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# From Structure from Motion and Multi-view Stereo to Gaussian Splatting

## Advanced digital documentation of underwater archaeological sites

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Underwater photogrammetry is widely recognised as the gold standard for documenting underwater cultural heritage (UCH), providing a non-intrusive method to generate high-resolution geometric documentation for underwater sites. Despite its utility, the medium's inherent optical challenges – notably, refraction at the air-water interface and spectral attenuation – continue to impede the achievement of survey-grade accuracy and radiometric fidelity. This feature paper examines the evolution from traditional photogrammetry to modern structure-from-motion and multi-view stereo (SfM-MVS) techniques and beyond. Critically, it highlights the transformative potential of machine learning (ML) in mitigating these physical constraints, using underwater archaeological sites from the eastern Mediterranean as case studies. To demonstrate the transformation of methodologies, several test cases are mentioned; how the SfM methodology affected the network setup, coordinates' calculation and monitoring, the use of ML to restore colour information and to correct water refraction in coastal sites, and finally the potential of underwater 3D Gaussian splatting (3DGS) to bridge remaining challenges.

underwater photogrammetry | Structure from Motion | machine learning | underwater network  
Unterwasserphotogrammetrie | Structure from Motion | maschinelles Lernen | Unterwassernetzwerk

Die Unterwasserphotogrammetrie gilt weithin als Goldstandard für die Dokumentation des Kulturerbes unter Wasser und bietet eine nicht-invasive Methode zur Erstellung hochauflösender geometrischer Dokumentationen von Unterwasserstätten. Die medienbedingten optischen Herausforderungen – insbesondere die Brechung an der Luft-Wasser-Grenzfläche und die spektrale Dämpfung – behindern weiterhin das Erreichen einer in der Vermessung üblichen Genauigkeit und radiometrischen Wiedergabetreue. Dieser Fachartikel untersucht die Entwicklung von der traditionellen Photogrammetrie zu modernen Structure-from-Motion- und Multi-View-Stereo-Techniken (SfM-MVS) und darüber hinaus. Er verdeutlicht insbesondere das transformative Potenzial des maschinellen Lernens (ML) zur Minderung dieser physikalischen Einschränkungen und verwendet dabei Unterwasserarchäologiestätten im östlichen Mittelmeerraum als Fallstudien. Um die Weiterentwicklung der Methoden zu veranschaulichen, werden mehrere Testfälle aufgeführt: wie sich die SfM-Methode auf die Netzwerkeinrichtung, die Berechnung und Überwachung von Koordinaten, die Verwendung von ML zur Wiedergabe von Farben und zur Korrektur der Wasserbrechung an Küstenstandorten ausgewirkt hat; und schließlich das Potenzial von Unterwasser-3D-Gaussian-Splatting (3DGS) aufgezeigt, um die verbleibenden Herausforderungen zu überwinden.

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### 1 Introduction

Photogrammetry has been widely accepted as a 3D documentation technique and method for underwater heritage sites. Still, from early implementations using PhotoModeler (Green et al. 2002), to modern structure-from-motion (SfM) and multi-view stereo (MVS) approaches (Skarlatos et al. 2012), underwater photogrammetry has undergone a significant evolution. Currently, MVS algorithms can generate dense point clouds that

describe complex surfaces with unprecedented detail. This has been used on a wide scope of archaeological fieldwork procedures, including daily mapping in excavation projects, or documentation of sites during surveys and extended reality applications (Bruno et al. 2019). This integration of SfM and MVS has effectively democratised underwater photogrammetry, transforming it from a specialised, rigorous methodology into a widely accessible tool utilised by non-specialists in several

small-scale expeditions or rapid monitoring visits, by research teams or student groups.

Nonetheless, several key challenges persist, among which the most critical ones are the establishment and long-term stability of underwater control networks, the accurate colour restoration and effective visual representation, as well as the correction of water refraction during airborne mapping of shallow coastal heritage sites. While alternative 3D acquisition technologies exist, such as acoustic methods (Benetatos et al. 2024; Janowski et al. 2024) and LiDAR (Janowski et al. 2024; Agrafiotis et al. 2020), they are excluded from this discussion on archaeological documentation, as they are typically deemed either insufficiently precise, dense or prohibitively expensive.

