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Quantitative Comparison of ROV and Diver-Based Photogrammetry to Reconstruct Maerl Bed Ecosystems

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ABSTRACT

In a time of ever-increasing pressure on the coastal ocean and rising costs, the development of effective and efficient methods for assessing the health of marine ecosystems is becoming essential for continued conservation efforts. Taking advantage of technologies such as remotely operated vehicles (ROVs) may be a way of achieving this, but a quantitative check on the quality of ROV-derived data is necessary. Here, using coralline algae reefs (maerl beds) as a model habitat, we compared 3D seabed reconstructions obtained from structure-from-motion photogrammetry surveys from diver-held and ROV-mounted camera systems. We found that both approaches achieved satisfactory alignment and mm-scale resolution, allowing small-scale features and individual organisms in the maerl bed to be resolved. The higher quality camera system available to divers resulted in generally lower modelling errors, but the spatial extent of surveys was highly restricted. In contrast, although associated with a slightly higher error, we show that much larger areas can be surveys by ROVs—we reconstructed 11,285 m^2 of seabed in just 400 min of ROV deployment time. Moving forward, we recommend that a hybrid survey approach is adopted: utilising ROV surveys for large-scale monitoring and diver surveys for higher detail insights that are informative for areas with highly complex and fine-scale morphologies (like coralline algae reefs). Here, even small changes in complexity can be indicative of habitat change, and associated species can be small in size so multiscale visual assessment is beneficial.

1 | Introduction

Sustainable advancement in the aquaculture sector necessitates the adoption of more stringent environmental regulations to preserve protected species and habitats in coastal marine and aquatic environments. Traditional diving-based survey methods have historically been fundamental in marine data collection (e.g., Lang 2007; Sayer 2007; Sayer, Fischer, and Feral 2008). However, these methods present a number of limitations, especially for hard-bottom substrates and sensitive biogenic habitats such as coralline algae (maerl/rhodolith) reefs and seagrass beds. Although traditional diver surveys are able to include cryptic and understorey species (Spyksma, Miller, and Shears 2022), these methods are also time-intensive, spatially limited (by area and depth), can be destructive (Lavy et al. 2015; Marre et al. 2019; Pizarro et al. 2017), entail high costs and have inherent human risks. Additionally, accurate measurement of habitat-relevant lengths, areas and volumes is difficult to achieve with traditional methods such as the chain-tape method (e.g., Knudby and LeDrew 2007). We therefore have a paucity of reliable data compared to other bottom types, limiting our capacity to accurately predict ecosystem vulnerability to environmental change and human activities such as aquaculture (Bernard et al. 2019; Ferrari et al. 2016; Fukunaga et al. 2019, 2020; Tillin et al. 2020). These limitations have prompted the exploration and integration of remotely operated vehicles (ROVs) for broader seascape-scale assessments (Tait et al. 2023; Zereik et al. 2018). Recent advancements and availability of ROV technologies (Buscher et al. 2020) have led to their routine use in biodiversity surveys (e.g., Andaloro et al. 2013; Boavida et al. 2016; Lam et al. 2006; Pacunski et al. 2008). ROVs offer a novel approach to data gathering in marine surveys, thus broadening the scope and efficiency of underwater research (Sward, Monk, and Barrett 2019; Zereik et al. 2018).

Coralline algae reefs—complex, three-dimensional (3D) habitats created by calcified red macroalgae commonly called 'maerl' or 'rhodolith' beds—have global ecological (Riosmena-Rodríguez 2017), biogeochemical (Burdett, Hatton, and Kamenos 2015; Mao et al. 2020) and cultural (Jardim et al. Forthcoming) importance but are one of the most poorly understood marine ecosystems (Tuya et al. 2023). Maerl beds are globally threatened by projected climate change (McCoy and Kamenos 2015; Simon-Nutbrown et al. 2020; Cornwall et al. 2022) and are slow to recover from physical disturbance (Kamenos, Moore, and Hall-Spencer 2003; Bernard et al. 2019). Their complexity, fragility, high associated biodiversity and large depth ranges means that maerl beds may be of prime benefit for the development of ROV-based survey techniques. Previous ROV efforts on maerl/rhodolith beds have used image stills to estimate factors such as distributional extent, calcium carbonate production and habitat biodiversity (e.g., Illa-López et al. 2023; Amado-Filho et al. 2016; Amado-Filho, Moura et al. 2012; Amado-Filho, Pereira-Filho et al. 2012; Pereira-Filho et al et al. 2012; Pereira-Filho et al. 2011). Developing ROV methodologies would elevate our capacity to accurately map and monitor these ecosystems, thereby providing critical data to inform their conservation and management.

Structure-from-motion (SfM) photogrammetry is a technique that employs photography to measure and map environments (Bayley and Mogg 2020; Figueira et al. 2015). SfM photogrammetry is particularly valuable in the study of maerl beds and other hard-bottom, complex or fragile seabeds because it captures high resolution (mm-cm scale) 3D models of these complex habitats without seabed disturbance (Ferrari et al. 2021). This enhances our capacity to detect subtle elevation changes over various timescales (Burns et al. 2015; Hatcher et al. 2020; Marre et al. 2019), which can be indicative of changing community structure or ecosystem health. This 3D methodological framework generates a variety of visual and spatial data types, such as orthomosaics and 3D reconstructions like digital elevation models (DEMs), meshes and point clouds. Orthomosaics (2D data) are useful for deriving quantitative biological measures, including species count and percentage coverage—key factors in assessing community structure, abundance and biodiversity (Marre et al. 2019; Mizuno et al. 2017). Three-dimensional data allow for accurate measurements of parameters including the surface complexity ratio (i.e., the ratio of 3D to 2D surface area; Ferrari et al. 2016; Lavy et al. 2015) and a robust quantification of slope, rugosity and other structural attributes (Friedman et al. 2012). These metrics thus provide new ways to monitor environmental impacts (e.g., from aquaculture; Read and Fernandes 2003). Improvements in photogrammetry data collection, processing and interpretation in recent years have stimulated their adoption into aquatic conservation, facilitating measurable conservation objectives, providing reference system baselines and enabling the development of new standardised, high accuracy and high precision ecological indicators (Ferrari et al. 2021; Urbina-Barreto et al. 2022). The high spatial resolution of photogrammetry allows for improved habitat restoration success by enabling parallel monitoring of individual, community and seascape dynamics (Remmers et al. 2024), meaning conservation relevance at species to habitat scales (Bayley and Mogg 2020). Since photogrammetry can be applied both on land and underwater, it can also yield comparable conservation metrics across ecosystems, helping to 'join up' conservation management—which is becoming more prominent in nature restoration policies (Keith et al. 2020; Burdett 2024).

