Development of a novel seismic acquisition system based on fully autonomous gliding ocean bottom nodes

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Summary

This paper discusses the development of a novel seismic acquisition system that utilizes a fleet of fully autonomous underwater vehicles (AUVs) as ocean bottom nodes (OBNs). The primary objective is to eliminate a reliance on remotely operated vehicles (ROVs) or ropes for deployment, making ocean bottom seismic acquisition significantly more efficient and cost-effective. This is achieved here by employing AUVs with long endurance that are capable of self-locating to pre-determined positions without the need for any direct surface control. Additionally, the system is designed for scalability, allowing for large inventories of AUVs to be deployed in parallel.

Introduction

Today, the demand for OBNs exceeds supply – and it is likely to do so for some time (McBarnet, 2022). This demand is fueled by a desire for better seismic data for reservoir optimization and by new advances in imaging technologies; in particular, full-waveform inversion (FWI), which greatly benefits from data containing ultra-long offsets that are rich in azimuthal coverage.

Accordingly, we see a variety of survey designs ranging from ultra-dense (e.g., Clair Ridge, UK North Sea; Smith et al., 2019), to produce the best possible 4D image, to ultra-sparse (e.g., Amendment, US GoM; Xing et al., 2020), to enable effective FWI at target depths. We are also beginning to see hybrid approaches to acquisition, such as streamer and sparse node combinations (e.g., Barents Sea, Norway; Dhelie et al., 2021) that augment streamer data with long-offset, multi-azimuth data for model building.

Hybrid survey designs are typically born out of necessity, principally due to the high cost of OBN acquisition. In an ideal world, with adequate inventories and no cost (or time) penalties, ultra-dense ocean bottom sampling would be preferable. The reality is, however, that the deployment and retrieval of nodes at the seabed, whether via ROVs or using ropes, is a complex operation. This is particularly so when dealing with large numbers of nodes or widespread arrays across large operational areas – all of which comes at a cost. Therefore, a compromise is often necessary between time, cost, and quality.

For these reasons, we propose an acquisition system based on long-endurance, fully autonomous, and self-positioning/self-repositioning nodes. These will be extremely efficient in almost any design configuration and, given an adequate inventory, will not require any compromise on sampling (akin to approaches achieved on land; Manning et al., 2019).

A key characteristic of this system is its ability to achieve continuous rolling of a receiver patch at speeds that eliminate any need for the source vessel(s) to wait. This means that the acquisition process can proceed without interruption, resulting in a step change in efficiency and productivity. Node deployment time becomes directly proportional to the rate that AUVs can be placed into the water, with no need for the node-handling vessel to fully traverse receiver lines.

System development

Our development objectives cover the entire seismic acquisition method, from the AUV’s design to its deployment, management, and retrieval. Factors such as geophysical coupling, affordability, power consumption, and the vehicle’s autonomy (e.g., navigation, steering, landing, recording, repositioning, surfacing) are all considered.

To ensure uninterrupted rolling of patches during acquisition, we prioritized long endurance as a fundamental requirement. Our AUVs are hybrid buoyancy-thruster propelled gliders. The variable buoyancy is the main propulsion method, while the thrusters are used mostly for yaw control. Changes in buoyancy are controlled by a piston displacing water with oil of a lower density, stored in an internal reservoir. Compared to fully active thrusters, this design significantly reduces energy consumption.

We have incorporated a layer of intelligence within the AUVs, enabling a high level of automation for independent actions and reactions, without the need for external intervention but with the ability for direct underwater and surface communication of instructions if desired. Provided with additional localisation information by a surface network of acoustic communications, each unit autonomously calculates and continuously optimizes its trajectory towards a pre-determined seabed position. The AUVs may also automatically reattempt their landing and coupling if the initial placement is suboptimal, utilizing...
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information from onboard sensors. This high degree of autonomy enables scalability and an ability to accommodate large nodal fleets, meeting commercial requirements for high-density receiver-side sampling.

Supporting the nodal fleet is a surface infrastructure comprising acoustic communications and fleet-management systems that ensure efficient coordination and operations (Figure 1). The central offshore site for control and communication is the master vessel, which hosts the launch and recovery system, AUV storage and charging, and data harvesting and handling facilities.

A limited number of small uncrewed surface vessels (USVs) will act as surface-underwater communication gateways and provide underwater navigation support for AUVs transiting through the water column. Additionally, a subset of landed vehicles can also act as seabed beacons, broadcasting information acoustically to the transiting vehicles to allow collaborative navigation.

It is important to point out that only a proportion of the deployed AUVs will be active at any given time, with landed vehicles remaining in a low-power acquisition state until triggered to reposition. This limits the amount of communications needed during operations.

The geophysical payload is currently an industry standard four-component sensor package, with one hydrophone and three geophones. The vehicles have a maximum landing mass in water of 4.5 kg, however this mass can be decreased as required by limiting the change in buoyancy (for example, when landing on very soft sediments).