Regarding data acquisition platforms, small and cost-effective remotely operated vehicles (ROVs) present a potential alternative to diver-based surveys, when project budget allows for their deployment. However, for an ROV to reliably deliver high-quality image data, it must be stable, integrated with positioning systems such as ultra-short baseline (USBL) and capable of carrying adequate camera payloads with lights. This requirement necessitates a complex and costly system, often unaffordable for small-scale expeditions. Consequently, ROV deployment is primarily reserved for deep-water operations (Alexandrou et al. 2024) or cases where bottom-time limitations prevent divers from adequately recording a site.

This paper examines the evolution from traditional photogrammetry to modern SfM-MVS techniques, drawing from lessons learned over more than 15 years of interdisciplinary collaborative work between the Department of Civil Engineering and Geomatics of the Cyprus University of Technology and the Archaeological Research Unit of the University of Cyprus.

## 2 Underwater network

In terrestrial surveying, the establishment of a geodetic network is a standard process, necessary in complex sites, where obstacles and terrain morphology block direct lines of sight, or in sites where the landscape undergoes constant change. Both scenarios resemble the operational reality of underwater archaeological sites, where visibility is restricted and excavation activities can alter the seabed topography daily. However, the underwater environment further exacerbates these challenges; Global Navigation Satellite System (GNSS) and standard optical instruments cannot be used, hence surveyors are deprived of the absolute positioning tools taken for granted on land. Consequently, the establishment of a stable underwater control network is not a trivial task but a challenge. The network serves as the

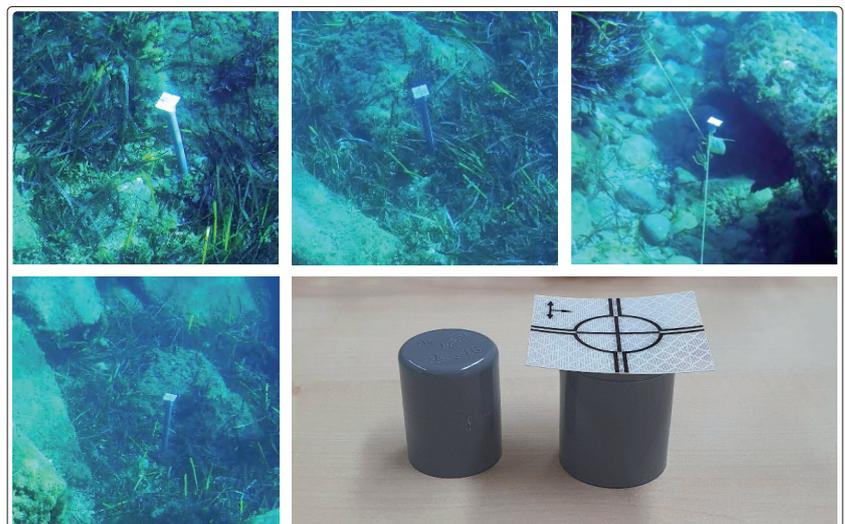
rigid skeleton to spatially and temporally relate measurements and 3D reconstructions. Without fixed reference points, it is impossible to maintain metric integrity for long-term monitoring or to accurately co-register the progress of an excavation spanning multiple years.

It should be noted that the best way for establishing an underwater network is the use of ultra short baseline acoustic positioning systems (USBL) or short baseline acoustic positioning systems (SBL). Although their recent drop in price presents an opportunity, however, the use of such systems in underwater archaeology tends to be very rare.

