

Over-horizon Awareness of Seafloor Imaging Surveys from Long Range AUVs

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Abstract—Long-range Autonomous Underwater Vehicles (AUV) enable persistent seabed surveys over spatial and temporal scales that are impractical for conventional ship-based operations. However, the large volume of optical imagery collected during these missions prevents operators from obtaining timely situational awareness when communication is limited to low-bandwidth satellite links. This paper proposes an over-horizon awareness framework that uses onboard artificial intelligence to transform high-resolution seabed imagery into compact survey summaries suitable for satellite transmission. The framework enables operators to assess survey progress and seabed characteristics without recovering the vehicle or transmitting complete image datasets. Offshore validation over 41 AUV dives demonstrated the feasibility of semantic over-horizon awareness by successfully transmitting semantic survey summaries generated from 37,285 seabed images with an average latency of 8 minutes. This work provides a foundation for persistent ship-free seabed monitoring and future adaptive mission execution based on onboard interpretation of the surrounding environment.

Index Terms—Autonomous Underwater Vehicles (AUVs), Seabed Imaging, Onboard Machine Learning, Over-Horizon Awareness.

I. INTRODUCTION

The rising demand to sustainably monitor and explore the seabed is so great that it is critical for policy makers and operators to have higher resolution and timelier, field-scale measurements of these increasingly complex and stressed marine environments. The existing paradigm for seabed inspection, based on a single Remotely Operated Vehicle (ROV) tethered to an expensive support ship with a large crew for infrastructure inspections or the monopolisation of ship time to deploy, drop or tow cameras for habitat mapping, does not scale to meet the emerging needs for offshore renewables and Marine Protected Area (MPA) monitoring.

The Over-horizon Awareness of Seafloor Imaging Surveys (OASIS) project investigated an alternative approach in environmental monitoring by exploiting the benefits of ultra-endurance shore-launched AUVs operating over the horizon equipped with advanced subsea imaging technology [1].

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Fig. 1. Launching Autosub Long Range 8 (ALR8) in Lerwick Harbour, Shetland Islands (June 2025)

The proposed system has the potential to reduce Capital Expenditure (CapEx) and Operational Expenditure (OpEx) by removing the need for large support vessels, reduce the operational CO₂ footprint by minimising fossil fuel consumption during operations, and improve personnel safety by moving operators from hazardous offshore roles into higher-skilled shore-based roles (vehicle piloting and data analytics).

II. APPROACH

This project leverages existing ocean technology expertise and high Technology Readiness Level (TRL) systems from both the UK and Canada, to provide a new concept of operations for marine autonomy, which both enhances the development of component technologies and delivers new services. These include:

- The National Oceanography Centre's (NOC) Autosub Long Range (ALR) AUV has demonstrated shore-launched, basin-scale surveys in the Iceland Basin, North

Sea [2] and the Southwestern Approaches [3]. The sensor payload has been adapted for physical oceanography, biogeochemistry, under-ice and seabed habitat mapping.

- The Voyis Observer Micro camera system, which was recently used to successfully map the Titanic wreck in 3D [4] and the Endurance, Sir Ernest Shackleton’s sailing ship lost in Antarctica [5].
- The University of Southampton’s (UoS) Remote Representation of Image Semantics (R2IS) algorithm for remote awareness of seafloor images [6].

By combining these technologies, the project aimed to develop an integrated seabed survey system that acquires high-resolution imagery at low-altitude while providing detailed habitat assessment, condition monitoring of subsea infrastructure, and over-horizon situational awareness for long-range AUV operations.

III. PROPOSED SYSTEM

The proposed system consists of three main components described in sections III-A, III-B and III-C, while section III-D describes the difference between the conventional approach and the one proposed.

