COMPLETED PROJECT CASE STUDY

USING 3D PHOTOGRAMMETRY TO MONITOR AQUACULTURE IMPACTS ON HARD SUBSTRATE SEABEDS

PARTNERS

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PROJECT LEADS

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BACKGROUND

Sustainable aquaculture development relies on robust environmental regulation that effectively protects sensitive marine ecosystems. Traditional seabed monitoring techniques, such as grab sampling, are often ineffective - or indeed impossible to use - in areas with hard substrates or where Priority Marine Features (PMFs) are present. These limitations can hinder our understanding of how such habitats respond to aquaculture-related pressures, creating knowledge gaps that restrict evidence-based regulation and protection.

3D photogrammetry, a technique that creates detailed three-dimensional models from overlapping photographic images, offers a solution. By enabling repeated, high-resolution surveys of the seafloor, it can improve accuracy, provide permanent records, and increase visibility in turbid or low-light conditions. Its ability to reveal fine-scale benthic structures makes it especially valuable for monitoring sensitive or complex habitats where traditional tools fall short.

AIMS

This project sought to validate 3D photogrammetry as a regulatory tool for monitoring aquaculture impacts on hard substrate seabeds. Specifically, it aimed to:

- Determine whether models generated from ROV (remotely operated vehicle) imagery are accurate and consistent enough to detect environmental changes.
- Evaluate the feasibility, quality, and cost-effectiveness of using ROVs in underwater habitat assessments.
- Identify measurable indicators of seabed stability, guided by input from regulators and industry stakeholders.
- Compare diver- and ROV-based photogrammetry methods and assess their respective strengths and limitations for regulatory application.

Datasheets and modelling workflows were also evaluated and refined, with academic partners conducting independent validation to support the method's use in environmental decision-making.

OVERVIEW

A steering group including the Scottish Environment Protection Agency (SEPA), NatureScot, Salmon Scotland and industry partners, coordinated and supported by SAIC, oversaw the project. Three sites were chosen for diver- and ROV-based photogrammetric surveys, with key ecological indicators defined early in the process.

LOCATIONS

The following three sites were chosen as essential for evaluating the quality and accuracy of our diver- and ROV-based photogrammetric models:

SITE 1.1
Seaweed farm

The seaweed farm at the Port A' Bhultin Reef is characterised by a combination of sandy silts and rocks. The site supports a diverse range of species, including various sponges (both encrusting and branching forms), sea stars (*Asterias rubens*), mussels (*Mytilus edulis*), crabs (*Cancer pagurus, Carcinus maenas*), sea urchins (*Echinus spp.*), and razor clam shells. Notably, kelp species such as *Saccharina latissima* (sugar kelp) and *Laminaria digitata* (oarweed) are present, along with other commercially valuable species like *Palmaria palmata* (dulse) and *Ulva spp.* (sea lettuce).

SITE 1.2
Maerl bed

The maerl bed located adjacent to the seaweed farm shares similar environmental habitats and species composition as the Port A' Bhultin Reef. The maerl bed consists of the calcareous red algae *Phymatolithon calcareum* (maerl). The habitat supports various organisms, including molluscs such as scallops and different species of clams. Crustaceans like edible crabs, spider crabs and squat lobsters are commonly found, as are anemones (e.g., beadlet anemone, dahlia anemone) and sea stars (e.g., cushion star, brittle star). Polychaete worms, including the spaghetti worm and fanworm, thrive in the maerl bed. Seaweeds, including kelp species (e.g., sugar kelp, oarweed) and smaller algae like dulse and sea lettuce, are also present. The maerl bed may contain sand, sediment, shell fragments, and organic matter, contributing to its overall composition.

SITE 1.3
'The Crack,' Dunstaffnage channel

The site known as 'The Crack' in Dunstaffnage channel features large bedrock and coarse sand. The area is home to Alcyonium, sea urchins (*Echinus esculentus*), sun stars, various crustaceans (including crabs), calcareous algae, kelp species (such as *Laminaria*), and sponges. Invertebrates like crabs, lobsters, shrimp, sea stars, anemones, sea urchins, and molluscs such as mussels, scallops, and clams can be found in abundance. The rocky substrate in the area provides attachment points for seaweeds, while boulder fields and cobbles/gravel offer complex habitats and shelter for benthic organisms. Sandy and sedimentary areas, as well as muddy substrates, contribute to the overall habitat diversity.

SITE 1.4
Mowi's Hellisay fish farm, Sound of Barra

To complement these, the project team included a fourth location: Mowi's Hellisay fish farm, situated in the Sound of Barra, northeast of the Isle of Barra in the Outer Hebrides. This site is environmentally significant due to its designation as a Site of Community Importance, protecting features like reefs, subtidal sandbanks, and maerl beds. As an active commercial aquaculture site, Hellisay allowed the team to test ROV photogrammetry in a fish-farm setting. It also provided a valuable comparison for assessing habitat features and survey effectiveness across different spatial scales.