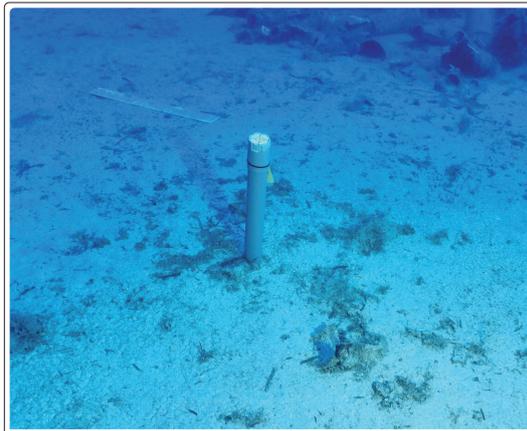
### 2.1 Network materialisation

The reference points of a network need to serve two purposes: recognisability and stability. In terrestrial surveying, identifying stable ground and fixing reference points is a trivial process with a variety of possible fixations, varying from concrete landmarks to nails and spikes. The most common solution involves drilling holes in which special surveying marks are fixed with epoxy resin. In the underwater environment, however, none of these processes are straightforward. While fixing points on a rocky seabed might be achieved using drills and screws, securing stable reference points on sandy bottoms or seagrass meadows presents a challenge. A solution that can be adopted (Alexandrou et al. 2024) on rocky seabed or in seagrass meadows is hammering a metal rod, with a 16-mm PVC end pile cap and a retroreflective target on top (Fig. 1). The cap on the rod can be attached using a two-material plaster like epoxy, which can be hand-mixed and placed underwater.

For a more robust solution, adopted and validated across multiple sites in Cyprus, 2-inch PVC tubes



**Fig. 1:** Rods and 16-mm PVC pipe end cap, with retroreflective target. Reference points placed at Amathous harbour, 3 m depth



**Fig. 2:** Example of a 2-inch PVC tube, used as reference points (Mazotos shipwreck site, 45 m depth)

can be used for stable points (Fig. 2). These tubes are pushed deep into sand at selected positions around the site that must be mapped. A threaded cap with a retroreflective target attached is then screwed onto the top of each pole. The friction of the sediment along with the water pressure ensure that the tube remains fixed and cannot be removed accidentally. This modular design is crucial for long-term monitoring. If targets require cleaning or replacement after several years, the caps can be easily unscrewed, brought to the surface, and subsequently re-installed without disturbing the deep-seated pole. However, as this methodology does not protect the poles from external disturbances (e.g., fishing gear, anchors, accidental hits with divers' fins), their stability must be verified in the beginning of every new excavation season, preferably on an annual basis.

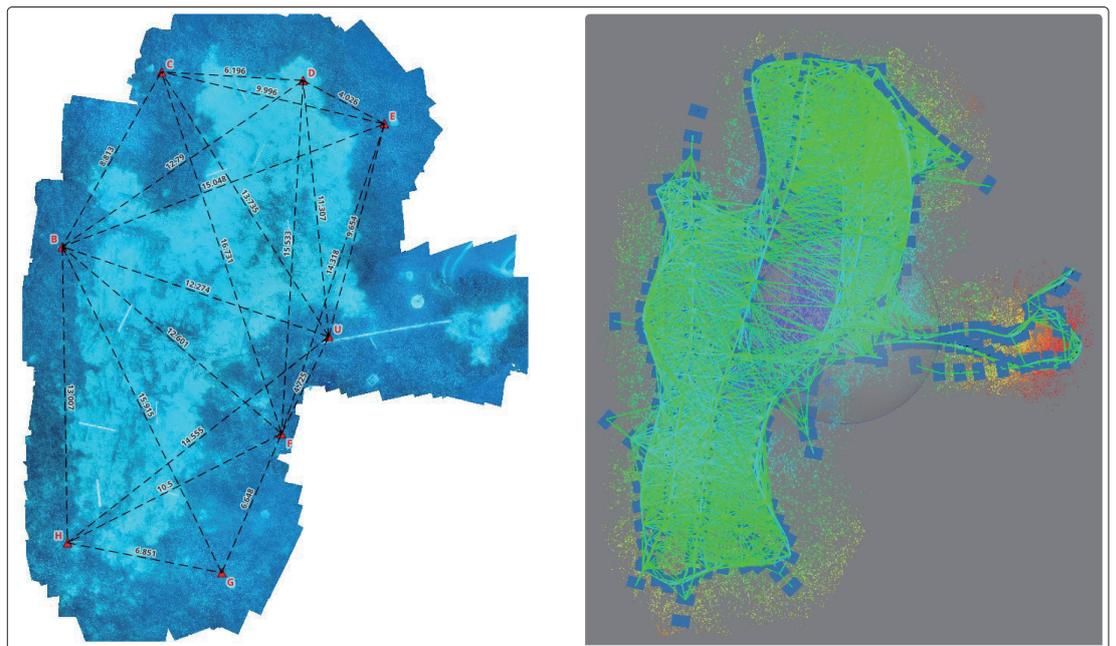
## 2.2 Coordinate estimation using trilateration or photogrammetry