A. ALR AUV

The ALR class of AUVs was developed to provide ultra-endurance ocean observations and survey capabilities over spatial scales that are impractical for conventional AUVs. In particular, ALR1500 combines the manoeuvrability and payload capacity of a flight-style AUV with endurance measured in months and operational ranges of several thousand kilometers, allowing shore-launched missions without vessel support. The vehicle architecture supports a diverse suite of oceanographic, pelagic and benthic survey sensors, including Conductivity-Temperature-Depth (CTD) instruments, Acoustic Doppler Current Profilers (ADCPs), fluorometers, turbulence probes, bio-geochemical sensors and higher-power acoustic imaging payloads such as Side-Scan Sonars (SSS) or Multi-Beam Echo Sounders (MBES), as well as a variety of high-resolution and wide field of view camera systems. Recent field demonstrations have validated long-distance autonomous operations exceeding 2000 km, highlighting the platform’s suitability for persistent environmental monitoring, seabed mapping, and remote inspection tasks [3]. These characteristics make ALR an ideal platform for over-the-horizon seabed imaging applications, where large-area coverage, low operational costs, and minimal human intervention are key requirements.

B. R2IS Algorithm

The Remote Representation of Image Semantics (R2IS) algorithm is an onboard Artificial Intelligence (AI) framework developed to provide over-the-horizon awareness of seabed imaging surveys conducted by autonomous underwater vehicles equipped with low-bandwidth communication capability, e.g. satellite communication using a non-directional antenna. Rather than transmitting complete image datasets,

R2IS communicates compact survey summaries consisting of compressed representative imagery together with georeferenced metadata, enabling operators to assess survey content while the vehicle remains deployed. The method employs self-supervised visual representation learning to extract semantic features from acquired imagery and project images into a feature space in which visually similar observations can be compared and grouped. Hierarchical clustering is then applied to identify representative images that characterise the principal image types present within a survey, while semantic data describing a much larger set of observations are retained. These metadata and compressed versions of the representative images can be encoded into compact binary files that can be transmitted over low-bandwidth communication links. The framework also supports query-based image retrieval, allowing images most similar to a user-provided example to be identified and prioritised for transmission. By combining self-supervised AI, autonomous semantic analysis, representative image selection, and low-bandwidth data packaging within a single onboard pipeline, R2IS enables near real-time situational awareness and adaptive mission management during long-range autonomous seabed imaging operations.

C. Voyis Observer Micro Camera System

The Observer Micro is a purpose-built subsea survey camera designed for integration into autonomous underwater vehicles and other subsea robotic platforms. At its core is a 12-megapixel colour sensor delivering 12-bit dynamic range, providing the sensitivity required for high-quality low-light imaging in challenging subsea environments – down to 6000 m below sea level. The global shutter architecture eliminates spatial distortions at survey speeds up to 6 knots, while water-corrected fixed-focus optics maintain sharpness and geometric consistency across the full image field at operational altitudes between 1 and 7 m from seabed.

Onboard processing performs image undistortion, colour correction, and illumination normalisation to ensure a high level of consistency across survey datasets. Image data can be output or stored to the 2 TB onboard Solid-State Drive (SSD) either as processed 8-bit JPEG or raw 12-bit TIFF files. A Voyis factory calibration eliminates field recalibration requirements and ensures undistorted images that can be directly used in post-processing photogrammetry and mosaicking applications. The camera has a single connection point to the vehicle for power, ethernet, and a pulse-per-second (PPS) trigger, providing a straightforward vehicle integration. Time sync is possible not only via PPS but also via Precision Time Protocol (PTP) and Network Time Protocol (NTP). Every image captured by the Observer camera system is embedded with navigation metadata: timestamp, position, depth, and altitude, enabling direct georeferencing, photogrammetric reconstruction, and machine-learning-based analysis without additional post-processing overhead.

The Observer Micro is paired with the NOVA LED system which provides super-high intensity strobe lighting directly synchronised with the camera exposure via hardware trigger

output. The system consists of a dedicated electronics bottle containing the LED drivers and capacitor bank, and a pair of NOVA LED panels, with the potential to output up to 700,000 lumens. The LED system is downstream of the camera making integration simple on any Unmanned Underwater Vehicle (UUV).

