example application *pSearch* is shown in Fig. 2.

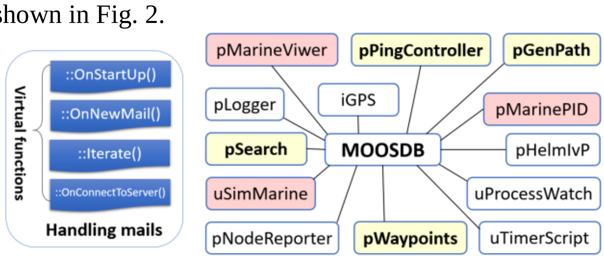

Figure 2. The essential virtual functions of the MOOS application. Four purpose-built MOOS applications (yellow) were developed. The rest of the applications were modified from the built-in subroutines provided by the MOOS-IvP software in accordance with the characteristics and requirements of each mission. Three MOOS applications (pink) were for simulation only.

The helm was built and configured for each mission through a unique behaviour file (in the form of *.bhv suffix). Therefore, respective behaviour files, in accordance with the missions' script, were developed as a pair for each mission. The behaviour files generated IvP functions to assist the decision produced by the helm. The decisions were typically the desired heading, speed and depth. Fig. 3 illustrates the pHelmIvP iteration loop.

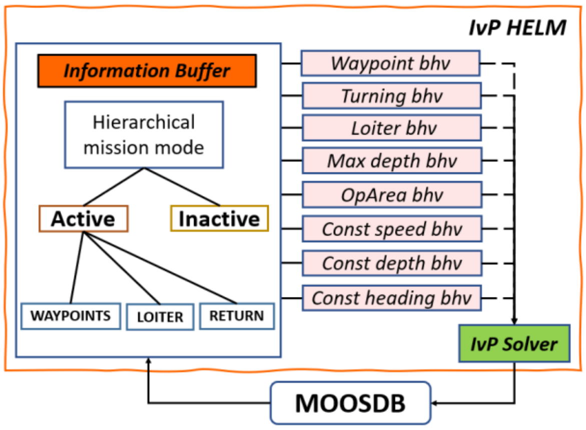

Figure 3. The pHelmIvP iteration loop. A list of variable-value pairs is subscribed for and published between the MOOSDB and IvP Helm. The hierarchy on the left was constructed from the set of mode declarations by the given conditions.

D. *Operational Safety*

Dual fail-safe protocols were embedded with constraints set by the Frontseat Driver computer and each MOOS mission file. The constraints were set as the three-dimensional space below the surface with the boundary of the operational area in the horizontal plane and the maximum depth of water.

When the AUV flies beyond the predefined operational area by any unexpected external events or factors, the MOOSDB publishes safety warnings and aborts the mission. If the safety monitoring system on the Backseat Driver computer fails, the fail-safe protocol of the vehicle control computer will override the Backseat Driver and either stop the mission or return to a safe location. The constraints of the operational area are described in Table III.

TABLE III. OPERATIONAL AREA DEFINED BY FAIL-SAFE PROTOCOLS

Layer	Minimum	Maximum
Latitude	47.389271 (South)	47.402551 (North)
Longitude	-53.134431 (West)	-53.127791 (East)
Depth	0 (Surface)	10 meters

IV. SIMULATION

In mission 1 (*alpha-1*), eight random waypoints were generated, then the most optimum path between the waypoints was created by using a Travelling Salesperson algorithm. Table IV shows the assigned waypoints.

In mission 2 (*alpha-2*), the region of interest was tentatively set at the centre of the operational area; its local coordinate was x = 250, y = 500 from the start location (origin, $x = 0$, $y = 0$). The AUV surveyed around the region of the interest for 1000 seconds by following the designated polygon, which in this case was an octagon. The size and the shape of the polygon could be adjusted by setting the radius (distance between the region of interest and each vertex of the polygon) and the number of vertices.

