Research Note: AUV Design and Development for Validation of Low Frequency Underwater Ambient Noise

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I. INTRODUCTION

A. *Low Frequency Underwater Ambient Noise*

Ambient noise in the ocean is a complex combination of numerous types of natural and anthropogenic noise. The noise is dominant in all frequencies from 1 Hz to over 100 KHz with the various noise sources contributing in specific frequency bands as per their acoustic attributes. Shipping Noise in the frequency of 50–300 Hz is the most dominant anthropogenic contributor to the Noise Level (NL) in shallow oceans near to shipping lanes. This noise travels far and disperses into the background at large ranges. [1] It is also notable that the recent developments in the designs of ships as well as the increase in demand for international merchant shipping is resulting in an increase in ambient underwater noise. [2]

B. *Autonomous Underwater Vehicles*

An Autonomous Underwater Vehicle (AUV) is an unmanned submersible vehicle that requires no real-time input or control from a human operator or driver and, therefore, operates autonomously. AUVs have a number of underwater applications. They can be used for commercial applications such as exploring for oil and gas or locating ship and plane wrecks, for military applications such as reconnaissance or anti-submarine warfare, and for research applications such as ocean mapping or measuring the physical, chemical and biological properties of the water column. [3]

The first AUV was developed at the Applied Physics Laboratory at the University of Washington as early as 1957 by Stan Murphy, Bob Francois and later on, Terry Ewart. The "Special Purpose Underwater Research Vehicle", or SPURV, was used to study diffusion, acoustic transmission, and submarine wakes. Acoustic signals from the accompanying research vessel guided SPURV in moving below the surface of the water. SPURV then generated models of underwater physical properties such as ocean currents and temperature.

II. AMBIENT NOISE MODELLING IN SHALLOW OCEANS

A. *Ambient Noise Contributors*

There are two definitions of shallow waters— hypsometric and acoustic. The hypsometric definition is based on the fact that most continents have continental shelves bordered by the 200 m contour line, beyond which the bottom generally falls off rapidly into deep water. Therefore, shallow water is taken to mean continental shelf waters shallower than 200 m. Acoustically, shallow water conditions exist whenever the propagation is characterized by numerous encounters with both the sea surface and the sea floor [4]

Ocean ambient noise is the residual noise background in the absence of individual identifiable sources that may be considered as the natural noise environment for hydrophone sensors. A direct connection between wind force and the level of ambient noise is observed for a frequency range of 500 Hz to 25 kHz. Wind speed dependence is dominant in the frequency band of 22Hz to 5KHz.

Sha'ameri et al. (2014) suggest that it is appropriate to model Underwater Acoustic Noise (UWAN) as coloured instead of white with a non-Gaussian probability distribution function. [5]

Muthuraj et al. (2015) claim that when both heavy rain and winds are present, noise generated due to the rain is the predominant contributor to the NL. [6]

Hildebrand (2009) classifies ambient oceanic noise into 3 frequency bands – low frequency: 10-500 Hz, medium frequency: 500Hz – 25 kHz, high frequency: > 25 kHz. The low-frequency band is dominated by anthropogenic sources: primarily, commercial shipping and, secondarily, seismic exploration. Shipping and seismic sources contribute to ambient noise across ocean basins, since low-frequency sound experiences little attenuation, allowing for long-range propagation. [7]

B. *Low Frequency Ambient Noise Modelling*

In tropical regions like the Indian Ocean Region (IOR), Commercial off-the-shelf (COTS) SONAR technology is not very effective and custom-made technology is required as the Indian sub-continent presents its own set of challenges regarding acoustic measurements. [4]

As the measurements of the underwater ambient noise level are very difficult, especially in remote oceanic regions, where conditions are often inhospitable, there is a need for simulation and model studies for estimation of noise level. The noise level for the frequency range from 500 Hz to 5000 kHz is simulated using Feed forward Neural Networks (FNN) by training the neural network using experimental data with wind speed and wave height as input and Noise spectrum values for the corresponding input as output vector. Analysis of experimental data reveals that the noise level increases with wind speed and the variation of noise level is not linear with wind speed for every frequency. It is also shown that the noise level is higher for low the low range of frequencies and it decreases with the increasing frequency. Comparison between simulated noise levels for different wind speed and the experimental data for a range of frequencies show close agreement. This is supported by analysing the Mean Squared Error values obtained for different wind speeds. [8]