D. Conventional vs Proposed Approach

Conventional seabed imaging surveys require the AUV to be launched, undertake the planned survey, and then be recovered before operators can access and analyse the collected imagery. Following vehicle recovery, the image dataset is downloaded, processed, and interpreted, after which any newly identified targets or areas of interest can only be investigated through a subsequent deployment. In contrast, the proposed framework enables semantic interpretation during the mission. After a single low-altitude survey, imagery is processed onboard by the R2IS algorithm, which generates compact semantic summaries that are transmitted over low-bandwidth satellite communication. These summaries provide operators with situational awareness approximately 8 minutes after the completion of data acquisition, enabling informed decisions and, where required, over-the-horizon re-tasking without vehicle recovery.

IV. SYSTEM INTEGRATION

For the OASIS project, the Voyis Observer Micro camera system was mechanically integrated into ALR8 by vertically mounting the camera housing within the free-flooded nose section, with the lens oriented downward. The strobes were installed at the rear of the platform using an adjustable mounting bracket as shown in Fig. 2, allowing precise orientation to the desired illumination angle.

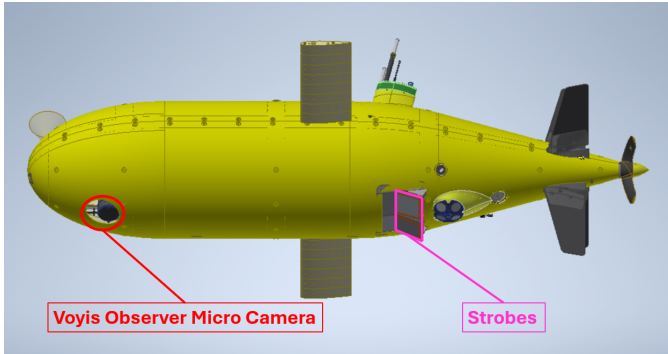


Fig. 2. ALR 8 - Voyis Observer Micro Camera System integration

The software integration of the camera payload into ALR8 was performed using the existing capabilities of the NOC On-board Control System (OCS) [7], the multi-platform software developed to control the NOC AUV fleet [8], by developing a bespoke node within the Robot Operating System (ROS) environment on which the OCS is built. This OCS node manages the interaction between the vehicle and the camera system. The internal computer onboard the Voyis camera

hosts an Application Programming Interface (API) through which the OCS is able to communicate with the camera. This includes sending camera configuration parameters (e.g. capture rate, LED intensity), providing the navigation solution (containing the AUV position and orientation) and issuing primary control commands (e.g. start/stop acquisition, initiate new dataset). The OCS node also retrieves general camera system diagnostics, allowing onboard system health monitoring and the encryption of packages to be transmitted over-the-horizon via satellite communications.

Alongside the API, the onboard computer of the Voyis system also hosts the R2IS algorithm. The algorithm receives the images acquired during low-altitude surveys directly from the camera system for onboard processing.

To enable over-the-horizon awareness and Near Real-Time (NRT) capability, the OCS node also handles the vehicle-side of the communication interface. This comprises two functions.

First, the OCS node adds some of the camera diagnostics collected through the Voyis API into the vehicle status. This is a message sent to the topside system periodically over Iridium satellite communication when the ALR is on the surface. By including the state of the OCS node, and parameters like camera temperature, number of images acquired and remaining camera storage, pilots are able to verify that the system is functioning as expected without requiring direct vehicle access.

