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Short Communications

Digital Preservation of Submerged Biological Specimens Using Underwater Photogrammetry: Insights from Sipadan Turtle Tomb, Sabah, Malaysia

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Abstract - *Underwater caves are among the least accessible marine habitats, often containing delicate biological specimens. Traditional sampling in these environments is logistically difficult and risks damaging the site. This study demonstrates the use of underwater photogrammetry as a non-invasive method for documenting submerged specimens within the Sipadan Turtle Tomb in Malaysia. Using a diver-operated camera system, high-resolution datasets were captured to generate 3D models of a sea turtle carcass. These reconstructions successfully preserved the spatial context, morphological details, and precise positioning of skeletal elements within the cave. Despite challenges like low light, limited visibility, and constrained maneuverability, the results provided a vivid, true-to-life model suitable for qualitative and semi-quantitative analysis. This methodology offers a practical, reproducible workflow for in situ digital documentation that eliminates the need for specimen removal and minimizes physical disturbance to sensitive ecosystems. The resulting 3D datasets serve as a baseline for long-term monitoring, allowing researchers to assess site stability, taphonomic processes, and human impact over time. Beyond research, digital archiving enhances accessibility for education, tourism, and conservation planning without increasing physical pressure on the environment. Ultimately, this study confirms underwater photogrammetry as an essential tool for the digital preservation and management of biological specimens in vulnerable marine cave systems.*

Keywords - *Conservation, Photogrammetry, Turtle, Sipadan, Sabah, Malaysia.*

I. INTRODUCTION

Underwater marine caves represent unique and fragile environments that remain among the least explored habitats in tropical marine ecosystems. Characterized by limited light penetration, restricted water circulation, and complex geomorphology, these systems often harbour specialized and poorly documented biological communities (Iliffe & Kornicker, 2009). Despite their ecological significance, access limitations and the risk of disturbance have constrained detailed biological and structural investigations in such habitats (Chevaldonné & Lejeusne, 2003).

Sipadan Island (Sabah, Malaysia) is globally recognized for its rich marine biodiversity, yet its submerged cave systems, particularly the Turtle Tomb, remain relatively understudied. Ongoing faunistic investigations within this cave have revealed a remarkable diversity of previously undocumented taxa. Notably, these efforts led to the discovery of a new genus of calanoid copepod, *Sipadantonius roihani* (Boonyanusith et al., 2024). More recent work has further documented the first occurrence of the harpacticoid copepod genus *Peltidium* in Malaysian waters, including the description of a new cave-associated species, *Peltidium penyu* (Boonyanusith et al., 2026).

These findings underscore the ecological importance of the Turtle Tomb as a reservoir of unique and potentially endemic fauna, while also highlighting the challenges associated with studying such sensitive environments using conventional sampling approaches. In addition to its biological significance, the Turtle Tomb is well known for the accumulation of marine vertebrate remains, particularly sea turtles, which are believed to have entered the cave system and subsequently become trapped. These assemblages provide valuable insights into taphonomic processes, cave ecology, and the interactions between geomorphology and marine fauna. However, traditional methods of documenting such remains often involve physical disturbance or specimen removal, which may compromise the integrity of the site.

Recent advances in underwater photogrammetry offer a promising alternative for the non-invasive documentation of submerged environments (Remondino & Campana, 2014). By reconstructing high-resolution three-dimensional (3D) models from overlapping image datasets, photogrammetry enables accurate recording of spatial relationships, morphology, and site context without direct physical impact. This approach has been increasingly applied in marine habitats for habitat mapping, structural complexity analysis, and cultural heritage documentation, but its application within confined and low-light underwater cave systems remains limited.

In this study, we apply underwater photogrammetry to digitally document marine vertebrate remains within the Turtle Tomb at Sipadan Island. Specifically, we aim to (i) develop a practical workflow for image acquisition and 3D reconstruction under challenging cave conditions, (ii) evaluate the quality and limitations of the resulting models, and (iii) assess the potential of this approach for non-invasive monitoring and conservation of submerged vertebrate assemblages. By establishing a reproducible method for digital preservation, this study contributes to the broader application of photogrammetry as a tool for conservation and management in vulnerable marine cave ecosystems.