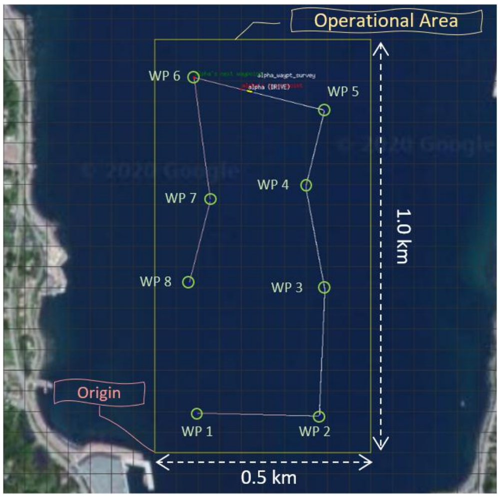

Figure 4. The AUV trajectory of the *alpha-1* mission during simulation. Eight randomly generated waypoints are marked. The box (in yellow) represents the maximum operational area.

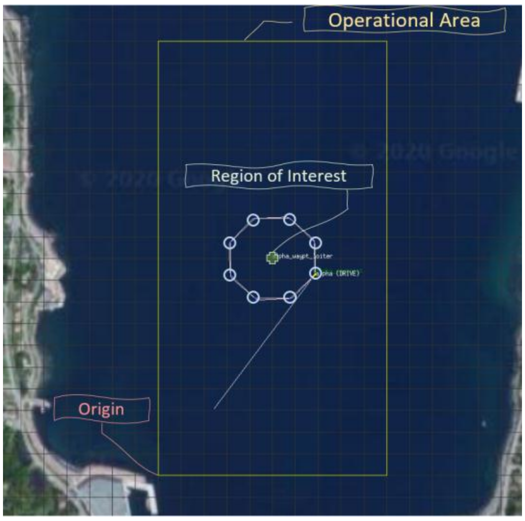

Figure 5. The AUV trajectory of the *alpha-2* mission during simulation. The region of interest is marked (cross). The AUV surveyed the vicinity of the region of interest by following the created polygon (octagon).

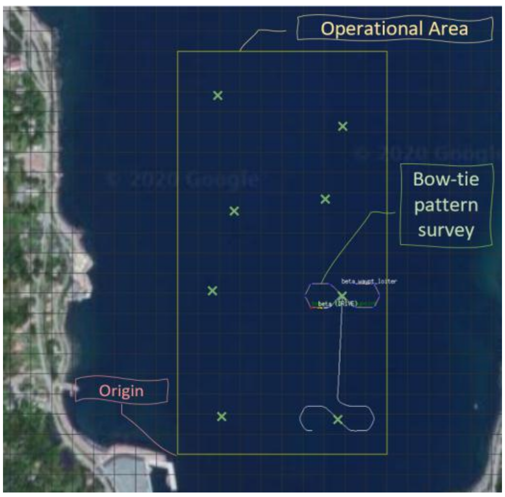

Figure 6. The AUV trajectory of the *beta* mission during simulation. The same waypoints as the *alpha-1* mission are set (in green). A bow-tie pattern survey was executed on arrival at each waypoint.

Finally, in mission 3 (*beta*), we designed a new search pattern by combining *alpha-1* and *alpha-2*. The vehicle carried out a survey on arrival at each waypoint. To achieve that, two behaviours (*Waypoints* behaviour and *Loiter* behaviour) were implemented in this mission. Each survey behaviour triggered the other on completing a set of tasks. In other words, the *Loiter* behaviour was triggered when the first *Waypoints* behaviour was achieved; then the second *Waypoints* behaviour was executed when the first *Loiter* behaviour was complete and so on until all assigned waypoints were visited. The waypoints that were generated in mission *alpha-1* were recycled for comparison. This time, we also varied the depth of survey while the *Loitering* behaviour was active and modified the survey pattern to a bow-tie shape. The simulation results are shown in Fig. 4 through 6, respectively.