Roul et al. (2019) used Automatic Identification System (AIS) data to create a spatial noise (primarily shipping noise) map of the Arabian sea near the Mumbai coast. The shipping noise was assessed using the Research Ambient Noise Directionality (RANDI) 3.1 Model, modified for the IOR to incorporate the specifics of the shallow ocean water region under study. [1]

Bagočius et al. (2018) analyse low-frequency underwater ambient noise in the Baltic Sea based on measurements obtained from vessel source spectra, AIS data, hydro-acoustic and geo-acoustic information, and environmental data such as bathymetry, sediment types, wind force, and precipitation intensity. The model consists of 3 models to separately account for NL using vessel data, Transmission Losses (TL) using hydro-acoustic and geo-acoustic factors, and noise contributions from environmental factors. [9]

III. Acoustic Noise Measurement Challenges

- *Sensitivity:* Hydrophones of high sensitivity are required to detect noises of low amplitude. An amplification system where the gain can be selected is preferred. Additionally, a higher resolution Analog to Digital Converter (ADC) is desired.
- *Frequency Response:* It is desirable that sensitivity is independent of frequency recorded. Strong dependence of sensitivity on frequency will result in a distorted signal. Note that low frequencies (1-10Hz) can get severely attenuated by damaged hydrophones.
- *Self-Noise:* Often dubbed ‘noise floor,’ the noise generated by the AUV is electrical in nature and must be calculated (and minimized). The self-noise equivalent sound pressure level must be at least 6dB lesser than the lowest noise-level to be measured in the frequency range of interest.
- *Dynamic Range:* Refers to the amplitude range where reliable readings of the sound pressure can be taken. Hydrophones must be chosen of appropriate dynamic range with regards to the soundscape of the location where noise is being measured.
- *Calibration:* It is very risky to rely on indicative or nominal calibration values produced at the system design stage, and this is not recommended. The calibration should cover the full frequency range of interest for the specific application at hand. It is possible to calibrate a hydrophone and recording system with an overall uncertainty of better than 1 dB. A full laboratory calibration is recommended before any major deployment. [10]

IV. Acoustic Measurements using AUVs

A. *Acoustic Measurement Techniques*

Deployment tests of a prototype hydrophone array showed that a small diameter, low noise, AUV towed array is achievable. Further, the AUV was able to tow the array at speeds of about 2-3 knots in a stable configuration. The excellent coherent beamforming results observed in the small Dodge Pond clearly show that this system is a feasible and valuable acoustic measurement tool. [11]

Arrichiello et al. (2016) suggest that the replacement of a towed array system with a team of AUVs introduces several issues in the localization of hydrophones needed to allow the processing of acoustic data, since they are no more on the sea surface. [12]

This claim is countered by Edwards et al. (2004), who propose a robust leader-follower control algorithm to control multiple autonomous vehicles. In the formation control algorithm, only the leader vehicle periodically broadcasts its position to the other vehicles that use this information to maintain a fixed distance from the leader while following a prescribed trajectory. The algorithm assumes that the vehicles determine their position using the leader vehicle and follow a set trajectory derived from the leader. [13]

B. *Acoustic Measurement Applications*

- Bathymetric Simultaneous Localization and Mapping (BSLAM): BSLAM Techniques could provide long-term underwater navigation results for AUVs and provide self-consistent bathymetric maps simultaneously [14]
- Underwater Acoustic Sensor Networks (UW-ASNs): Basic underwater acoustic (UWA) networks are formed by establishing two-way acoustic links between various instruments such as autonomous underwater vehicles (AUVs) and sensors. The network is then connected to a surface station which can further be connected to a backbone, such as the Internet, through an RF link. This configuration creates an interactive environment where scientists can extract real-time data from multiple distant underwater instruments. After evaluating the obtained data, control messages can be sent to individual instruments and the network can be adapted to changing situations. Since data is transferred to the control station when it is available, data loss is prevented until a failure occurs. [15]
- Underwater Ambient Noise Measurement: Shipping noise, and signatures of noises emitted by specific ships

is measured using AUV mounted acoustic vector sensors [16]

V. Types of AUV

AUVs are designed for various depths underwater and have appropriate design specifications. It is possible to classify most AUVs as the following types based on their operating depth.

A. Shallow Water Survey AUVs

Shallow Water Survey AUVs are rated up to 500m, and are used for performing oceanographic surveys from close to the surface. These are often tiny in size since they don't have to withstand a great deal of water pressure, have a good thrust-to-drag ratio, and can manoeuvre in places with strong currents. Furthermore, because these sorts of vehicles typically conduct surveys on a vast scale with limited resolution, their operating speeds are relatively high, on the range of a few knots per hour.