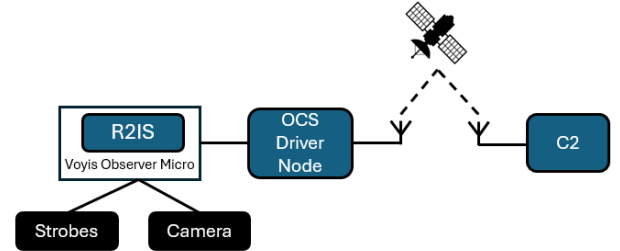


Fig. 3. System Integration Diagram

Second, the OCS node facilitates the transmission of the AI-based R2IS algorithm's output to the pilots via Iridium, as shown in Fig. 3. The R2IS algorithm performs feature clustering on a dataset of images acquired during low-altitude flight, grouping visually similar observations into clusters and assigning a unique identifier to each cluster. This information is then combined with metadata and passed as a byte array from the camera computer to the OCS node. This byte array is then compressed into a bespoke message format using Dynamic Compact Control Language (DCCL) [9], which packages data into compact binary datagrams, designed for efficient transmission over low-bandwidth networks. The metadata includes the image identifier, latitude, longitude, depth and altitude. Protobuf has library support across a wide array of programming languages, whilst DCCL provides more efficient packing of Protobuf schemas, with libraries for the

C++ and Python programming languages. The two combined afford greater flexibility of OCS sensor integration; novel and bespoke sensor data can thus be transmitted within the same framework whilst lowering the effort required to integrate that data into OCS NRT transmissions.

A Protobuf schema was defined by Voyis and NOC, to summarise R2IS outputs for each camera survey mission. These summaries include a total image count for the survey, the total number of features sampled across the captured images, and a collection of representative clusters identifier sets with associated metadata: time of image capture, estimated latitude and longitude, depth, and sea-bed altitude. Constrained by a satellite modem Maximum Transmission Unit (MTU) of 1890 bytes, the first approximately 60 identifiers representing features detected by R2IS could be transmitted in each summary, including the time and location of image capture.

The NRT messages transmitted by the OCS via satellite communication are received and processed by the NOC Command and Control (C2) system [10], which is a multi-platform piloting interface used to operate the NOC AUV and glider fleet over the horizon. Data are decoded and ingested into a time-series database allowing efficient querying of the telemetry data. This is coupled with a data visualisation web application which supports multidimensional plotting of all transmitted sensor and engineering data on line and scatter charts.

Support was added to NOC C2 to decode the third-party Voyis Protobuf messages embedded within the DCCL messages, such that the R2IS clusters identifier and accompanying metadata were made available as queryable data within NOC C2. To provide direct visual feedback on the geospatial distribution, number, and type of clusters identified by the algorithm within a dataset, the C2 data visualisation application was updated to support plotting of NRT sensor variables on a map.

Before the deployment, the AUV, the Observer Micro, and the C2, underwent end-to-end testing in the water tank at the NOC. This testing helped identify and address a number of issues that could have jeopardised the project: hardware faults, software misconfiguration, API misunderstanding around specific fields, as well as NRT parsing and decoding limitations due to the lack of data sanitisation.

V. RESULTS

The integrated system was initially commissioned during a two-week field campaign conducted in Loch Ness, Scotland (UK), in April 2025. The primary objective of these trials was to verify the hardware and software integration between the AUV and the camera system prior to offshore deployment.

The campaign successfully validated the execution of commands controlling the camera system as part of the mission script, the retrieval of diagnostic information from the device, and the continuous transmission of the vehicle navigation solution to support metadata generation. These trials validated the integrated imaging system under representative operational conditions and provided the foundation for subsequent offshore validation.