Geodetic theory dictates that a network should ideally consist of equilateral triangles to maximise geometric strength. In the context of a shipwreck, this is rarely feasible, because placing control points in the middle of cargo concentration may damage the artefacts. Consequently, the only viable solution is to establish the network at the periphery, typically leaving empty a buffer zone of 1 to 2 metres off the main concentration, so that to avoid the risk of disturbing buried archaeological material.

Such a layout forces the network into a configuration with large open voids in the middle (Fig. 3). In shallow waters up to 4 m deep, use of long poles with GNSS sensors on top or retroreflective and total stations on shore (Alexandrou et al. 2024) can provide coordinates with approximately 5-cm accuracy (Balletti et al. 2016). However, when the site is deeper, measuring long baselines with traditional tape and processing them with trilateration is not only tedious, but also prone to significant gross errors due to tape sag, currents or divers' nitrogen narcosis. Furthermore, in flat sites where the network lacks significant height variation, trilateration suffers from inherent geometric weakness, leading to unacceptably high uncertainty in the Z-axis (depth).

Using photogrammetric measurements (x,y coordinates on the surface of the photo) to estimate coordinates for the network reference points has three distinct benefits:

- Creation of a true 3D network, with increased vertical precision. The camera projection cen-



**Fig. 3:** The network at the *Nissia* shipwreck site. Left: with artificial trilateration. Right: actual photogrammetry

tres are acting as additional network points, on a different depth. Three-dimensional precision may be further enhanced using oblique photos if necessary.

- Increased redundancy of observations, which translates into more stable geometry, better detection of outliers and ultimately increased precision.
- Increased precision due to photographs resolution; depending on the camera-to-object distance, this can be at the order of 1 mm per pixel, or better.

There are two main disadvantages of photogrammetry, however: scale recovery and visibility. Scale recovery may be overcome using several scale bars spread around the site (see Fig. 3), to avoid long baselines, which suffer from the tape measurement problems. Poor visibility affects marking accuracy of the retroreflective targets in the photos and reduces the camera-to-object distance, resulting in an increased number of photos. For example, in a Monte Carlo simulated trilateration scenario (Skarlatos et al. 2019) applied on the *Nissia* shipwreck site in Cyprus (see Fig. 3), with rather optimistic uncertainties applied to tape measurements, it was possible to achieve uncertainties of  $\pm 6$  cm in horizontal accuracy and  $\pm 64$  cm in vertical accuracy. When measured using a geometrically moderate photogrammetric network, with 1 mm average ground pixel size, the same network, may achieve  $\pm 0.2$  cm in horizontal accuracy and  $\pm 0.2$  cm in vertical accuracy. The simulation of using tape measurements and trilateration on a real site verifies the theoretical assumption that photogrammetry is superior for network's coordinate estimation in underwater environment.