Diver and ROV-derived photogrammetry both have advantages and limitations. Diver-derived photogrammetry benefits from the ability to utilise higher specification cameras, enabling the capture of higher resolution images and more detailed photogrammetric analysis (Bayley and Mogg 2020). Divers provide the added advantage of immediate adaptability and precise manoeuvring, which is particularly valuable in complex underwater terrains or when focusing on specific points of interest. However, divers are limited by their physical endurance, maximum depths, dive times and human safety risks. Conversely, ROVs operate at depths beyond safe diving limits and can conduct surveys with greatly extended time capacity (Teague and Scott 2017) and spatial coverage. Nevertheless, practical limitations of mounted camera gear (due to weight and size) mean that equivalent high-quality imagery can only be obtained by large ROVs; smaller ROV imagery is of necessarily lower quality.

Despite the widespread application of photogrammetric models, especially in terrestrial landscapes (Klapa, Mitka, and Zygmunt 2017; Martin, Tannant, and Lan 2007; Piermattei et al. 2016), a standardised, universal methodology for evaluating the accuracy and precision of the photogrammetry modelling process does not yet exist. Standardisation of approaches becomes increasingly important in complex environments (e.g., underwater) because of external influences such as depth variation, water movement and visibility. Achieving a standardised approach would enable robust assessment of data accuracy and increase confidence in the use of these approaches for scientific research and conservation management. To effectively apply 3D reconstruction to the characterisation of benthic features and biodiversity in complex marine systems such as maerl beds, both sub-cm resolution and spatially extensive survey scope are necessary, with high accuracy and precision. Here, we compared the efficiency and effectiveness of ROV-derived and diver-derived SfM photogrammetry data using maerl beds in Scotland, NW Europe, because of their recognised ecological and conservation importance, and known interaction with commercial aquaculture activities. Comparative analysis focused on quantifying the fidelity and accuracy of the constructed models, providing new insight into the role ROV-based photogrammetry can play in modern underwater surveying and establishing a path towards more efficient, accurate and sustainable conservation and management decisions.

2 | Methods

A comparative analysis of the accuracy and metric performance of diver versus ROV methods was conducted. Divers were equipped with a high-end photographic system (Nikon D850 SLR; Table S1) that served as the reference benchmark for the lower cost ROV components-based system (GoPro HERO10; Table S1).

2.1 | Study Sites

Survey data were collected at two maerl bed sites on the west coast of Scotland:

1.A maerl bed adjacent to Port A' Bhuiltin reef (56°29′19″ N 005° 28′16″ W; Figure 1A). Data were collected during September and October 2022 and included three survey sizes to determine the influence of spatial scale: 5 × 5 m, 10 × 10 m, and 20 × 10 m (water depth 8–12 m; Figure 1B).

2.The MOWI Hellisay fish farm, located to the northeast of the Isle of Barra, Outer Hebrides (Figure 1A). Data were collected at the MOWI Hellisay fish farm in June 2023 at a depth of 15–30 m. To demonstrate the flexibility and spatial coverage potential of ROV-based surveys, multiple survey areas were conducted: (1) four transects north, south, east and west of fish farm cages, with each transect comprised of three 225 m^2 plots: directly adjacent to fish farm cages, plus 50 m and 100 m from the cage edge (T1-4 in Figure 1C), (2) two plots further from the fish farm (650 m^2 each; 400 m^2; 'Ref B&C' in Figure 1C) and (3) one larger 6000 m^2 plot (the 'Pitch' in Figure 1C).

2.2 | Data Collection/Image Acquisition—Port a' Bhuiltin Reef

The three survey plot sizes were outlined underwater using string and pegs. Tile markers with dimensions of 10 × 10 cm were systematically positioned throughout the plots to serve as scale references for the diver-constructed models. Additionally, a reference block with measurements of 42 × 42 cm and a height of 8 cm was positioned within the survey area to validate the geographic scaling accuracy of the ROV-generated models.

2.2.1 | Diver Survey

To capture images for diver surveys, a SCUBA diver swam over the entire rectangular area, at a depth of ~1 m above the substrate, following a 'lawnmower pattern' (Bayley and Mogg 2020; Burns et al. 2015) with at least 75% linear overlap and at least 50% lateral overlap on turns.

2.2.2 | ROV Survey

The ROV photogrammetry survey was aligned with the trajectory of the diver survey, mirroring the pattern used in diver-conducted surveys to ensure consistency in data collection. Images were captured by deploying a Blue Robotics BlueROV2 Heavy equipped with a GoPro HERO10 camera (see Table S1 for camera system specifications). The ROV was modified with station keeping and cm-scale positioning with

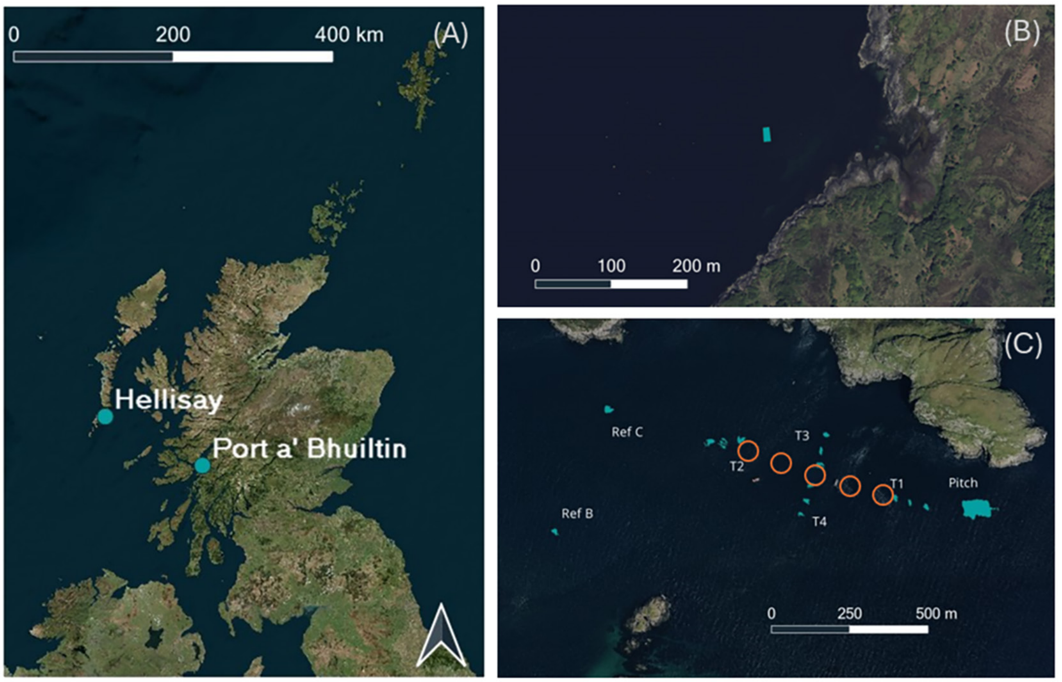

FIGURE 1 | Geographic location of the survey sites. (A) Location within Scotland, (B) Port a' Bhuiltin reef and (C) the MOWI Hellisay Fish Farm. Teal shading in B and C indicates the spatial extent of the underwater surveys. Orange circles in C indicate location of fish farm cages.