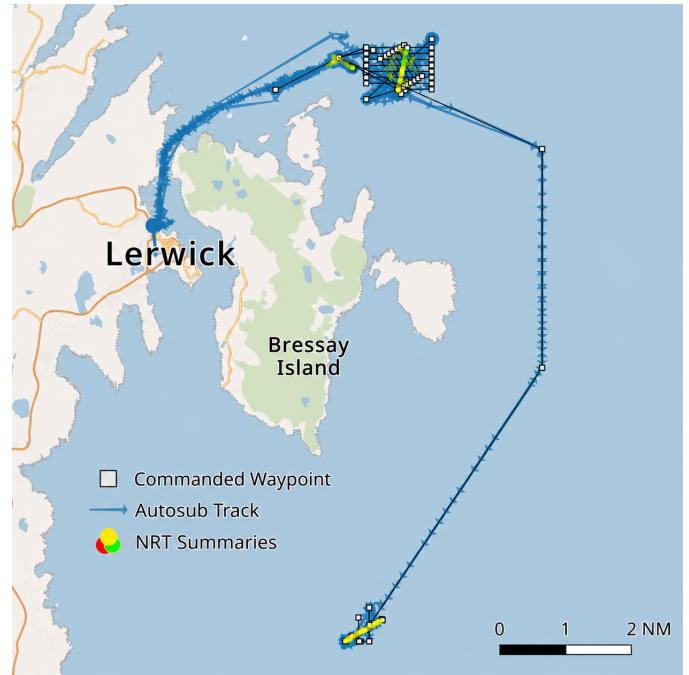


Fig. 4. Map of the operational area in Shetland (UK) showing AUV transect and Image Labels from the R2IS for low-altitude missions in north and south survey areas. The data shown on the map comes from NOC C2, after it has decoded the OCS NRT messages transmitted via satellite communication. (Basemap attribution: OpenFreeMap, OpenStreetMap)

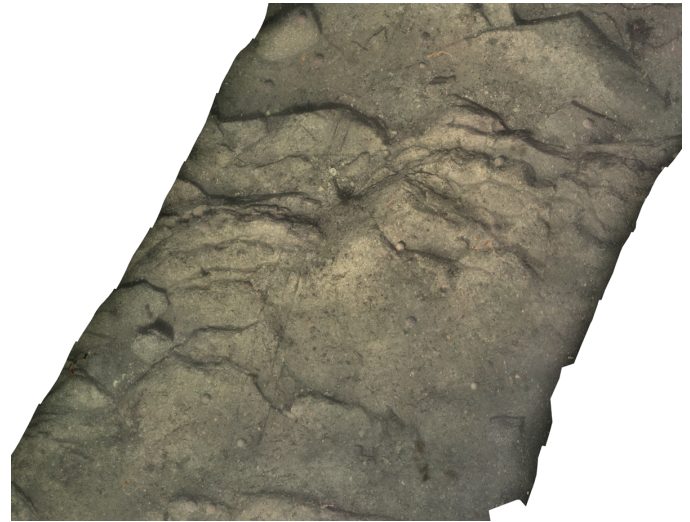


Fig. 5. Segment (3.7 m width) of a wide-area seabed photomosaic generated from images acquired by the Voyis Observer Micro camera during a low-altitude survey conducted in the northern survey area, north of Bressay Island.

The integrated system was validated during a final demonstration campaign conducted in the Shetland Islands, Scotland (UK), over a two-week period in June 2025. Lerwick served as the operational base from which the vehicle completed a total of 41 dives, accumulating approximately 100 hours of underwater operations and covering more than 250 km.

As shown in Fig. 4, the campaign focused on two primary survey areas located to the north and south of Bressay Island. These sites were selected based on previous ALR operations, providing well-characterized environments that enabled a direct assessment of the integrated imaging and over-horizon awareness capabilities under representative operating conditions. During the demonstration campaign, 9 dedicated camera surveys were conducted at an altitude of 3.5–5.0 m above the seabed. Fig. 5 shows a section of the photomosaic created in post-processing combining the AUV navigation solution with the pictures acquired during a mission performed at 3.5 m altitude in the north area. The quality and spatial consistency of the acquired imagery, exemplified by the photomosaic, enabled the successful application of the R2IS clustering algorithm to identify and cluster similar seabed features.