### 2.3 The vertical reference challenge

While in terrestrial networks, vertical reference can be easily determined via GNSS or bullseye spirit levels, underwater depth measurement relies on pressure sensors. To establish vertical reference, depth measurements are acquired next to

each landmark, using the same dive computer, in a single dive. It is important to note that dive computers have readings of  $\pm 0.1$  m and cannot attain the necessary precision for such network. However, these measurements should be used to define the vertical axis of the network rather than the shape. When distributed across a network of 20 m in length, i.e. approximately the length of the *Nissia* (Fig. 3), the relative levelling error can be reduced to  $\pm 2$  cm (Skarlatos et al. 2019). The internal geometry of the network remains defined by the rigid photogrammetric block, while the pressure readings merely orient this block to the gravity vector.

### 2.4 Monitoring network's stability

The main benefit of a surveying network comes from its guaranteed stability, which in constantly changing underwater environment is not a given. In the underwater environment main risks come from trawlers' fishing nets, divers with fins, airlift anchors, etc. Therefore, established networks should be thoroughly checked in the beginning of each excavation period. The ability to detect and identify movement is based on Least Square theory, which provides extensive statistics for blunder detection (data snooping).

As a rule, a dedicated photographic data acquisition is performed prior archaeological work, covering the reference points and the site, with emphasis on the geometry of the photogrammetric block rather than on covering the archaeological remains. When coordinates on the reference points are considered stable, the coordinates from field seasons are used with  $\pm 0.02$  m accuracy. Tie points and reference points are assigned one pixel accuracy in image level. The internal sigma estimation of the solution and the residuals (error) from the coordinates are checked against each other. In case any landmark demonstrates error, which is three times larger (equivalent to 99.7 % confidence level) than the estimated sigma (Table 1). There isn't any strict protocol for checking suspicious points. Usually, they are first double-checked for image residuals, then they are individually checked for error

GCP	X	Y	Z	X error	Y error	Z error	XYZ error	X sigma	Y sigma	Z sigma	XYZ sigma
B	18.213 m	28.805 m	-26.360 m	0.001 m	-0.001 m	-0.003 m	0.003 m	0.001 m	0.001 m	0.002 m	0.002 m
C	22.531 m	36.488 m	-27.129 m	0.005 m	0.000 m	0.000 m	0.005 m	0.001 m	0.001 m	0.002 m	0.002 m
D	28.715 m	36.106 m	-27.484 m	-0.004 m	0.000 m	0.002 m	0.005 m	0.001 m	0.001 m	0.001 m	0.002 m
E	32.261 m	34.199 m	-27.415 m	0.001 m	0.006 m	-0.001 m	0.006 m	0.001 m	0.001 m	0.001 m	0.002 m
F	27.777 m	20.601 m	-26.328 m	-0.006 m	-0.003 m	0.000 m	<b>0.007 m</b>	0.001 m	0.001 m	0.002 m	0.002 m
G	25.163 m	14.488 m	-25.757 m	-0.002 m	-0.004 m	-0.002 m	0.005 m	0.001 m	0.001 m	0.002 m	0.002 m
H	18.439 m	15.800 m	-25.534 m	0.005 m	0.002 m	0.003 m	<b>0.007 m</b>	0.001 m	0.001 m	0.002 m	0.002 m

**Table 1:** Typical Least Square bundle adjustment results. This represents the *Nissia* network checking during the beginning of 2017 excavation period, three years after the initial excavation. Values marked blue represent points' movement exceeding triple the equivalent sigma

magnitude on the neighbouring reference points, if the point under investigation is treated as check point. Finally, if the point is assumed displaced, then new coordinates are assigned. It should be mentioned that only rarely have we identified movements across different field seasons, which validates the stability of the chosen tubes to act as reference points. Nevertheless, the same verification approach is used when there is a suspicion for accidental displacement of a reference point. While the collaboration and proper reporting of all divers is necessary to maintain a stable network, it must also be pointed out that for a sound estimation of precision, measurements must be accompanied with realistic and not overoptimistic accuracy.