SURVEY METHODOLOGY

Two main survey methods were employed: diver-based and ROV-based photogrammetry. The ROV, fitted with a GoPro HERO10 camera, captured images along predefined transects at half-second intervals while logging GPS and depth data. Meanwhile, divers used a high-resolution Nikon D850 to take still images along parallel transects, ensuring image overlap and recording metadata such as depth and orientation.

Repeat surveys were conducted at selected sites to evaluate the consistency and temporal resolution of photogrammetric models. Both image sets were processed using Agisoft Metashape software to generate 3D models, point clouds, and orthomosaic maps.

Tritonia Scientific Ltd led model generation using a structure-from-motion (SfM) workflow, which included aligning images, applying scale, building dense point clouds, meshing the data, and applying textures to create detailed, navigable 3D environments.

MODEL EVALUATION AND STATISTICAL ANALYSIS

Model quality was assessed using several metrics, including reprojection error, Ground Sample Distance (GSD), Ground Control Point Root Mean Square Error (GCP RMSE), and scaling accuracy. Statistical analyses, including linear regression, ANOVA, and Pearson correlation, were conducted to identify relationships between survey method, photo density, model resolution, and point density. Validation steps included comparisons to ground-truth data and replicate surveys to assess repeatability and internal consistency.

At the Hellisay fish farm, photogrammetric models were used to investigate habitat structure and quantify physical impacts from nearby aquaculture activities. Key metrics included surface complexity, terrain ruggedness and curvature, derived using open-source tools like GDAL and QGIS. These were analysed alongside maerl and biota cover, using grid-based sampling and statistical modelling in RStudio.

Metric	Unit	Definition
Accuracy of bundle adjustment		
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/pixels	Distance between the center of two pixels measured on the ground ["pixel size in object space units" (Granshaw, 2016)]. GSD = [sensor width (mm) × flying elevation (m)]/[real focal length (m) × image width (pix)] for a given image. This value is 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).
*Ground Control Point Root Mean Square Error (GCP RMSE)	mm	Root mean square error of the position of a given ground control point across all photos in object space units.
Accuracy and Precision of the models		
Relative measurement error	%	*Measure on the 3D model–Real dimension* / *Real dimension*. The accuracy and precision of objects measurements were assessed with the mean and standard deviation of the relative measurement error, respectively.
Cloud-to-cloud distance (C2C)	mm	Absolute distance between a 3D point of the ROV-generated model and the diver reference model. The accuracy and precision of 3D geometries were assessed with the mean and standard deviation of the C2M distance, respectively.
Model Statistics		
Point density	million points	Total number of points in the dense cloud.
Model resolution	mm/pixels	Average distance between adjacent elevation points in a DEM.

**GCP RMSE*: For ROV-based models, the residuals on the individual GPS marked images serve this purpose.

Table 2. Definitions of metrics used throughout this study

RESULTS

PHOTOGRAMMETRIC MODEL PERFORMANCE

ROV surveys generated more tie points - key features that align images during 3D reconstruction - thanks to higher image overlap and varied viewing angles. This led to more consistently aligned images compared to diver data. However, diver models had higher point densities, driven by superior image quality and lighting from the Nikon D850.

Point density decreased as survey size increased, particularly for diver-based methods.

For example, diver point density dropped from 6.54 to 3.51 points/mm² between 5×5m and 20×10m surveys, while ROV density declined more gradually (1.58 to 1.32 points/mm²). Diver models were better suited for fine-scale detail, while ROVs offered broader, more scalable coverage.

Textured mesh models were analysed, using face count as a proxy for surface detail. Diver models had higher face counts in smaller surveys, but ROVs outperformed divers in larger, more complex environments. At site 1.3, for instance, ROVs generated significantly higher face counts due to favourable conditions and a greater number of captured images.

Although high face counts indicate granularity, they do not always translate to accuracy if the data is noisy. The optimal survey method depends on specific site conditions and the intended regulatory application.

	Reprojection error (pix)		GCP RMSE (m)		GSD (mm/pixels)	
	ROV	DIVER	ROV	DIVER	ROV	DIVER
1.1 Seaweed Farm						
5x5	1.64	0.35	1.5260	0.0006	0.398	0.196
10x10	1.47	0.38	1.9484	0.0010	0.501	0.213
20x10	1.42	0.41	1.6542	0.0006	0.435	0.267
1.2 Maerl Bed						
5x5	2.64	0.40	1.5965	0.0010	0.226	0.185
10x10	2.33	0.59	1.3161	0.0008	0.259	0.167
20x10	2.64	0.38	1.6958	0.0007	0.293	0.198
1.3 The 'Crack'						
5x5	3.63	0.62	1.1411	0.0013	0.291	0.264
10x10	3.21	0.63	1.4454	0.0012	0.289	0.228
20x10	2.99	0.62	1.4306	0.0011	0.321	0.282

Table 3. Comparison of Reprojection Error (pixels), GCP RMSE (metres), and GSD (millimetres/pixel) for each respective site

SPATIAL ACCURACY AND SCALING

Diver-based models showed consistently lower reprojection errors, often under the one-pixel benchmark considered ideal. ROV models exceeded this threshold across all sites, largely due to limitations in the ROV's Short Baseline (SBL) geolocation system, image quality, and lighting. At Site 1.1, for example, diver models achieved reprojection errors of 0.35–0.41 pixels, compared to 1.42–1.64 pixels for ROV models.