a WaterLinked doppler velocity log (DVL) A50. Fine-scale positioning data was fused with coarser scale (1 m) hydroacoustic positioning data from a WaterLinked G2 Short Base Line (SBL) positioning system with A1 locators, allowing all imagery to be georeferenced prior to processing. During the mission, the ROV maintained an altitude of 1–1.5 m above the seabed with a forward speed of 0.25 $m\,s^{-1}$, to achieve a balance between image coverage, resolution and illumination. The camera system was set to capture images at 1-s intervals, resulting in a significant overlap between consecutive images, which is crucial for accurate 3D model generation through photogrammetry. Lighting was provided by 4 Lumen Subsea 700 lights.

2.3 | Data Collection/Image Acquisition—Hellisay Fish Farm, Barra

Underwater image acquisition was performed solely using an ROV, equipped with a stereo-camera system. The stereo-camera setup comprised two synchronised, calibrated GoPro HERO10 cameras, mounted in parallel with a separation of 23 cm; this measurement provided a form of scale validation (see Section 2.4). The system's lighting was provided by two Weefine Smart Focus 3000s, delivering consistent illumination across the field of view to mitigate the low-light conditions inherent to underwater environments.

2.4 | Scaling

The scaling of diver-derived models at Port a' Bhuiltin reef was achieved using the aforementioned tile markers. For ROV models, scaling must be achieved without using physical markers or objects on the seabed, since these can be difficult and time consuming to install and maintain without divers. One alternative is to scale the models geographically, using global navigation satellite system (GNSS) technology paired with underwater acoustic positioning (Hatcher et al. 2020; Teague and Scott 2017). This method derives scaling from distances between images, leveraging increased image count to improve accuracy. In this study, positions sourced from the SBL (Short Baseline) were correlated with imagery using timestamps. However, non-real time kinematic GNSS systems have a known 3-m georeferencing error. Without GCPs, this error becomes crucial for the model's georeferencing precision. Furthermore, acoustically derived positions, like those from SBL, tend to be error-prone due to sound propagation complexities in water layers (Cario et al. 2021). As a result, scale discrepancies in ROV surveys can be expected to be higher than diver surveys—but the extent of this difference has yet (to our knowledge) to be quantified.

A second approach, which we employed at the Hellisay fish farm, is to employ a stereo-camera system consisting of two synchronised cameras mounted at a fixed distance apart on the ROV. The known distance between the cameras serves as a critical parameter for calculating the scale of the captured images. This method enables models to be locally scaled (non-georeferenced), or can be used to validate the measurements derived from GPS data.

2.5 | Parameter Acquisition

A range of metrics were derived to quantify the accuracy and precision of the photogrammetry surveys (Table 1). A quantitative assessment of the final 3D models was conducted to ascertain the fidelity and accuracy of the corresponding models derived from the diver and ROV surveys. It is acknowledged that some differences between diver and ROV surveys were due to the differences in the camera specifications. However, since ROVs are currently limited to smaller camera systems, this difference represents the practical reality and comparisons thus integrate both methodological and technological differences.

2.5.1 | Check Points

In both diver and ROV photogrammetry workflows, the final models were validated for scaling accuracy by comparing linear measurements in the SfM point clouds of the reference block on the seafloor—which had a known length of 42 cm. To further evaluate accuracy, check points were implemented on the reference block, and the root mean square error of these check points (CP RMSE; see Table 1) was calculated.

2.5.2 | Generation of the 3D Models

Prior to photogrammetry reconstruction, images were subtly corrected (each plot batch-processed) for white-balance, exposure and clarity (dehaze) using Adobe Lightroom Classic. Once imported to Agisoft Metashape Professional version 2.0 (Agisoft LLC., St. Petersburg, Russia), image quality was assessed, and those with lower scores (<0.5), resulting from motion blur or more prominent backscatter, were disabled.

The construction of 3D models was facilitated by employing Agisoft Metashape, utilising a SfM algorithm to process the overlapping images (Bayley and Mogg 2020; Fukunaga et al. 2019). The processing pipeline for 3D model creation in Agisoft Metashape was adjusted in accordance with the parameters specified in Table S2. Following this, DEMs and orthomosaics were generated and exported as GeoTIFF files containing elevation data at a resolution of 2.5 mm, together with local coordinate information for subsequent analysis. The analysis was performed using a PC with 12th Gen Intel Core i7-12700H @ 4.7 GHz, 2300 MHz, CPU with 14 cores, 16 GB of RAM, 64-bit operating system, 8 GB GPU Intel.

2.5.3 | Processing Report

All marker positions and model statistics were exported from Agisoft Metashape as text and PDF files. These 'processing reports' contained the basic parameters of the project, processing results and accuracy evaluations.

2.5.4 | Model Construction and Integrity

The final quality of a photogrammetry model is inherently tied to the conditions under which the survey was conducted, the

TABLE 1 | Definitions of the metrics used in this study to quantitatively compare survey approaches.