II. MATERIALS AND METHODS

A. Study Site

Fieldwork was conducted at the Turtle Tomb (Fig 1), an underwater cave system located off Sipadan Island, Sabah, Malaysia. Surveys were performed at a depth of approximately 16 m within a semi-enclosed chamber characterized by limited water circulation and low ambient light conditions. Located at a depth of approximately 20 m on the island's limestone pedestal, the Sipadan Turtle Tomb is a fully submerged, horizontal cave system spanning over 375 m of complex passages. Sampling was conducted under calm conditions with a water temperature of 27 °C and visibility exceeding 20 m.

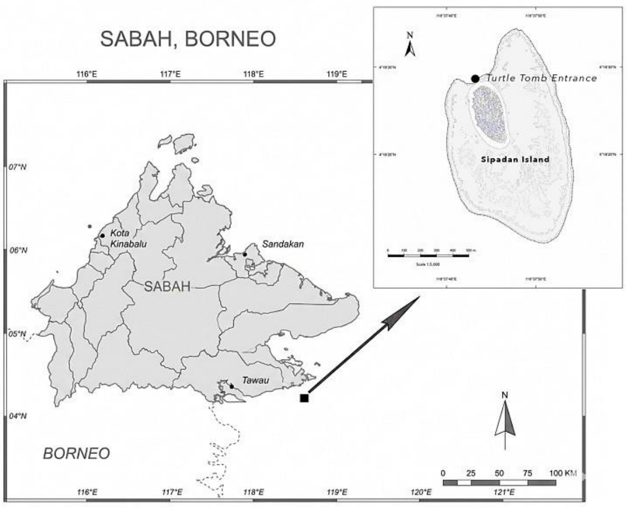

Figure 1. Geographic location of the study area, Sipadan Island, Sabah, East Malaysia. The Turtle Tomb entrance on the northern drop-off, the adjacent sand flat, and the extensive Seagrass meadows to the east and south. Coordinates and scale bars are provided for spatial reference

However, the cave interior remains structurally challenging due to restricted light penetration and an abundance of fine, easily disturbed sediments. The layout originates at a wide cavern zone before narrowing into a labyrinth of branching passages such as the "Triangle" and "Spiral Staircase" where limestone breakdown and silt accumulation create an uneven ground. This development terminates in isolated "cul-de-sacs" like the "Deadly Zone," where stagnant water and pocketed ceilings facilitate the trapping of sediment and biological remains, resulting in the high density of turtle skeletons that define the "tomb" phenomenon.

B. Image Acquisition

The images were captured with a Panasonic Lumix GH5 camera in a Nauticam NA-GH5 underwater housing with a glass dome port (N120). The system was run by a diver that was very close to the target assemblage (Fig. 2, 3). Images were taken in the time-lapse mode, and the resulting images were saved as RAW files with 20.3 megapixels resolution. A total of 291 images were taken with an average overlap between successive images of 90% to achieve good photogrammetric reconstruction. The camera was set to a focal length of 12 mm (24 mm equivalent in 35 mm format), an aperture of f/7.1, an ISO number of 800, and a shutter speed of 1/125s. These parameters were fixed during the survey in order to ensure the consistency in exposure and image quality. Artificial illumination was provided using two Keldan Flux 4X video lights, operated at 60% power. The lighting was arranged to even out the lighting of the subject, to reduce shadows and backscatter. This setup allowed for even lighting, an important requirement for the correct texture reconstruction of the photogrammetric model.