TABLE IV. WAYPOINTS LIST

Waypoint	Latitude	Longitude
# 1	-53.133180	47.390160
# 2	-53.129430	47.390170
# 3	-53.129370	47.392780
# 4	-53.130030	47.395100
# 5	-53.129550	47.396770
# 6	-53.133520	47.397450
# 7	-53.132960	47.394830
# 8	-53.133520	47.393010

Three variables of heading, speed and depth, were set in the IvP domain and their specified values are shown in Table V. Through these, the AUV heading, speed and depth was controlled. The speed in all three missions remained constant using the *ConstantSpeed* bahaviour. Therefore, the IvP domain had 1,127,160 distinct possible decisions in total as shown in (1). The heading of the AUV was achieved by a yaw control through a given helm iteration. As a result of the vehicle turning by yaw control, the speed temporarily drops and then recovers by the *ConstantSpeed* control. The desired speed was set to be 2.0 m/s for missions *alpha-1* and *alpha-2*, and 1.5 m/s for mission *beta*. The speed and yaw control graphs are shown in Fig. 7 through 9.

$$360 \times 31 \times 101 = 1{,}127{,}160 \qquad (1)$$

TABLE V. THE IVP DOMAIN CONFIGURATION

Domain	Lower bound	Upper bound	The number of points
Heading	0	359	360
Speed	0	3	31
Depth	0	10	101

The depth of the vehicle remained constant (set at zero) both in mission *alpha-1* and *alpha-2* using the *ConstantDepth* behaviour. Therefore the vehicle was operated on surface. So for the period of visiting a waypoint (active behaviour was *Waypoints*) the depth was set to zero. However, when the AUV was following the bow-tie path (active behaviour was *Loiter*) the depth was changed to 5.0 metres so that the vehicle could expand the survey in water column around the waypoint. Fig. 10 shows the pitch control during the mission *beta* for changing the AUV depth.

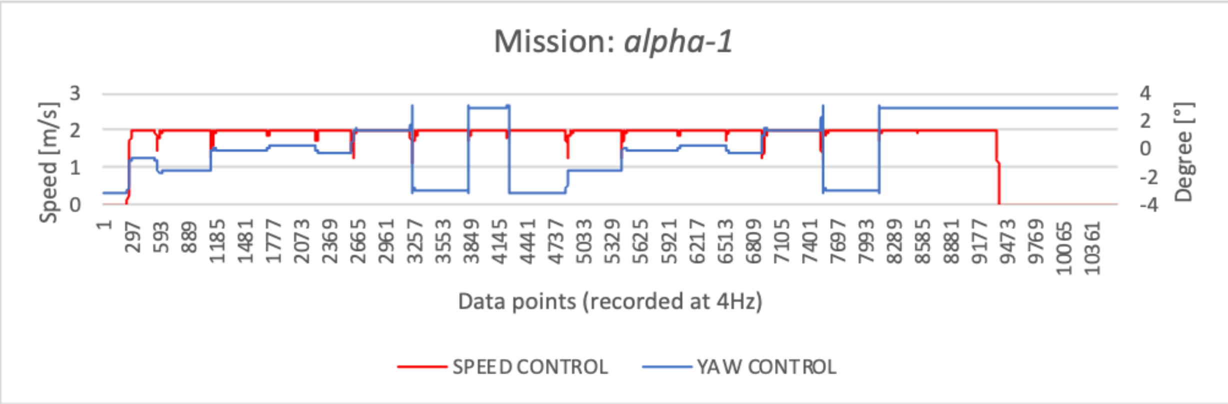

Figure 7. Speed and yaw control during the *alpha-1* mission.