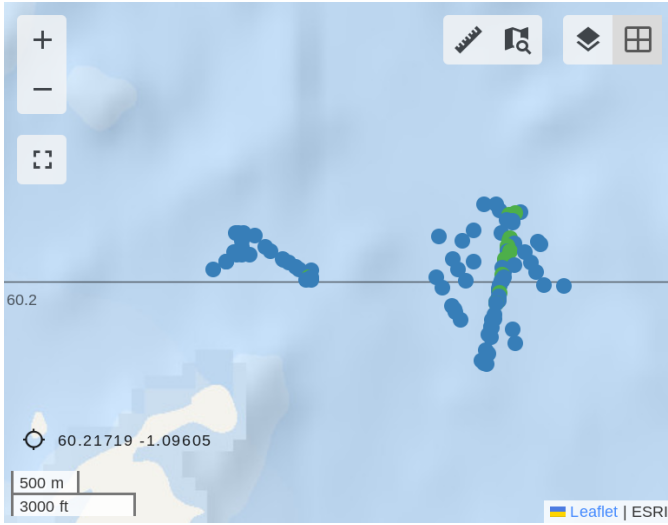


Fig. 6. Spatial distribution of the R2IS survey summaries transmitted via satellite following a low-altitude survey conducted in the northern survey area, north of Bressay Island. Each coloured marker represents a representative feature identified by the R2IS algorithm, with different colours indicating different outputs generated by the hierarchical clustering process. (Basemap attribution: OpenFreeMap, OpenStreetMap)

As recorded by the NOC C2, a summary generated for each low altitude survey was successfully transmitted via the satellite communication link. Fig. 4 and 6 present the survey summaries received by the C2 system, illustrating the spatial extent of the low-altitude imaging operations. The summaries reported a total of 37,285 images captured, representing more than 4 GB of image data stored in multiple formats, and 429,237 features classified by R2IS across all nine imaging surveys, with a total of 493 cluster identifiers included in the summaries (0.1% of the reported feature counts). The summary data contained three distinct cluster identifiers. The total size of the data transmitted was approximately 12.7 kilobytes, with an average message size of 1,735 bytes. Latency between the ALR’s transmission of the summaries and the data made available to visualize on C2 was on average 8 minutes.

VI. LIMITATIONS AND FUTURE IMPROVEMENTS

The results show it is only practical to report on a small proportion of the detected features via low-bandwidth satellite transmission, constrained in this case by the 1,890 bytes per message limit. It is possible to further condense the structure and allow a larger number of labelled features to be reported on within the limit; this should be achievable by optimising the message format for encoding data with the DCCL library. Future work may also explore how to prioritise detected features to be reported on over-the-horizon, making more effective use of the available messaging capacity to prioritise reporting on surveyed features with the highest detection confidence, another measure of importance, or selecting a statistically representative distribution of features to include in a summary.

The demonstrated capability of the ALR platform to support multiple survey modalities, SSS, MBES and high-resolution optical imaging (Fig. 4), together with the over-horizon awareness framework presented in this work, highlights its potential as a versatile platform for onboard AI-based interpretation of seabed data. Although these sensing modalities have not yet been operated simultaneously on the same vehicle, their successful deployment on the ALR platform provides a pathway towards multi-modal autonomous seabed surveys. Furthermore, the semantic information generated by onboard AI algorithms could be exploited not only for remote situational awareness but also to enable adaptive mission execution, allowing the vehicle to autonomously re-task or re-plan its survey in response to features detected in the surrounding environment.

While the experimental validation presented in this paper was conducted in water depths of up to approximately 90 m, the proposed over-horizon awareness framework is equally applicable to deep-water seabed imaging surveys. The principal challenges associated with extending the demonstrated approach to abyssal environments arise from the operational characteristics of the vehicle employed rather than from the imaging, processing or communication framework itself. ALR does not incorporate a dedicated buoyancy engine and therefore experiences increasing positive buoyancy with depth as a consequence of increasing water density, making precise depth and altitude control progressively more challenging during low-altitude imaging surveys.