Unit design and active-seismic tests

The AUV’s design has evolved over several iterations. The main challenge was to find a shape which is both efficient in water and stable on the seabed, as these two requirements are opposed. Figure 2 shows the development from an early concept in 2018 to today’s shape. The initial proof of concept consisted of a cylindrical hull supported by a sled (Figure 2, top). Early passive-seismic tests indicated this form to be inadequate, since currents flowing beneath the unit generated lift and led to instability at the seabed (Mancini et al., 2019).

The first bespoke prototype was developed in 2021 (Figure 2, middle; Mancini et al., 2023). The form was still mostly cylindrical but with a flatter base that increased the surface area on the seabed. Active-seismic tests still indicated some residual instability, manifesting as low-frequency noise that was absent in commercial control nodes co-located with the AUVs. Further refinement of the shape based on laboratory experiments (reproducing the instability effect in a sandpit), passive-seismic sea trials, and computational fluid dynamics modeling resulted in the current prototype design (Figure 2, bottom).

In October 2022, active-source seismic field trials were conducted offshore UK to validate the coupling capability of the latest form. In these tests, five AUVs were deployed alongside seven static commercial nodes. All units (AUVs...
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and static nodes) were equipped with identical geophysical payloads and placed over an area measuring 20 by 20 m. A series of 2D lines, 10 km long, were acquired over various orientations. A 650 in3 source was used, firing every 50 m.

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Analysis of the data recorded confirmed that the latest design achieved satisfactory coupling with the seabed (Figures 3 and 4). The noise observed in 2021 when using the previous shape, attributed to inadequate coupling, was eliminated. The Z component's signal is consistent across all five AUVs, which is encouraging considering that, currently, they are assembled by hand. Furthermore, the amplitude spectrum of the Z component for all lines and all AUVs closely match those of the hydrophone.

The X and Y components demonstrate good vector fidelity; when rotated to radial and transverse, consistent signals are observed on the radial component.

Functional tests

Multiple sea trials were conducted in the UK and Australia (Figure 5) to verify several aspects of the system, including the vehicle’s in-water behavior, the guidance and navigation performance, the onboard autonomy, and the system’s communication, command, and control performance.

The fundamental objectives of the trials were:
1. To simulate full acquisition cycles. Each AUV was tested to ensure its ability to perform controlled flights, execute successful landings on the seabed, and autonomously reposition itself as required. This involved assessing the vehicle’s in-water behavior, its ability to compute and continuously optimize its trajectory to a pre-planned location (accounting for factors such as currents), and its landing accuracy.
2. To conduct simultaneous multi-vehicle operations.
3. To demonstrate the topside system functionality, including tracking, control, positioning, and status monitoring in real time.

These objectives were successfully met in April 2023 at Loch Linhe (UK), where we successfully completed a series of full multi-vehicle acquisition cycles that involved navigation, landing at seabed targets, passive-seismic acquisition, and repositioning.

Although these tests were executed in environmentally challenging conditions, including 3 m tides, freshwater layers, and high surface currents, we managed to consistently achieve landing accuracies within 10 m radii from the pre-planned targets (Figure 6).

During these tests, it became apparent that having vehicles that can reposition without needing to surface is an important benefit. On days when meteorological conditions were adverse enough to prevent ROV operations, the AUVs were able to continue their test programs without interruption.

Conclusions

In this paper, we provide an update on the ongoing development of a novel seismic acquisition system based on fully autonomous underwater gliders.
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Figure 5: 2023 functional tests at Loch Linnhe (UK), which involved being open to the sea with 3 m tides and a freshwater surface layer generated by the Scottish Highlands. Top, single-vehicle deployment, and bottom, multi-vehicle operations.

We assessed feasibility and effectiveness through multiple functional tests that evaluated the performance of the system during various stages of the acquisition cycle, such as navigation, landing, and repositioning. The results of these tests provided validation of the system's current capabilities and provided an extensive engineering dataset for further development and refinement of the technology.

Additionally, active-source tests were carried out to specifically evaluate the AUV’s ability to couple to the seabed. The outcomes of these tests were central to the design of the current form. Reliable seismic data were recorded by all four components during the most recent trials, with the Z component showing consistent signal between all AUVs (with spectra that match those of the hydrophone) and the X and Y components demonstrating good vector fidelity.

With this solid foundation in place, focus has now shifted to the next phase of development. The main objectives for the next twelve months are to perform further joint seismic/functional trials in varying sea bottom conditions and to embark on the task of scaling up the number of units involved in a single operation.

Figure 6: Top, screenshot from the ultra-short baseline (USBL) tracker showing an AUV’s path (red) from its starting position on the seabed (yellow circle, top right) to its new landing position (yellow crosshair, bottom left). Note how the AUV initially overshot its target due to currents but self-corrected its trajectory (yellow arrow). Bottom, zoomed view of the seabed target showing the position of three AUV landings (magenta dots), with each landing being within or close to a 10 m radius from the target (red diamond).

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