B. Mid-water AUVs

These are AUVs with a depth rating of up to 2500 metres that are primarily employed for mid-water column surveys or shallower seafloor surveys. To handle the high pressure at depth, these are often bulky, which means they require more thrust and power, which adds to their size. This class of AUVs can have a low thrust to drag ratio because there isn't much current at these depths. Operating speeds for a typical AUV of this class can range from less than one knot per hour for a photographic survey to a few knots per hour for a multibeam or side-scan survey, depending on the application.

C. Deep-water AUVs

Deep-water AUVs are the class of AUVs designed to be used at depths of more than 2500m. The housings are huge and substantial due to the enormous oceanic pressures that these vehicles must withstand. Also, because diving to such depths takes a long time, one would like to get more missions out of each dive, which necessitates more power storage, which increases the size of these vehicles. These vehicles feature a low thrust to drag ratio to keep their sizes modest and make them more power efficient. Because AUVs of this class are typically used for high-resolution surveys close to the ocean floor, they must be able to manoeuvre at low speeds. Their design cannot include manoeuvring control surfaces, resulting in multi-hull designs with many thrusters.

D. Gliders

Gliders are underwater vehicles that convert vertical motion into forward propulsion by utilising changes in buoyancy and water temperature in conjunction with wings. These buoyancy engines are often significantly more efficient than traditional electric thrusters, allowing them to reach ranges of thousands of kilometres. These vehicles normally operate in the upper water column and have a maximum depth rating of less than 1000 metres.[17]

VI. AUV Subsystems

There are several aspects that must be looked at closely while designing an AUV. Broadly, they can be divided into 3 broad classes and consequently 3 subsystems which the AUV comprises of – the mechanical, electrical and software subsystems.

A. The Mechanical Subsystem

The Mechanical Subsystem focuses on the design, prototyping, and manufacturing of the pressure vessels (hulls) which house the electronics, sensors, actuators and batteries as well as the frame, and underwater connectors. Solidworks, Catia or Solid Edge are software applications used for 3D Computer Aided Designing (CAD). Ansys, COMSOL or Abaqus may be used for Solid Structural Analysis, Computational Fluid Dynamics (CFD) for drag analysis, and Thermal analysis of the members of the AUV. [18]

B. The Electrical Subsystem

The Electrical Subsystem is designed to meet the power and control needs of the AUV. A single board computer (SBC) is installed to handle higher level processing such as vision, mission planning and controller signals. It reads/publishes data from various sensors and electronics stack on serial and Controller Area Network (CAN) buses respectively.

For acoustic sensing, a custom board can be designed to condition the signals coming from hydrophones. Amplification, Filtering, Processing and Time Difference of Arrival (TDOA) estimation allows to establish the Direction of Arrival (DOA). [18, 19]

C. The Software Subsystem

The Software Subsystem is designed to automate the vehicle. Drivers take data from sensors and publish them to Robot Operating System (ROS) topics. Localisation is performed and a set-point containing desired positions, orientations and velocities is received by the controller, which returns the appropriate forces and torques required. An allocator distributes these values to the thrusters. Vision is implemented from data obtained from cameras. The Navigator is responsible for deciding on the best path to follow between 2 locations. It works in tandem with the data obtained from localization. States are defined to organize how a task is carried out. A mission planner is implemented on top of the architecture which tells the vehicle what tasks to perform next and it maintains the pre-requisites to each task.

Note: Relevant information is discussed at length in Appendix A

VII. AUV Payload

- *Thrusters / Propellers:* Generally motor-based, ESC controlled components designed to allow rotation and translation of the vehicle, like BlueRobotics T200
- *Cameras:* Sensors to provide data for vision based scanning and navigation. Generally designed for low light

and cased in a custom hull with an acrylic end-cap. May not be effective in murky or turbid water.