Metric	Unit	Definition
Accuracy of bundle adjustment		
Image residuals	Pixels	Difference between the observed image positions and the positions projected from the 3D model, with their length proportional to the magnitude of the error. Image observation residuals (r) were computed as follows: $r_{x_i = x_i - \bar{x}_i} a$ $r_{y_i = y_i - \bar{y}_i}$ $r_i = \sqrt{r_{x_i} 2 + r_{y_i} 2}$ where the image coordinates (x_i, y_i) correspond to the observed positions in the image plane, while (x^{-}_{i}, y^{-}_{i}) represent the re-projected positions of 3D coordinates as estimated through the bundle adjustment process (image coordinate residuals).
RMS reprojection error	Pixels	Root mean square reprojection error, averaged over all tie points on all images. The reprojection error represents the average distance, in pixels, between a tie point on the image (from which a 3D point has been reconstructed) and the reprojection of its 3D point back on the image.
Ground sample distance (GSD)	mm pixel^{-1}	Distance between the centre of two pixels measured on the ground ('pixel size in object space units'; Granshaw 2016). For a given image: $GSD = \frac{sensor\ width\ (mm) \times flying\ elevation\ (m)}{real\ focal\ length\ (m) \times image\ width\ (pix)}$ The GSD value was averaged over all images by PhotoScan and is available in the model processing report (see 'Ground resolution' in the 'Survey Data' section of the report).
Check points root mean square error (CP RMSE)	mm	Root mean square error of the position of a given check point across all photos in object space units.
Accuracy and precision of the models		
Relative measurement error	%	$\frac{\text{Measure on the 3D model} - \text{Real dimension}}{\text{Real dimension}}$ The accuracy and precision of objects measurements were assessed with the mean and standard deviation of the relative measurement error, respectively.
Model statistics		
RMS reprojection error		Paired t-test: $t = \frac{\bar{d}}{S_d / \sqrt{n}}$ where • $\bar{d}$ is the mean of the differences between paired observations. • S_d is the standard deviation of the differences. • n is the number of pairs.
Ground sample distance (GSD) and check points RMSE (CP RMSE)		The Pearson correlation coefficient: $r = \frac{\Sigma (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\Sigma (X_i - \bar{X})^2 \ \Sigma (Y_i - \bar{Y})^2}}$ where • X_i and Y_i are the two variables being compared. • $\bar{X}$ and $\bar{Y}$ are the means of the variables X and Y.
Relative measurement error		Independent t-test: $t = \frac{\bar{X}_1 - \bar{Y}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$ where • $\bar{X}_1$, $\bar{Y}_2$ are the sample means. • s_1^2, s_2^2 are the sample variances. • $n_1 n$, n_2 are the sample sizes.

survey methodology opted for and the nuances of the model-building process (Turner, Lucieer, and Wallace 2014). As images are procured and subsequently processed, distortions in the form of noise, blurring and ringing (edged distortions) can manifest, leading to potential degradation in the quality of the model (Slocum and Parrish 2017). Therefore, an understanding of photogrammetric parameters associated with the reconstruction process is essential for resolving model accuracy.

In comparing model constructions between ROV and diver surveys, we employed four key metrics:

1. Total number of images aligned: A higher number of aligned images can reduce overlap errors and contribute to a more accurate and comprehensive model.
2. Percentage of camera alignment: The success of image matching across the survey area. Higher alignment percentages indicate more effective matching and coverage.
3. Number of tie points in the sparse point cloud: Tie points are specific features within images used to establish correspondence and triangulate the 3D positions of objects or surfaces (Triggs et al. 1999). The quantity of these points can indicate the model's detail level and structural integrity.
4. Point density: A proxy for the accuracy of image-based reconstruction (Javadnejad et al. 2021). A higher point density typically correlates with a more precise model with finer spatial resolution.

2.5.5 | Textured Mesh Quality Assessment

To compare the quality of the textured mesh models between ROV and diver surveys, a multi-faceted approach was employed. Initially, the total number of faces within the mesh was calculated, providing a collective count of the triangular facets that comprise the surface mesh of the 3D representation. This count serves as an indicator of the resolution of the wireframe mesh, with a higher number of faces generally suggesting a more detailed model (Nocerino et al. 2020).

Colour fidelity was evaluated based on how accurately the colours in the orthomosaics matched the known colours of the surveyed environment, considering factors such as colour saturation, hue accuracy and the presence of any colour distortion or aberration.

Resolution and image clarity were assessed through both visual inspection of the orthomosaics and quantitative analysis of the spatial resolution achieved in the DEMs and orthomosaics. Visual inspection involved a qualitative assessment of the level of detail, sharpness and recognisability of features within the orthomosaics. The spatial resolution, expressed in terms of ground sampling distance (GSD), was measured to provide a quantitative comparison of the fine-scale detail captured by the two methods. A higher spatial resolution indicates a finer level of detail in the 3D models, which is essential for accurate morphological analyses and for documenting small-scale changes over time.

2.6 | Statistical Analysis

Statistical analyses to compare parameters between survey methods were performed using RStudio V2024.04.1 with R V4.3.0 (RStudio 2024). Visualisation of models were performed using RStudio.

3 | Results

3.1 | Model Integrity

The ROV data consistently had a higher number of aligned images and tie points compared to the diver data in all survey sizes (Figure 2a,c and Table S3), and the number of tie points

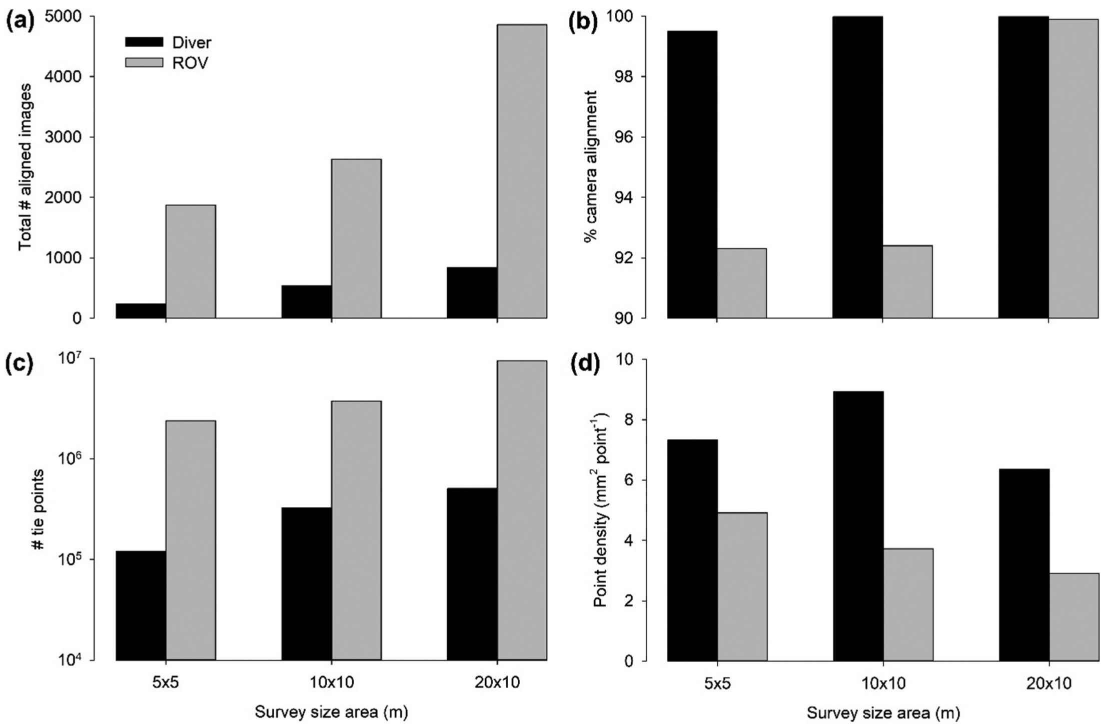

FIGURE 2 | Comparison of model construction metrics between diver and ROV photogrammetry survey methods. (a) Total number of aligned images, (b) % camera alignment, (c) number of tie points and (d) cloud point density (mm point^{-1}). Metrics presented for survey sizes of 5×5 m, 10×10 m and 20×10 m.