GSD values confirmed that diver models delivered higher spatial resolution, especially at smaller scales. At Site 1.1, the average GSD difference between methods was 0.2194 mm/pixel. Nonetheless, both methods achieved millimetre-scale resolution, suitable for detecting subtle seabed changes such as sediment accumulation or benthic shifts.

GCP RMSE values were higher for ROV models but remained within acceptable bounds, averaging around 1.5m, better than the theoretical 2m accuracy of the SBL system. High image redundancy and effective post-processing contributed to this performance.

CloudCompare analysis showed low mean distances (around 1cm) between diver and ROV point clouds in 5x5m surveys, though differences grew at larger scales due to inherent differences in model construction.

Scaling accuracy improved at larger grid sizes. Relative error at 5x5m reached 18% but dropped substantially at 10x10m and 20x10m. The 10x10m grid offered the best balance of resolution, accuracy, and repeatability. Stereo-camera scaling at the Hellisay site further reduced error and variability, suggesting its promise for high-precision monitoring.

Repeat ROV surveys showed high internal consistency, with mean differences of 0.63–2.66 cm and standard deviations under 2.63 cm.

STATISTICAL TRENDS

Linear regression models revealed that increasing photo density consistently reduced GSD and GCP RMSE, while slightly increasing reprojection error. Diver methods significantly outperformed ROVs on all three metrics. The models explained over 94% of the variance in reprojection error and GCP RMSE, indicating strong predictive power.

Survey method and photo density also strongly influenced point density and model resolution. ROV surveys produced lower point densities, while higher photo densities increased detail. However, denser point clouds were associated with reduced model resolution, highlighting a trade-off between completeness and clarity.

HABITAT ANALYSIS AT HELLISAY

Five photogrammetric surveys around the Hellisay fish farm enabled analysis of aquaculture impacts on benthic habitats. Structural metrics such as slope, aspect, curvature, and terrain ruggedness were derived from 3D models.

Surface complexity and Terrain Ruggedness Index (TRI) served as indicators of ecological condition. Lower TRI values, particularly in impacted areas, suggested sediment smothering. In contrast, higher TRI at reference sites signalled intact habitat structure. Correlation analysis revealed consistent relationships between slope and surface complexity, and between curvature metrics.

Grid-based analysis also quantified benthic cover, including maerl beds and associated species. Systematic mapping and visualisation provided regulators with quantitative evidence of aquaculture impacts.

IMPACT

The integration of 3D photogrammetry with ROV surveys offers a powerful tool for monitoring aquaculture impacts while supporting environmental protection.

Compared to diver-based photogrammetry, ROVs provide broader coverage and higher face counts, making them ideal for large-scale surveys. However, diver methods continue to yield higher data quality, with denser point clouds and better resolution in smaller, more detailed areas.

A key limitation of ROV photogrammetry is its lower georeferencing accuracy, due to constraints in GNSS and SBL sensors. The project team aims to overcome this by achieving centimetre-level precision through further innovation projects funded by the Seafood Innovation Fund (SIF), further supported by SAIC, exploring technologies like RTK and DVL. Scaling accuracy improves with survey size, and the 10×10 metre scale was found to offer an effective balance between coverage and detail. The introduction of stereo-camera systems further enhanced scaling precision, particularly in complex or smaller environments.

This approach has proven effective in assessing aquaculture impacts on sensitive hard-substrate habitats such as maerl beds, capturing changes in surface complexity and habitat condition. These findings underscore the importance of sustainable aquaculture practices.

Looking forward, key recommendations include adopting a hybrid ROV/diver approach, improving georeferencing accuracy, enhancing scaling with larger survey areas, and integrating advanced camera systems. Expanding these methods to other sensitive habitats will support more informed environmental management and reinforce the role of ROV photogrammetry in sustainable marine monitoring. Such insights amplify our capability to oversee, nurture, and shield these vital marine habitats while also accommodating for important food production systems to continue operating.

FURTHER READING

Quantitative Comparison of ROV and Diver-Based Photogrammetry to Reconstruct Maerl Bed Ecosystems (Iona L. R. Paterson, Kathryn E. Dawson, Andrew O. M. Mogg, Martin D. J. Sayer, Heidi L. Burdett. First published: 25 November 2024)