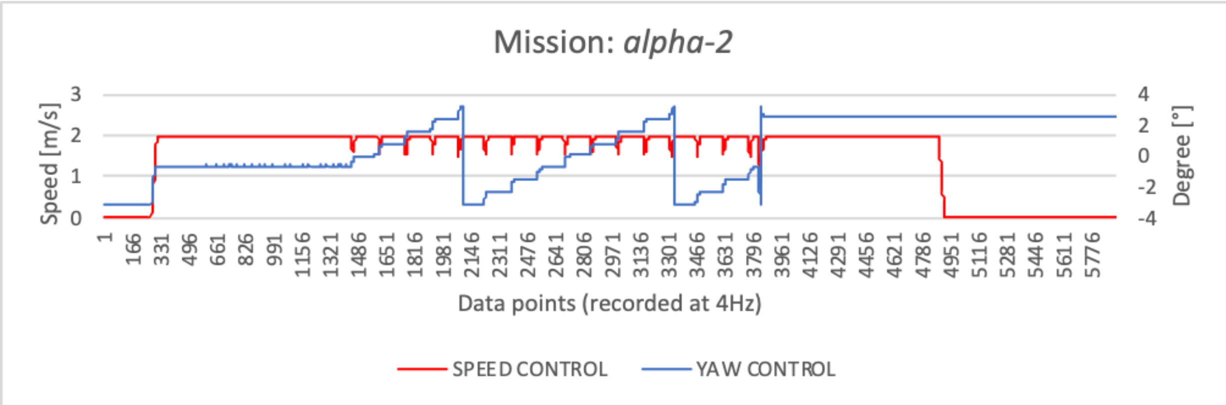

Figure 8. Speed and yaw control during the *alpha-2* mission.

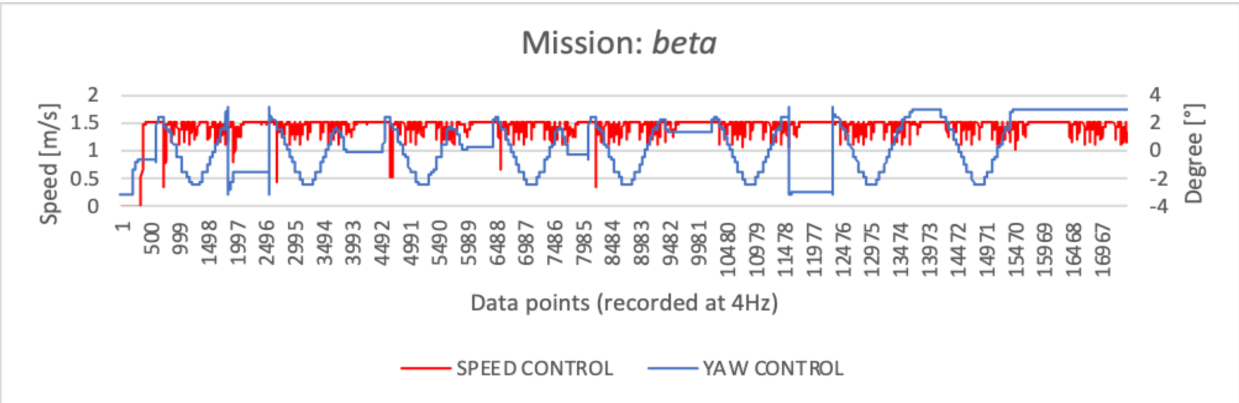

Figure 9. Speed and yaw control during the *beta* mission.

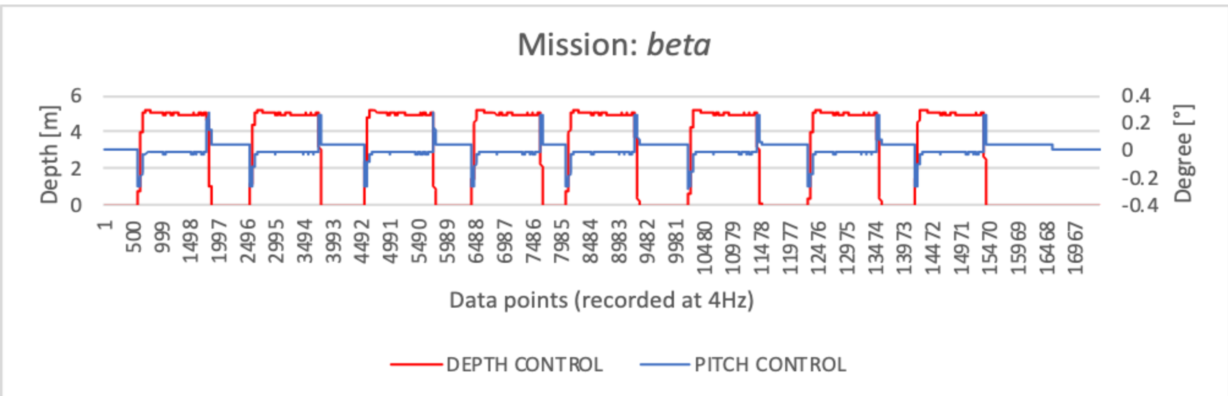

Figure 10. Depth and pitch control during the *beta* mission.