Figure 2. A technical diver uses high-output lights and a specialized camera to perform an integrated Structure-from-Motion (SfM) photogrammetric survey. This technique is used to create high-resolution 3D models of the skeletal remains of the Hawksbill turtle (Eretmochelys imbricata) seen in the foreground

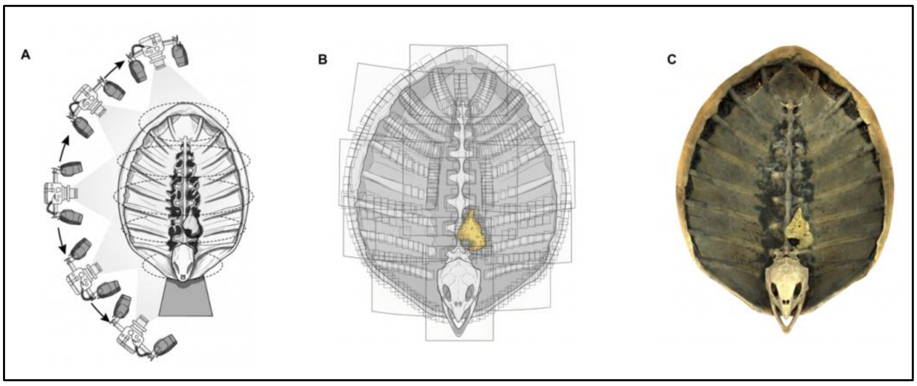

Figure 3. Workflow for in-situ photogrammetry-based 3D reconstruction of a sea turtle carcass. (A) Image Acquisition: The specimen is photographed from multiple orbital and nadir camera positions using a dual-strobe underwater housing to ensure consistent illumination and maximize feature detection. (B) Point Cloud Generation: Overlapping 2D images are processed using Structure-from-Motion (SfM) algorithms in Agisoft Metashape. The software identifies homologous pixels across multiple frames to infer the spatial coordinates and depth of the specimen. (C) 3D Orthomosaic: The final high-resolution, full-color 3D model allows for precise compilation of morphometric data, including surface area, volume, and linear dimensions, providing a non-destructive digital record of the carcass

C. Photogrammetric Processing

Photogrammetric reconstruction was performed using Agisoft Metashape Standard following a structured workflow from image alignment to textured mesh generation.

a. Image Alignment and Sparse Point Cloud Generation

All images were aligned using a high-accuracy setting to generate a sparse point cloud. During this phase, the camera parameters were optimized, such as the focal length and lens distortion coefficients. Low-confidence points and erroneous matches were manually removed based on reprojection error and reconstruction uncertainty thresholds to improve alignment robustness.

b. Dense Reconstruction and Depth Map Processing

Depth maps were created with a high quality setting and low noise filter to remove noise but preserve fine structure details. This step resulted in a dense point cloud of the surface geometry of the target object. Noise due to suspended particles and background artefacts was decreased using depth filtering and point confidence selection before the mesh generation.

c. Mesh Construction

A polygonal mesh was constructed from the filtered depth maps using interpolation to fill small gaps in the dataset. This method allowed for both continuity of the reconstructed surface and for geometric fidelity in the well-resolved areas. This resulted in a mesh which was used for further texture mapping and visualization outputs.

d. Texture Mapping and Atlas Generation

The texture mapping was done in a generic mapping mode with blending on, to merge colour information from several overlapping images. A single texture atlas (4096 × 4096 pixels) was generated. The texture packing efficiency and coverage was tested via the built-in diagnostics of the texture mapping system, such as fill ratio, overlap ratio, and scaling distribution. These metrics can be used to evaluate image information spread over the model surface and to detect areas of low density or resolution.

e. Model Quality Assessment and Visualization

To evaluate reconstruction consistency, additional visualization outputs were generated, including dense point cloud inspection, texture atlas diagnostics, and false-colour surface representations. The visualization was used to mark areas where noise or occlusion was present, or where the overlap of images was not consistent, as well as to direct refinement steps, including point filtering and mesh interpolation.