increased with increasing survey size (Figure 2c). Both the ROV and diver methods had > 90% camera alignment across all sites and survey sizes (Figure 2b and Table S3). Generally, a higher number of tie points leads to a higher point density, but here the diver-derived data had a consistently higher point density (Figure 2d and Table S3). In the diver-derived models, the highest point density was achieved in the 10 × 10 m survey size, while in the ROV-derived models point density decreased with survey size (Figure 2d).

3.2 | Textured Mesh, Colour Fidelity and Resolution

The number of faces within the mesh increased with survey size (Figure 3). At the smallest survey size (5 x 5 m) the number of faces per model was comparable between diver and ROV-derived models, but the diver-derived models had progressively fewer faces as survey size increased (Figure 3).

The diver-derived models, facilitated by the Nikon D850, showcased superior colour fidelity, and a higher level of detail with

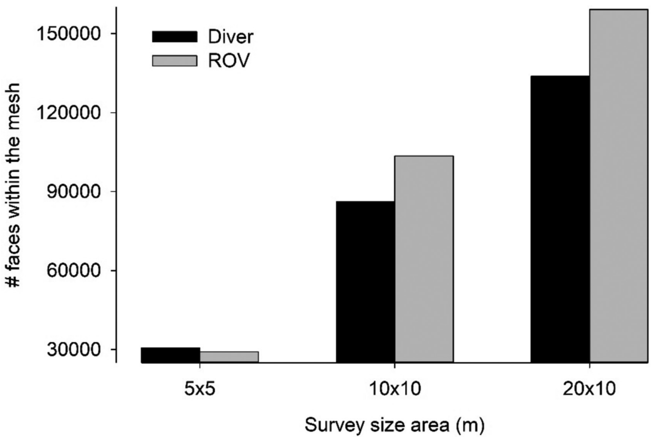

FIGURE 3 | Number of faces within the reconstructed mesh for ROV and diver-based photogrammetry surveys, for survey sizes 5 × 5 m, 10 × 10 m and 20 × 10 m.

a spatial resolution of 0.4 mm for the DEM and 0.2 mm for the orthomosaic (Figure 4; Table S4). In contrast, the ROV-derived models, captured by the GoPro, exhibited a noticeable deviation in colour accuracy – characterised by a slight colour cast – and a reduced spatial resolution of 0.6 mm for the DEM and 0.3 mm for the orthomosaic (Figure 4; Table S4). This resulted in a difference in derived seafloor topography between the survey methods, with calculated depth gradients of: 9.96–14.8 m (diver-derived) and 6.91–13.4 m (ROV-derived). Nevertheless, it was possible to use the same colour profiling (Figure 4), meaning that depth variations were uniformly presented and that visual comparative analysis of topographical changes between models was possible.

3.3 | Model Accuracy

A high-resolution orthomosaic was successfully created for each survey size, for both survey methods. All orthomosaics had sub-mm image resolution, with the lowest quality resolution being 0.3 mm pixel^{-1} in the ROV 20 x 10 m survey size (Table S4). A notable difference in the average image residual patterns for the two camera systems was observed, and this was consistent at the three survey sizes was observed. The residual patterns for the diver-held Nikon D850 had less pronounced distortions, excepting some stretching of residuals towards the corners (which is typical of many lens systems). This indicates a well-corrected optical lens with minimal systematic errors. In contrast, the ROV-mounted HERO10 displayed a pronounced radial distortion pattern, especially visible in the circular distribution of residuals around the centre and extending towards the corners. The radial pattern is indicative of barrel distortion and characteristic of wide-angle lenses, while the corner distortions likely arise from the lens-flat port combination.

The RMS reprojection errors in the ROV-derived models was significantly higher than the diver-derived models at all survey sizes, by a factor of at least four (Figures 5 and 6a and Table S5). CP RMSE, representing the accuracy with which the models matched real-world coordinates, were low for both

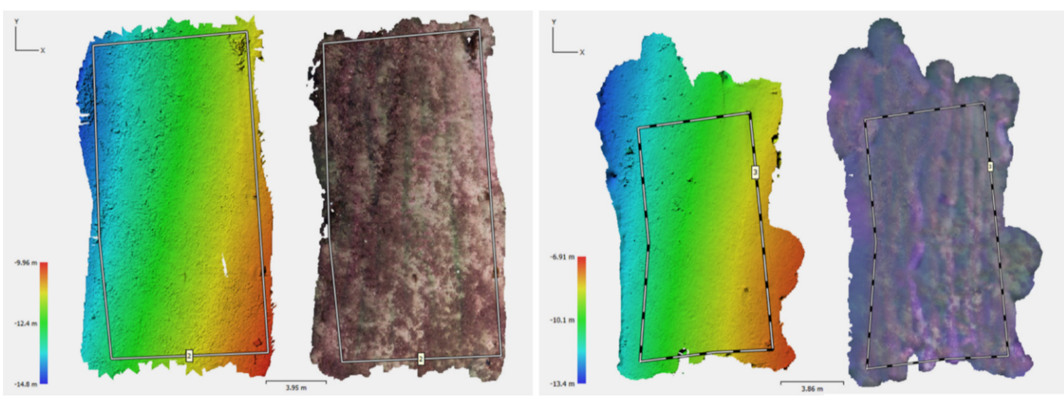

FIGURE 4 | Mapped bathymetry (digital elevation model; DEM) and orthomosaic. Outputs derived from the structure-from-motion dense point cloud for diver-derived (left) and ROV-derived (right) survey methods. Scale bars = 3.95 m (left) and 3.86 m (right). The spatial resolution of the DEM and orthomosaic for the diver-derived models were 0.4 mm (DEM) and 0.2 mm (orthomosaic) and for the ROV-derived models 0.6 mm (DEM) and 0.3 mm (orthomosaic)—demonstrating the nuanced differences in data capture techniques between diver and ROV models. Exemplary outputs shown for the 20 × 10 m survey.