- *Battery Packs:* Generally Li-ion, LiPo or NiCad in their chemistry; responsible for providing power to the entire vehicle. Possibly cased in their own hulls for easy hot-swap implementation.
- *Inertial Measurement Unit (IMU):* Determines the acceleration, angular rate and orientation of a vehicle by using a combination of accelerometers, gyrometers and magnetometers. Requires an acrylic casing to avoid magnetic interference.
- *Doppler Velocity Log (DVL):* Measures acoustic red-shift and blue-shift to determine velocity relative to the seabed. Generally waterproof, so it can be installed directly on the frame of the vehicle.
- *Pressure Sensors:* Calculates the depth at which the vehicle is by measuring the fluid pressure
- *Hydrophones:* The underwater analogue to microphones, they are deployed to perform acoustic measurements which can be used for bathymetry, SLAM, and communication.
- *Single Board Computer (SBC):* The on-board computer which reads and publishes data from sensors as well as the CAN bus; responsible for enabling software functionalities.
- *Graphical Processing Unit (GPU):* Responsible for implementing vision based algorithms. Forms the hardware, along with the SBC, where the software stack is implemented.
- *Electrical Stack:* Implements the Electric Subsystem. Handles the control and power needs of the vehicle.
- *Analog to Digital Converter (ADC):* Converts the analog signal read from nature to digital signals compatible with computers.
- *Data Acquisition (DAQ) System:* Comprises of the sensors and ADC, it handles acquisition of data and conversion to a retreivable format.
- Other Sensors/Actuators for specific use

VIII. GENERAL DESIGN OF AN AUV AND DEPLOYMENT CHALLENGES

A. Shape of an AUV

Most AUVs used in science and industry today can be classified into torpedo shaped design and the non-torpedo shaped design independent of other characteristics. This classification is important because it governs a lot of the characteristics of the AUV.

"The difference in the two classes of AUVs is analogous to that of the airplane and helicopter. The two have their own advantages and cater to different applications. The science community will always have these two kinds of AUVs co-exist to meet the complete set of requirements." [17]

B. Hull Design

An AUV must provide a pressure hull to house its components in a dry, watertight environment. The hull must allow components to be easily accessible and maintainable, as well as allowing for modularity in case of future changes or additions. As well as being light and strong, the hull should also be corrosion resistant as it will be subjected to a harsh saltwater environment.

Extensive structural, drag and thermal analysis must be performed to decide which hulls to design, and their dimensions. [20]

C. Buoyancy and Stability

All objects submerged in fluids experience a buoyant force equal to the weight of the fluid displaced (Archimedes' Principle). An object is positively, neutrally, or negatively buoyant depending on whether the weight of the object is less than, equal to, or more than the weight of the fluid it displaces respectively. An object is rotationally stable when the centre of gravity and centre of buoyancy lie on the same vertical axis. AUVs are generally designed to be stable and positively buoyant.

D. Degrees of Freedom and Propulsion

An underwater vehicle has 6 degrees of freedom. Three defining spatial coordinates: x, y and z. And three attitude defining angles: ϕ, θ and ψ. The translational motions are called surge, heave and sway; the rotational motions are called roll, pitch and yaw. Due to the six degrees of freedom an AUV is quite versatile. However, normally not all degrees of freedom are controlled by actuators. It is very common to inhibit a roll and pitch movement by a bottom-heavy design. [21] Thrusters must generate a force equal to the drag experienced by the AUV. CFD calculations are done using software applications like ANSYS – Fluent to estimate drag.

Note: Design and deployment challenges have extensively been covered in Appendix A

IX. RESEARCH AREAS

A. AUV Design and Development to validate low frequency ambient noise data

AUVs can be designed to carry a range of payloads, including hydrophones. They can be used to record oceanic ambient noise field data. Using AUVs provides an advantage over surface boats as AUVs are not affected by surface waves. [22] This data can be analysed without previous information concerning the environment or shipping in the area of interest. The spatio-temporal mapping of the noise data can be directly compared with AIS data-based noise mapping.

B. Swarm Algorithms

The use of an array of multiple AUVs for mapping noise can be looked at with the perspective of swarm robotics. Algorithms modelling swarm behaviour found in nature, like Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Bees Optimization have been developed. Communication remains a major roadblock in the implementation of these algorithms. Research can be pursued to look at ways to organize underwater swarm communication. [23]

C. Real-time visual Simultaneous Localization and Mapping (SLAM)

Research for real time visual SLAM algorithms has direct application to areas like AUV-based underwater ship-hull inspections. Tethered robotic inspections have issues like snagging, manoeuvre degradation and tether management which AUVs avoid. Deep-sea archaeology is another field where visual SLAM can provide high-performance navigation. [24]

X. APPENDICES

Appendix A: Placeholder for link

REFERENCES

[1] S. Roul, C. Kumar, and A. Das, "Ambient noise estimation in territorial waters using ais data," *Applied Acoustics*, vol. 148, pp. 375–380, 2019.

[2] D. Ross, "Ship sources of ambient noise," *IEEE Journal of Oceanic Engineering*, vol. 30, no. 2, pp. 257–261, 2005.