V. Field Experiment

A. Field Test Summary

Trials with the *Memorial University of Newfoundland (MUN) Explorer* AUV were carried out during the months of October and November 2020 in Holyrood Bay where the marine base of the Marine Institute is located as shown in Fig. 11. The sheltered water in the bay provided a depth of water ranging from 10 – 50 meters for the intended tests. Initial tests involved making single dives then recovering the vehicle to the support vessel for data collection, debugging and components repair. All three of the planned missions were successfully conducted.

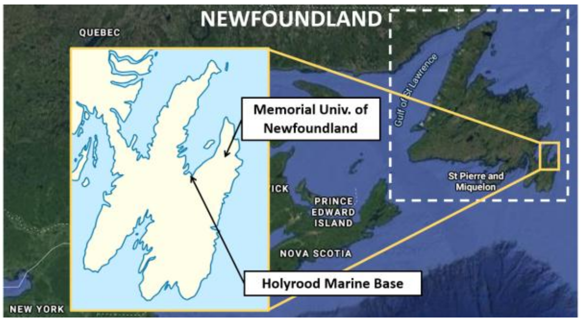

Figure 11. The experiment site: Holyrood Bay in Newfoundland, Canada.

B. Autonomous Underwater Vehicle

The *MUN Explorer* is a modular autonomous underwater vehicle with a torpedo shaped main body, nose cone and tapered tail as shown in Fig. 12. The pressure hull is made of aluminium alloy and it protects the components that need waterproofing such as the batteries and electronic units. The free-flooding sections (forward and aft of the pressure hull) are made of glass reinforced plastic; and contain the actuators (planes and thruster), navigation sensors (depth, doppler velocity log and obstacle avoidance sonar), communication and location devices (acoustic modem, GPS, USBL) and payload sensors (scanning, multi-beam and sidescan sonars).

While the AUV was in operation, the vehicle could communicate with the surface control computer through several ways: radio telemetry (when on the surface), underwater acoustic telemetry (when underwater) and an ethernet link (when on the deck). Table VI shows the specification of the *MUN* AUV.

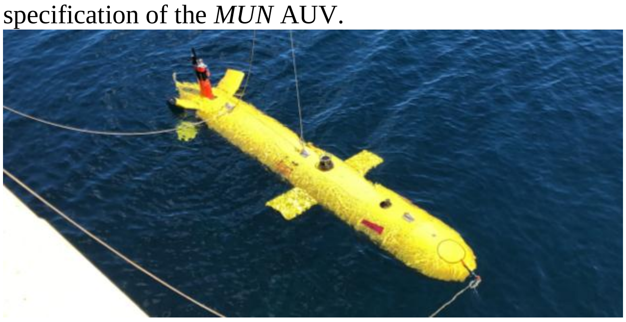

Figure 12. *Memorial University of Newfoundland (MUN) Explorer* AUV. being launched in Holyrood Bay.

TABLE VI. Specification of the *MUN Explorer* AUV

Length	5.3 m
Diameter	0.69 m
Dry weight	0.83 ton
Energy	17.6 kWh
Maximum depth	3000 m
Cruising speed	1.5 m/s
Speed range	0.5 m/s – 2.5 m/s
Power capacity	11 × 1.6kWh
Hydroplanes (fore)	2 × NACA 0026
Hydroplanes (stern)	4 × NACA 0026
Navigation INU	iXsea PHINS III
D – GPS	Sound Ocean System GPS
Velocity / Altitude sensor	RDI Workhorse 300 kHz DVL
Depth sensor	Paroscientific depth sensor
Obstacle Avoidance sensor	Kongsberg Simrad Mesotech 1007 Digital
Positioning	Acoustics Easy Track USBL
Acoustic telemetry	Teledyne Benthos modem and Applied
Integrated payloads	R2 Sonics 2024 Multibeam Edgetech 2200M Side Scan Sonar Seabird Fastcat 49 CTD sensor Ping360 Scanning sonar