III. RESULTS AND DISCUSSION

Photogrammetric reconstruction of the marine vertebrate remain resulted in a high-resolution three-dimensional (3D) model, preserving both geometric structure and surface texture of the specimen. A total of one carcass was successfully reconstructed, identified as a male hawksbill sea turtle (Eretmochelys imbricata). The model captured the entire body, achieving complete coverage of the remains within an approximate spatial extent of 4 m × 4 m. The final model, accessible via Sketchfab (https://sketchfab.com/3d-models/turtle-shell-6e59a53fff284d9e8ee224353f3cbb4f), enables interactive visualization of the reconstructed specimen, including rotation, zoom, and detailed inspection of fine-scale morphological features.

A. Model Geometry and Completeness

The reconstructed model successfully captured the overall morphology of the turtle carapace, including its curved dorsal surface and structural contours. The mesh, consisting of approximately 1.49 million faces and 744,968 vertices, provided a detailed representation of the specimen with minimal large-scale deformation. The dense point cloud (Figure 4) showed high point concentration around the main body of the shell, which is an indication of good image alignment and reconstruction. Surface curvature and scute boundaries were easily distinguished. Minor noise and point distribution were detected in the peripheral areas, especially outside the primary boundary of the object, which are thought to be background noise and suspended particles inside the cave environment.

Figure 4. Dense point cloud generated from photogrammetric processing of a marine vertebrate remain within the Turtle Tomb cave system. The reconstruction shows high point density across the main structure, with surrounding noise attributed to suspended particles and low-light conditions during image acquisition.

B. Surface Texture and Visual Fidelity

Texture mapping produced a visually coherent surface model with a 4096 × 4096 pixel texture atlas (Figure 5). The texture preserved natural coloration patterns and surface heterogeneity of the shell, allowing clear identification of morphological features. Despite an overall texture fill ratio of approximately 67%, the model retained sufficient detail for qualitative interpretation. Areas of reduced coverage and minor gaps were observed, primarily associated with occluded regions and variations in image overlap. These inconsistencies did not significantly affect the interpretability of the main structure.

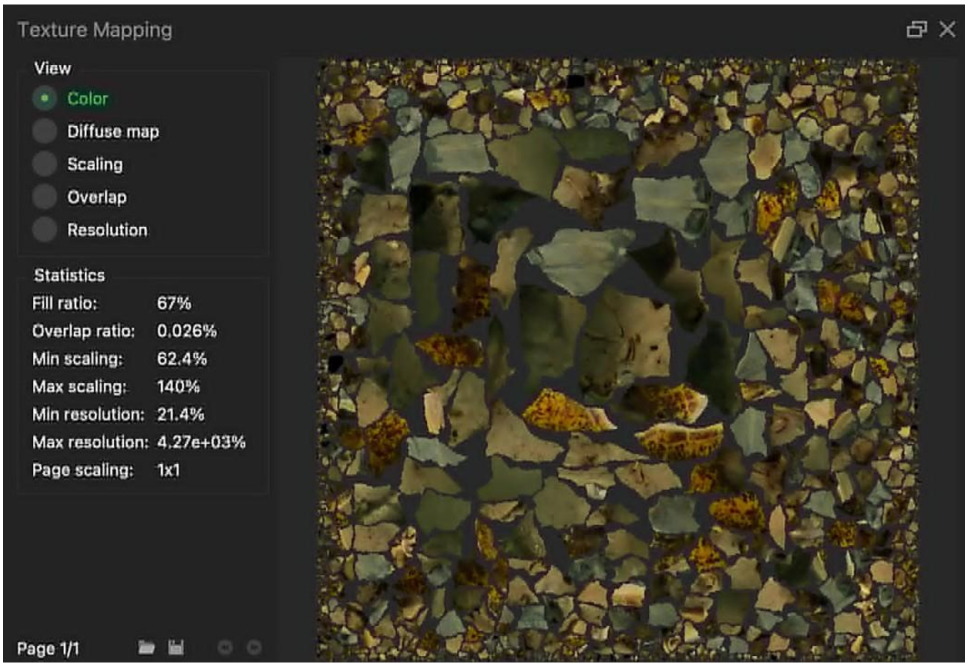

Figure 5. Texture atlas generated during photogrammetric processing, illustrating the distribution and coverage of image-based textures across the reconstructed mesh. Variations in resolution and coverage reflect differences in image overlap and acquisition conditions