As the AUV must surface each time data is transmitted via satellite, a high descent and ascent rate is essential when applying the proposed method to deep-water mapping missions. Although ALR variants can be rated up to 6000 m depth, its relatively low vertical transit speed of approximately 0.15 m/s would result in a significant proportion of the mission being spent descending to the seafloor and ascending to the surface. Consequently, although the proposed framework remains applicable to deep-water environments, maximising productive survey time at the seabed would require a vehicle configuration specifically optimised for sustained deep-water operations.

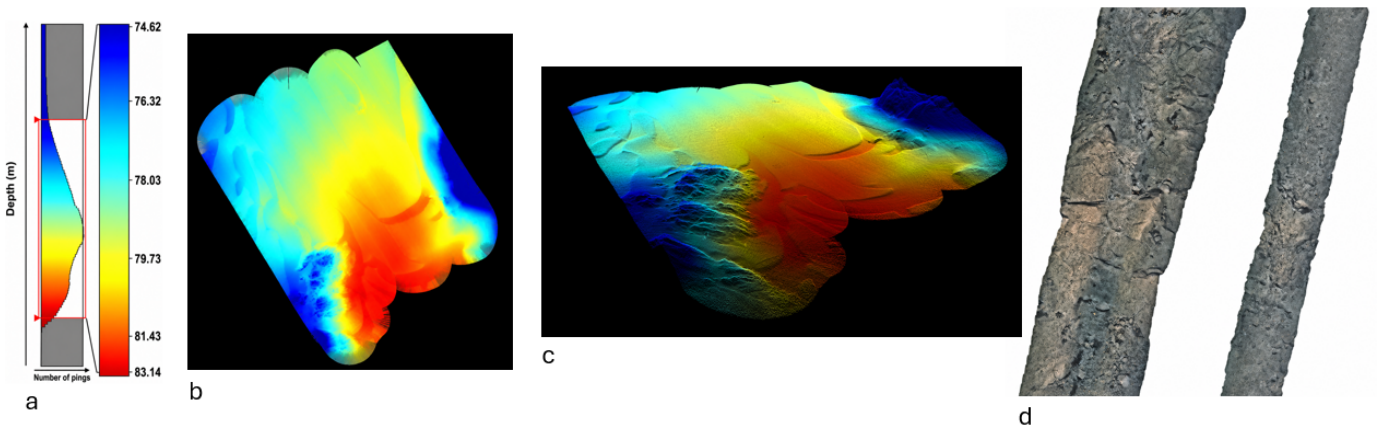


Fig. 7. (a) Colour scale. Top (b) and side (c) view of the bathymetry map created in post-processing using Multibeam data acquired during a previous ALR survey in the northern survey area, north of Bressay Island. (d) A section of the photomosaic created in post-processing combining four lines of the low-altitude mission in the north area performed during the final demonstration in the Shetland Islands.

VII. CONCLUSIONS

This paper presented the integration and field validation of an over-horizon awareness framework for long-range autonomous seabed imaging surveys. The proposed framework combines the Autosub Long Range platform, the Voyis Observer Micro camera system and the Remote Representation of Image Semantics algorithm within a unified architecture capable of providing near real-time semantic awareness through low-bandwidth satellite communications. The framework was successfully validated during an offshore demonstration campaign in the Shetland Islands.

The results demonstrate that meaningful situational awareness can be achieved without recovering the vehicle or transmitting complete image datasets, overcoming one of the principal operational limitations of long-range autonomous seabed imaging surveys. By providing operators with timely semantic awareness of the surveyed environment between dives, the proposed framework represents a significant step towards persistent, ship-free seabed monitoring based on on-board semantic interpretation rather than post-mission data analysis.

Future developments will focus on increasing the level of onboard autonomy by exploiting semantic information for adaptive mission execution, while extending the proposed concept to additional sensing modalities, including acoustic imaging, enabling a common over-horizon awareness framework for multi-modal autonomous seabed surveys.

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