[3] A. Trembanis, M. Lundine, and K. McPherran, "Coastal mapping and monitoring," in *Encyclopedia of Geology (Second Edition)*, second edition ed., D. Alderton and S. A. Elias, Eds. Oxford: Academic Press, 2021, pp. 251–266.

[4] A. Das, "Naval operations analysis in the indian ocean region," *Journal of Defence Studies*, vol. 7, pp. 49–78, 2013.

[5] A. Sha'ameri, Y. Al-Aboosi, and N. Khamis, "Underwater acoustic noise characteristics of shallow water in tropical seas," 09 2014.

[6] A. Muthuraj, G. Latha, R. Ramachandran, and A. Thirunavukkarasu, "Analysis of underwater rain noise from shallow water ambient noise measurements in indian seas," *Indian Journal of Geo-Marine Sciences*, vol. 0, 02 2015.

[7] J. Hildebrand, "Anthropogenic and natural sources of ambient noise in the ocean," *Marine Ecology-progress Series - MAR ECOL-PROGR SER*, vol. 395, pp. 5–20, 12 2009.

[8] R. Srinivasan, G. Latha, and R. Swaminathan, "Estimation and interpolation of underwater low frequency ambient noise spectrum using artificial neural networks," *Applied Acoustics - APPL ACOUST*, vol. 70, pp. 1111–1115, 08 2009.

[9] D. Bagočius and A. Narščius, "Simplistic underwater ambient noise modelling for shallow coastal areas: Lithuanian area of the baltic sea," *Ocean Engineering*, vol. 164, pp. 521–528, 07 2018.

[10] S. Robinson, P. Lepper, and R. Hazelwood, "Good practice guide no. 133 underwater noise measurement," 03 2014.

[11] J. Holmes, W. Carey, J. Lynch, A. Newhall, and A. Kukulya, "An autonomous underwater vehicle towed array for ocean acoustic measurements and inversions," 07 2005, pp. 1058 – 1061 Vol. 2.

[12] F. Arrichiello, S. Sarkar, S. Chiaverini, and G. Antonelli, "Localization of an array of hydrophones towed by an autonomous underwater vehicle," 06 2018, pp. 601–606.

[13] D. Edwards, T. Bean, D. Odell, and M. Anderson, "A leader-follower algorithm for multiple auv formations," in *2004 IEEE/OES Autonomous Underwater Vehicles (IEEE Cat. No.04CH37578)*, 2004, pp. 40–46.

[14] T. Ma, Y. Li, W. Rupeng, Z. Cong, and Y. Gong, "Auv robust bathymetric simultaneous localization and mapping," *Ocean Engineering*, vol. 166, pp. 336–349, 10 2018.

[15] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Underwater acoustic networks," *IEEE journal of oceanic engineering*, vol. 25, no. 1, pp. 72–83, 2000.

[16] D. S. Terracciano, R. Costanzi, P. Guerrini, V. Manzari, L. Troiano, M. Stifani, A. Tesei, and A. Caiti, "Bearing estimation in very shallow waters with an auv mounted acoustic vector sensor," 06 2019, pp. 1–6.

[17] V. P. Shah, "Design considerations for engineering autonomous underwater vehicles," Ph.D. dissertation, Massachusetts Institute of Technology, 2007.

[18] A. V. Sudhakar, A. Arun, M. Pandey, L. Majumdar, H. M. Santanam Bakshi, T. Shanavas, and A. Singh, "Research and development of matsya 4a, autonomous underwater vehicle."

[19] A. L. et al., "Technical design report of matsya 6a, autonomous underwater vehicle."

[20] P. Iyengar, S. Vaswani, C. Raikar, S. Singh, A. Joshi, A. Kumar, S. K. Savant, M. Gupta, S. Kottur, H. Godara *et al.*, "System design and implementation of matsya 2.0, a technology demonstrating autonomous underwater vehicle."

[21] B. Gerl, "Development of an autonomous underwater vehicle in an interdisciplinary context," Ph.D. dissertation, The University of Western Australia, 2006.

[22] S. Jaramillo and G. Pawlak, "Auv-based bed roughness mapping over a tropical reef," *Coral Reefs*, vol. 30, pp. 11–23, 06 2011.

[23] B. T. Champion and M. A. Joordens, "Underwater swarm robotics review," in *2015 10th System of Systems Engineering Conference (SoSE)*. IEEE, 2015, pp. 111–116.

[24] H. Brown, A. Kim, and R. Eustice, "An overview of autonomous underwater vehicle research and testbed at perl," *Marine Technology Society Journal*, vol. 43, 05 2009.