C. Ping360 Scanning Sonar

The Ping360 scanning sonar was integrated with the AUV for collecting the acoustic data of the ocean and oil droplets in water. Due to the restriction of release of oil in the ocean (in Canada, Canadian Environmental Protection Act. 1999) the oil recording section of our work was excluded in this trial. However, the Ping360 sonar measurements were continuously collected during the trial. This collected data is valuable in background filtering work for designing the future real-time acoustic data analysis development.

D. Support Vessel

The MV Cartwright survey vessel was used as a support vessel to conduct these trials. The AUV is never aboard the vessel, it is simply used to accompany the vehicle while it is in the water. The Cartwright was equipped with the acoustic modem and USBL positioning transponders that allow underwater communication and positioning with the vehicle while the underwater missions are underway. The Surface Control Computer and radio link are used to pilot (remotely drive) the vehicle to and from the mission start point.

Figure 13. *Memorial University of Newfoundland (MUN) Explorer* AUV being launched in Holyrood Bay.

E. Field Test Results

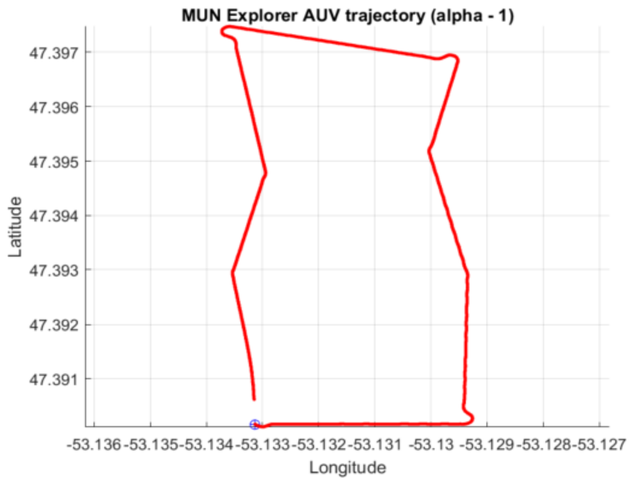

Figure 14. *MUN Explorer* AUV trajectory during the mission *alpha-1*.

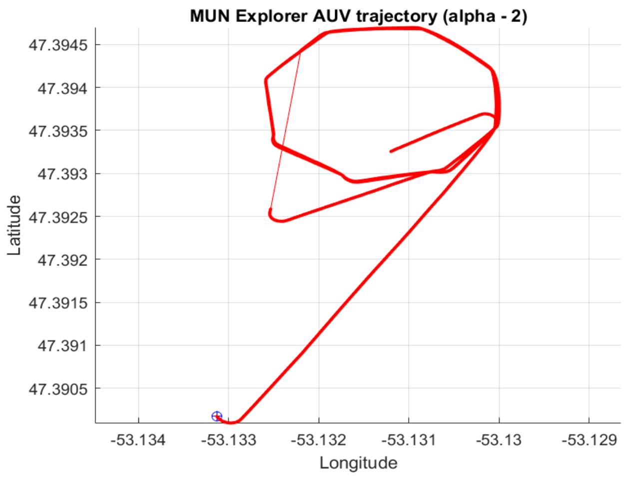

Figure 15. *MUN Explorer* AUV trajectory during the mission *alpha-2*.