C. Model Quality and Reconstruction Consistency

Surface quality assessment using false-colour visualization (Figure 6) revealed that the majority of the model exhibited high geometric consistency. A large part of the shell surface was represented by uniform colour values, which meant that the reconstruction was relatively stable and there was minimal variation. Variations were identified at edges and concave areas, and in regions with poor image coverage. These areas are associated with areas of reconstruction uncertainty, which is usually higher in these areas because of occlusion, less overlap in images and changing lighting conditions. However, these deviations were limited to a local area and did not affect the integrity of the model.

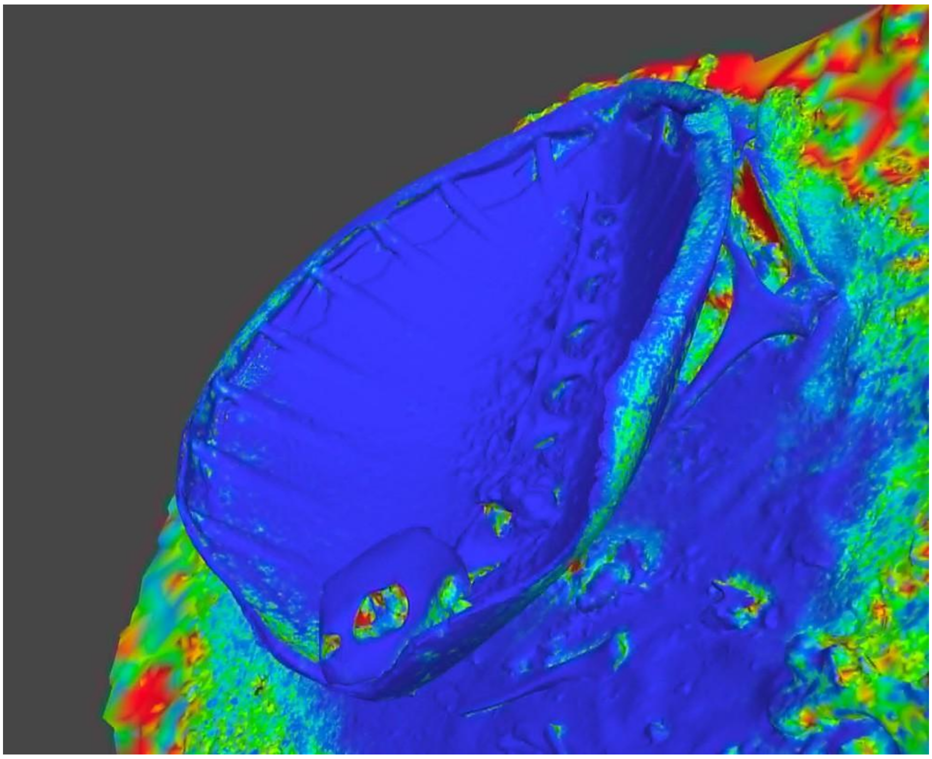

Figure 6. False-colour surface visualization of the reconstructed model, highlighting spatial variation in reconstruction quality. Blue regions indicate high surface consistency, while green to red areas represent localized deviations associated with edge effects, occlusions, and variable image coverage

D. Output Utility and Visualization

The final 3D model provides an accurate digital representation of the vertebrate remain in its in situ context, allowing detailed morphological inspection, spatial interpretation of features and non-invasive documentation of the specimen. The interactive format hosted on Sketchfab further enhances accessibility, enabling remote examination without the need for repeated site visits or physical handling of the specimen.

E. Performance of Underwater Photogrammetry in Cave Environments

This study demonstrates that underwater photogrammetry can be effectively applied in confined and low-light cave environments to produce high-resolution 3D reconstructions of marine vertebrate remains. Despite the inherent challenges associated with cave systems including limited visibility, restricted manoeuvrability, and the presence of suspended particles the workflow employed here successfully generated a complete and detailed model of a hawksbill sea turtle (Eretmochelys imbricata).