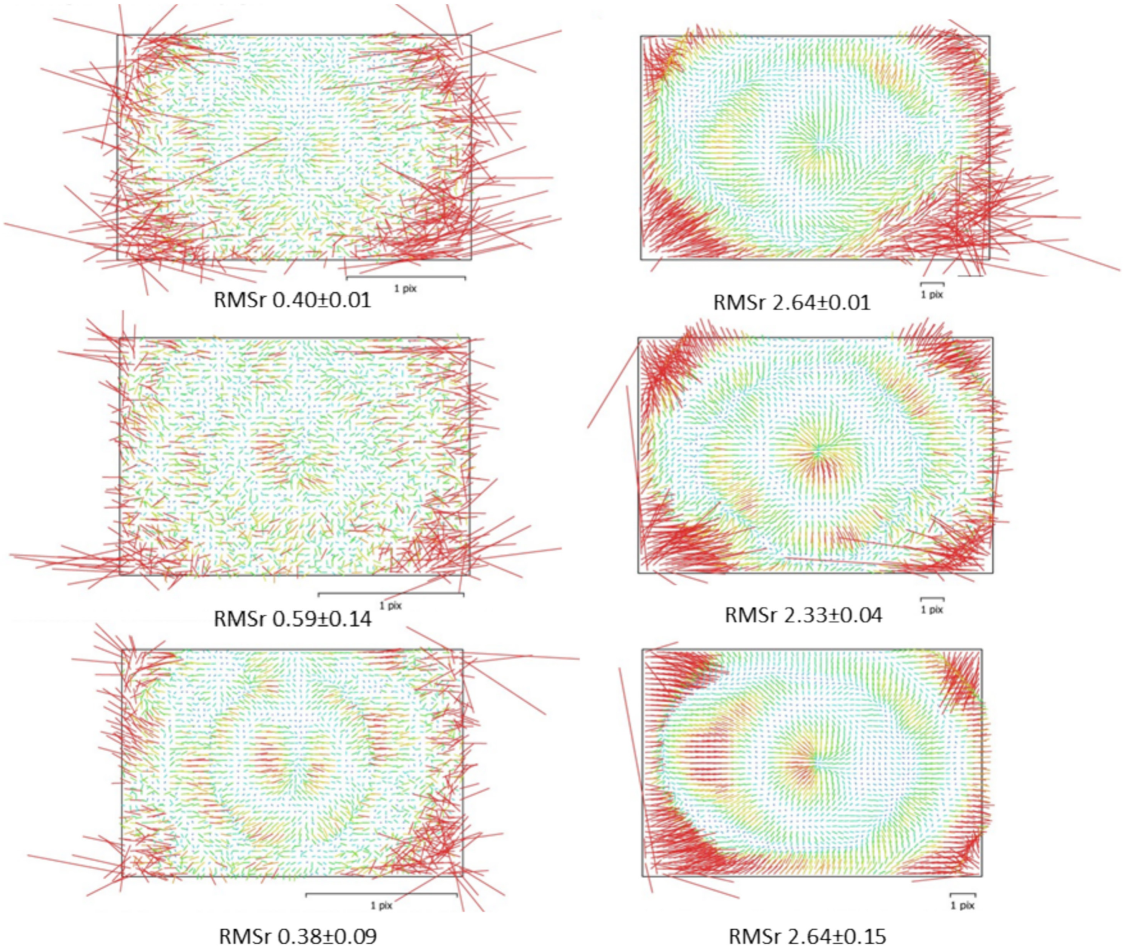

FIGURE 5 | Average image residual patterns at 1–1.5 m working distance with the root mean square (RMS) reprojection error (r) at survey sizes: 5 × 5 m (top row), 10 × 10 m (middle row) and 20 × 10 m (bottom row). Left: the diver-held Nikon D850; right: the ROV-mounted HERO10.

methods, indicating high precision. Nevertheless, differences were observed: while the ROV-derived models had a consistently low CP RSME, diver-derived CP RSME increased with survey size (Figure 6b). The GSD for the diver models was consistent across survey sizes and consistently lower than the ROV-derived models. The ROV-derived model GSD increased with survey size to a maximum of 0.293 mm pixel^{-1} (Figure 5c). Scaling errors (i.e., the difference between a model-derived distance and the real-world known distance) were significantly lower in the diver-derived surveys at 5 x 5 m size and tended to be less variable in all survey sizes, but scaling errors were not significantly different at the larger survey sizes between diver and ROV-derived models (Figure 5d, Table S5).

3.4 | Capacity to Scale-Up ROV Survey Extent

As a proof-of-concept for demonstrating the capacity for ROVs to conduct larger-scale surveys, multiple survey areas around the MOWI Hellisay fish farm were conducted. Surveyed over three days with just 400 min of ROV deployment time, we achieved a total survey area of 11,285 m^2. Based on our experience of diver-based photogrammetry surveys, we estimate that just achieving the four transects and reference sites (cf. Figure 1C) would have taken 28 working days with a diver-based method. To achieve this with a full HSE-compliant dive team (as would be required for a professional application in the UK) would cost >£55k at current rates. This is compared to the ca. £30k investment for the ROV set up, plus significantly reduced time and logistical commitment. Both options would also require ca. £10k for computing and software for data processing.

The range of plot sizes and the extent of the area covered illustrates an ROV's proficiency in surveying areas at a scale that is relevant for marine management. Benthic topographic features are clearly evident from the fish farm transect surveys, including ‘mega-ripples’ and identification of live maerl bed extent with mm-resolution detail (Figure 7).

In the absence of local scaling or clear geospatial markers, ROV-derived models may not have a precise real-world scale. To verify the georeferenced scaling of the ROV-derived 3D models the diameter of 14 sea urchins identified in both the stereo images and the georeferenced ROV-derived model for plot ‘T1_50M’ (cf. Figures 1C and 7) were used as reference markers. The stereo-derived distances were significantly higher than the georeferenced-derived distances by 1.07 ± 1.21 cm (mean ± SD) (Table S6).