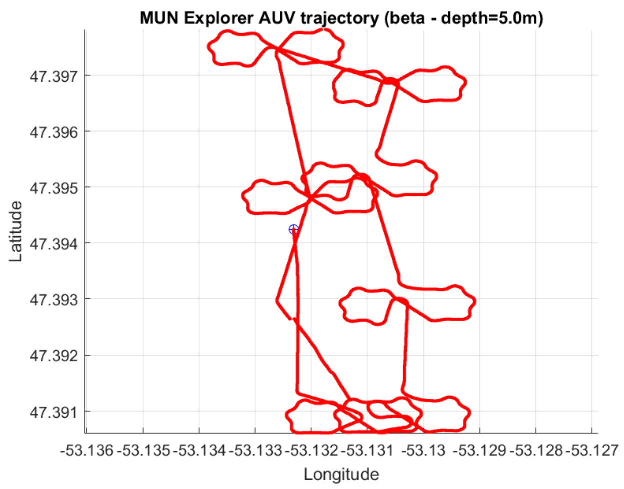

Figure 16. *MUN Explorer* AUV trajectory during the mission *beta*.

Three missions were successfully carried out. The AUV trajectories during the three missions are shown in Fig. 14 through 16, respectively.

These were the first successful MOOS Backseat Driver missions carried out on our underwater vehicle. It means we now have a robust link between the *brain* (which is ready to make commands) and the *body* (which can control the movement of the agent). Secondly, having this working autonomous system, we can henceforth develop an in-situ cognitive module (independent *sensory apparatus* which can sense the surroundings, then analyse the collected information). Combining the cognitive module with our Backseat Driving system means that a fully adaptive mission can be achieved; in other words, a full decision-autonomy of an underwater vehicle.

F. Future Work

Our next step is to develop a cognitive module based on our in-situ sensor process model. We have previously developed the first version of the sonar model for oil plume detection task in MATLAB program [24]. We will advance our existing model by utilising the Ping360 acoustic measurements obtained from our field trials. The next model will be compatible to the MOOS algorithms we formulated in this work. It will be capable of distinguishing our target of interest from other sensed objectives; then it will be capable of making its own decision to adapt a new given condition accordingly such as recreating the new path to follow or tracking the sensed target. This decision-autonomy will add a smart function to our AUV in the true sense of the term.

VI. Conclusion

We have designed a new adaptive mission planning and sampling approach for a survey class autonomous underwater vehicle, an International Submarine Engineering, Explorer class AUV. The ultimate objective was to establish an efficient system to delineate the discrete patchy nature of oil plumes in the ocean in real time. The approach presented improves conventional non-adaptive methods and systems via adopting a Backseat Driver control architecture which enhances autonomy and the sensing system. Its modular architecture separates the mechanical and cognitive components of the underwater vehicle control system leading to a more robust and versatile system, especially useful for less-known and more dynamic underwater conditions.

We implemented and tested this Backseat Driver autonomous system on the *Memorial University of Newfoundland (MUN) Explorer* AUV. Prior to the field trial for validation of our developed system, we simulated three sets of missions with varied survey paths and tested the virtual functions and the MOOS applications. Through the field trials, we have confirmed that the integrated autonomous system is robust. Having the Backseat Driver computer enables the vehicle control computer to remain dedicated to the control of the mission of the vehicle, much like the separation of the vessel crew and researchers achieve during a scientific mission on a research ship. The Backseat Driver computer can produce high level commands based on independent decisions made from real-time mission planning changes or sensor inputs. The combination of the two computers adds to the robustness of the control architecture and safe operation of the vehicle. Our next step is to develop a cognitive MOOS module coupled with a Ping360 scanning sonar to realise the decision autonomy for our AUV during an oil plume delineation mission.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

JH conducted the research and wrote the paper; NB supported and provided suggestions on the whole research paper; GM and AG carried the field experiments; HN and GW proof-read the manuscript; The final results were discussed and approved by all members of the group authors.

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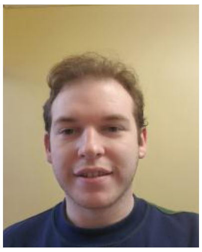

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Dr. Williams is excited by the massive potential for autonomous platforms to survey challenging oceanic environments, filling data gaps that guarantee paradigm shifts in our understanding of the planet and ability to predict its future.