The high geometric fidelity of the reconstructed model is consistent with previous studies demonstrating the reliability of structure-from-motion (SfM) photogrammetry for capturing complex underwater structures (Westoby et al., 2012; Burns et al., 2015). Adequate image overlap and stable acquisition parameters are known to be critical factors influencing reconstruction quality (Fonstad et al., 2013). Local artefacts, however, in the areas of occlusion and along structural edges are common features reported for structurally complex environments such as caves and reefs (Figueira et al., 2015).

The lighting conditions were a major factor in determining model quality. Dual continuous video lights allowed relatively uniform illumination of the subject and reduced the formation of shadows, thus improving the reconstruction of the texture. In particular, lighting is a key factor in photogrammetry as strong contrasts and shadows can negatively impact feature matching and texture blending (Menna et al., 2017). However, there were some slight differences in the quality of the texture and in how accurately it was reconstructed, probably stemming from slight variations in light angle and the presence of suspended particles. The same problems have been reported in underwater photogrammetry projects where turbidity and backscatter can cause loss of clarity in the images and noise in dense reconstruction (Bryson et al., 2017; Pizarro et al., 2017).

F. Advantages and Applications

Compared to traditional methods such as direct observation, photography, or physical sampling, photogrammetry provides a non-invasive approach that preserves both the morphology and spatial context of the specimen. The successful reconstruction of the entire carcass within a 4 m × 4 m area demonstrates the capability of this method for documenting large biological structures. Similar photogrammetric applications have been widely used in coral reef studies to measure habitat complexity and structural features with high precision (Ferrari et al., 2016; Figueira et al., 2015), highlighting its broader value for biological and taphonomic documentation.

The method also has strong potential for conservation and long-term monitoring of sensitive marine cave environments. The generated 3D model serves as a baseline digital archive that can support future comparisons of vertebrate remains over time. Digital documentation is increasingly recognized as an effective tool for non-destructive monitoring and repeatable assessments (Burns et al., 2015; Ferrari et al., 2016). In fragile cave systems, minimizing physical disturbance is essential, and photogrammetry offers a practical balance between research and conservation needs. In addition, integrating 3D models into online platforms improves accessibility for researchers, managers, and the public, supporting education and outreach while reducing repeated site visits. This is consistent with broader developments in digital conservation and virtual heritage documentation (Pizarro et al., 2017).

G. Synthesis and Future Outlook

Despite the inherent sensitivity of reconstruction quality to image coverage and environmental clarity, limitations consistent with previous assessments of SfM photogrammetry (Fonstad et al., 2013; Bryson et al., 2017), the workflow established here offers a robust methodology for biological and taphonomic documentation.

Future iterations should incorporate scaling markers for enhanced metric precision and optimized lighting to further reduce occlusions. As algorithms evolve, photogrammetry will likely become a cornerstone for quantifying structural complexity in sensitive ecological niches beyond standard habitat mapping.

IV. CONCLUSION

This study has proved underwater photogrammetry can be used successfully to document marine vertebrate remains in a limited cave setting at Sipadan Turtle Tomb. The method allowed for the creation of a detailed 3-D (three dimensional) model of a hawksbill sea turtle (Eretmochelys imbricata) that included the entire carcass, morphology, and spatial context. Given the difficulties of working in low-light conditions, in a limited space and with suspended particles, the workflow yielded consistent and reliable outputs, demonstrating the strength of the photogrammetry process when suitable imaging and lighting techniques are used. The result is a digital model that is a permanent baseline record that can be compared to in the future without having to physically disturb the site again. This study highlights the importance of photogrammetry as a tool to document in situ and to be reproducible, for conservation, digital archiving and research in sensitive marine cave ecosystems. The ability to share, educate, and manage data is further enhanced by the integration of accessible 3D visualization platforms, which help to further reduce the impact of humans while increasing the scientific output.

Conflicts of Interest

The authors declare that there is no conflict of interest concerning the publishing of this paper.

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