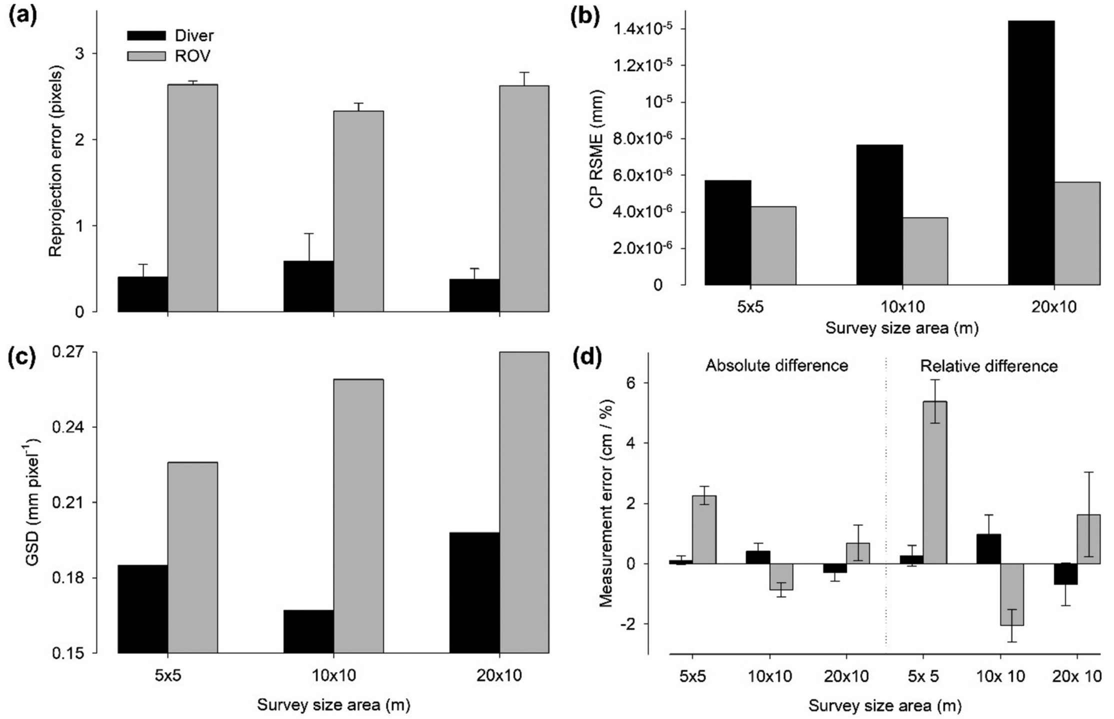

FIGURE 6 | Accuracy of the bundle adjustment metric comparison between divers and ROV. (a) Reprojection error (pixels; mean ± SE), (b) check point root mean square error (CP RMSE, mm), (c) ground sampling distance (GSD, mm pixel^{-1}) and (d) measurement error as the absolute and % difference between the reconstructed digital models and ground-truthed object (mean ± SE). Metrics presented for survey sizes of 5 × 5 m, 10 × 10 m and 20 × 10 m.

4 | Discussion

Understanding the environmental footprint of human activity in the coastal ocean is becoming increasingly important to achieve ocean sustainability. When human activities (e.g., aquaculture) are sited in close proximity to ecologically sensitive marine habitats, this becomes a priority conservation concern. There is therefore an urgent need to make marine monitoring more efficient and capable of surveying large areas of interest, while still maintaining high detail to identify small (but potentially important) changes in the natural habitats and/or species. Three-dimensional reconstruction of the seabed through photogrammetry is emerging as a powerful tool for this, but practical limitations in diver-based data gathering hinder its widespread deployment. Through comparative analysis of standard camera set-ups for diver and ROV-based photogrammetry systems, we demonstrate the potential ROVs have to survey large seabed areas and yield images of sufficient quality for detailed seabed assessments.

4.1 | ROV-Based Surveys Are an Advantage on Complex Seabeds

Both survey methods showed a high percentage of camera alignment across all survey sizes, indicating the successful matching of features (Barba et al. 2019) and a consistent achievement of mm-scale resolution. The ability of the ROV to cover a wide area enables multiple angles to be captured resulting in a higher number of aligned images and potentially better overlap. This can be beneficial in complex seabed types such as coralline algae reefs (maerl / rhodolith beds) because more coverage allows fine scale features to be identified. The higher number of tie points in ROV surveys enables distinct features to be robustly resolved, making it easier for software algorithms to identify corresponding points and accurately align them. Since the ROV can cover far great areal extents than what is practical for a diver-based team—logistically and financially—this is important to maintain model accuracy across the larger areas. In these cases, the lower cloud point density achieved from ROV models might be more advantageous by simplifying the processing of large datasets and expediting model completion. Automated underwater vehicles (AUVs) are beginning to play an increasing role in underwater surveying as their technologies advance and costs decrease. The surveys demonstrated here necessitate working close to the seabed (within 1 m) to overcome underwater visibility challenges. However, this means the risks of entanglement and collision are high. For ROVs, this can be somewhat mitigated by visual navigation from human ROV pilots, but this is more difficult for AUVs—their collision avoidance systems are improving, but remain power-intensive and expensive. We therefore believe that, for now, divers and ROVs remain essential and complementary tools for seabed mapping and surveying, particularly in lower visibility coastal areas and across complex seabeds.

4.2 | Considerations for ROV Deployments

It is not (yet) practical for the high-quality camera system used by the divers here to be deployed with smaller ROVs, fundamentally limiting the image quality and model fidelity from ROV surveys. When true-to-life colour, high-resolution texture or low image residuals are critical to the survey objectives, an ROV system may

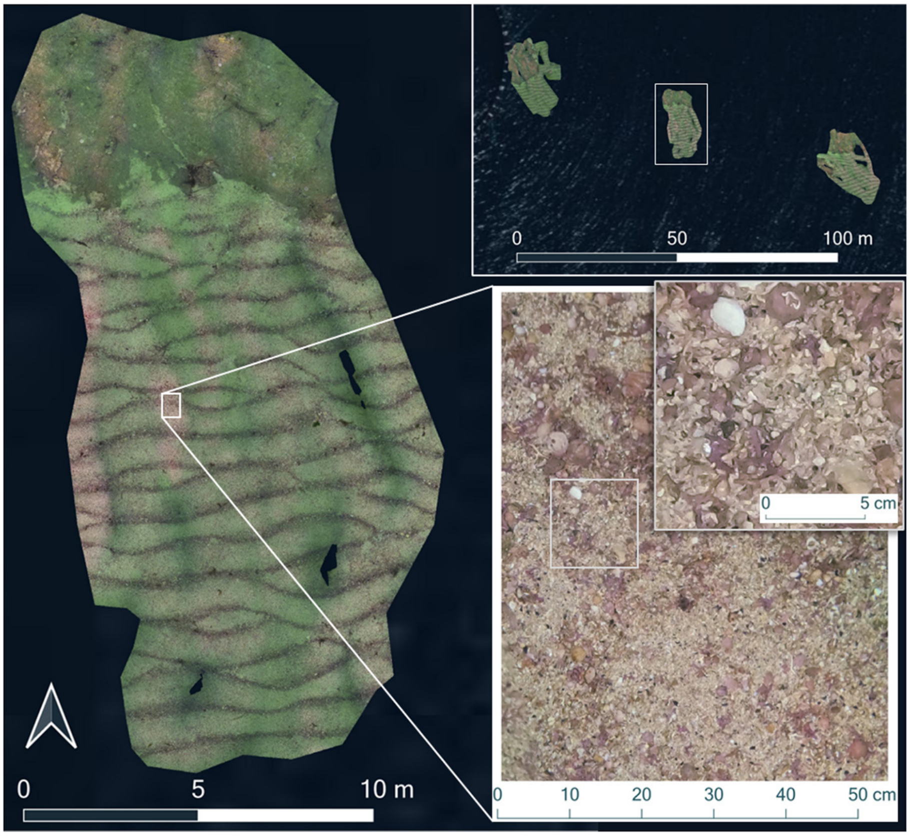

FIGURE 7 | Exemplary ROV photogrammetric survey views from the MOWI Hellisay fish farm. Anticlockwise from top right: Spatial arrangement of the three 225 m^2 plots within transect 1 (cf. Figure 1); the full seabed reconstruction from the middle survey area (plot T1_50M, located 50 m from the fish farm cages), with 'mega ripples' clearly evident and delineation of live maerl coverage (pink colouration); close-up view of a live maerl bed demonstrating mm-scale resolution of substrate texture.

therefore not yet yield good enough quality imagery (Menna, Nocerino, and Remondino 2017)—this was most evident here in the orthomosaic outputs, where diver-derived models had higher sharpness and clarity. Additionally, familiarity and competency with micro-ROV piloting for photogrammetric image capture, underwater positioning systems and photogrammetric processing are essential and may require investment in (re)training.

Reprojection error was a notable disadvantage with the ROV-based system. A reprojection error of 1 pixel indicates that, on average, the reconstructed points are within 1 pixel of their corresponding locations in the original images, which is typically deemed acceptable for many applications (Westoby et al. 2012). For more precise applications or when the highest quality 3D reconstruction is necessary, a reprojection error of 0.5 pixels is preferred (as achieved here with the diver-derived models). This level of accuracy indicates a high degree of alignment between the reconstructed model and the original images, signifying that the camera calibration and the 3D reconstruction process have been executed accurately (Lhuillier and Quan 2005). The consistently higher reprojection error in the ROV-derived datasets (~2.5 pixels) can be attributed to the different camera systems and the challenges introduced by the SBL sensor (georeferencing accuracy of 2 m). SBL systems, particularly in underwater environments, can be prone to noise and errors, especially if the acoustic signals are disturbed (Lhuillier and Quan 2005). This appears to have also led to a small but significant overestimation of distances within the ROV-derived models. We attribute projection errors to ca. 0.02–0.03% for a 10 mm measurement (see Supporting Information)—while small, this accumulates as survey size increases.

4.3 | Conservation Implications

3D habitat reconstruction is emerging as a valuable resource in conservation technology (Lahoz-Monfort and Magrath 2021), and photogrammetry is capable of quantitatively assessing key health features of aquatic ecosystems, such as biodiversity, complexity and colouration in a standardised way (e.g., Bayley and Mogg 2020; Figueira et al. 2015). Of greatest potential for reef-like habitats is the accurate determination of 3D complexity. While this is known to be related to important ecosystem services such as biodiversity, fish biomass, ecosystem resilience and wave energy dissipation (e.g., Steller et al. 2003; Graham et al. 2015; Harris et al. 2018; Voerman et al. 2022), seabed complexity has been historically difficult to accurately measure and therefore often missed from monitoring efforts. For highly complex seabeds such as free-living coralline algae reefs (e.g. Voerman et al. 2023), (sub)mm-scale resolution of 3D structure is necessary for an accurate analysis of their habitat morphology and associated biodiversity. In the context of local conservation concern (such as the placement of aquaculture or planned seabed disturbance [e.g., dredging]), these fine-scale insights can therefore be of great importance for empirically informing predictions of local ecosystem change.

These results show that there is not yet a clear choice for how to attain photogrammetry data—both divers and ROVs have their advantages and disadvantages. The choice of photogrammetry method should therefore take into account ecological, physical and economic factors, including the spatial extent required, the complexity of the seabed, the size of species present (or a focus on those of conservation interest), site accessibility and weather conditions, financial limitations and survey team expertise. Other methods such as side scan sonar may also complement photogrammetry outputs, especially in low visibility environments where photogrammetry can have reduced performance (Ternon et al. 2022).

4.4 | A Hybrid Approach for Enhanced Underwater Surveying

Here, we show that both diver and ROV-based photogrammetry surveying can yield high quality models that are able to resolve the complexity of a maerl bed habitat at mm scales. Although focused here on maerl beds, the same techniques could also be applied to other reef habitats such as coral reefs, bivalve beds and sponge reefs, as well as artificial reefs deployed for habitat restoration. Photogrammetry therefore has global conservation applications across multiple habitats and climates. ROV-based photogrammetry in particular offers several practical advantages, in terms of operational efficiency and human safety, that makes it a sensible choice for routine monitoring and large-scale assessments—although investment in high-performance computing may be necessary to cope with the large ROV datasets. However, until ROVs are able to host the highest quality camera systems and have improved geolocation and stabilisation, diver-based surveying will likely maintain a valuable place in photogrammetry survey efforts, particularly when highly detailed imagery is required. For now and the near future, we therefore suggest a hybrid approach, where both diver and ROV surveys are used to leverage the strengths of both approaches and to optimise data collection at multiple spatial scales.

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Ethics Statement

MOWI provided access to the fish farm site; no other approvals were required.

Conflicts of Interest

Tritonia is a company that uses georeferenced 3D photogrammetry in commercial seabed mapping projects. The results from the present study contributed to the onward development of these commercial capabilities.

Data Availability Statement

Model parameter data are available from Harvard Dataverse (DOI: 10.7910/DVN/JBCZAK). Due to the large size of the original survey images and the reconstructed 3D models, these data can be requested from Tritonia Scientific at any time.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.