### 2.5 Summary

To establish a stable control network in challenging underwater environments, several factors need to be taken into consideration, starting from the use of reference points. Photogrammetry is far more accurate than traditional trilateration, as it demonstrates significantly higher precision. Therefore, it has widely been adopted in free network solutions for initial estimation of the network's coordinates. Vertical reference is defined by averaging dive computer readings to orient the photogrammetric block to the gravity vector as a trade-off between simplicity and accuracy. Long-term integrity must be ensured through annual Least Square bundle adjustment, which statistically validates the network's stability and isolates any reference points displaced by external disturbances.

## 3 Colour restoration

### 3.1 Motivation

Optical underwater imaging is central to underwater archaeology and marine sciences. Wavelength-dependent absorption and scattering distort recorded colour, cause chromatic shifts, contrast loss and spatially inconsistent radiometry. As a result, raw imagery does not reliably represent true object or habitat reflectance, making colour restoration essential for meaningful interpretation. In underwater archaeology, colour is a critical cue for material identification, assessment of the state of preservation and temporal comparison in photogrammetric documentation. Without correction, variations induced by imaging geometry or water properties may be misinterpreted as archaeological features or markers of change, whereas inconsistencies propagate into mosaics and textured models, thus limiting scientific reliability (Rossi et al. 2021). In marine sciences, colour serves as a proxy for biological composition and condition, supporting habitat mapping and coral reef monitoring, yet attenuation reduces sensitivity to ecological variability. In structurally complex

habitats, visualization is often prioritised over radiometric reliability, hindering quantitative evaluation, as emphasised by Rossi et al. (2021). Moreover, restoration approaches demonstrate that visually appealing results do not necessarily correspond to accurate colour recovery when the underlying image formation is not properly addressed (Vlachos et al. 2025a). Consequently, underwater colour restoration is required for the transition from visually convincing representations to scientifically robust and quantitatively interpretable optical data across disciplines (Rossi et al. 2021).

### 3.2 Problems and limitations

Underwater colour restoration is constrained by environmental, optical and operational factors that vary between shallow and deep-water environment, requiring different approaches.

In shallow waters, variable natural illumination and mixed lighting conditions produce strong radiometric inconsistencies, while wavelength-dependent colour loss and contrast degradation persist despite reduced attenuation. In deep water, imaging relies entirely on artificial illumination, with strong distance-dependent attenuation, limited illumination footprint and dominant backscatter tightly coupling colour degradation to camera-to-object distance (CoD), often resulting in severe spatial colour variability even within single images. In both contexts, enhancement-based methods improve visual appearance but do not recover physically meaningful colour, limiting their suitability for evaluative applications (Rossi et al. 2021). In deep-water datasets, operational constraints typically preclude radiometric calibration, and colour degradation has been shown to affect photogrammetric performance, including feature matching and dense reconstruction (Vlachos et al. 2025a; Vlachos et al. 2022a).

Physically based approaches model absorption and backscatter to invert the underwater image formation process. Geometry-aware methods have demonstrated improved colour consistency in large-scale surveys (Bryson et al. 2016) and revised physical models that separate direct signal attenuation from backscatter address fundamental limitations of atmospheric formulations (Akaynak and Treibitz 2019). However, such methods generally require accurate range data, assumptions about water properties, stable illumination or controlled acquisition protocols, which are rarely available in diver-based surveys and legacy archaeological datasets (Vlachos and Skarlatos 2021).

Learning-based approaches estimate colour correction mappings directly from data but are constrained by the lack of reliable underwater ground truth and frequent reliance on synthetic training datasets. Many operate purely in image space, neglecting the strong dependence of col-

our degradation on depth and scene geometry, which can result in visually plausible but radiometrically inconsistent corrections that negatively affect photogrammetric processing (Vlachos et al. 2025b).

Mapping of the *Mazotos* and *Nissia* shipwrecks (Vlachos and Skarlatos 2024; Vlachos et al. 2025a; Skarlatos et al. 2019; Vlachos et al. 2025b; Bruno et al. 2019) exemplifies datasets acquired under realistic archaeological constraints, lacking dedicated radiometric calibration and exhibiting strong depth- and geometry-dependent colour degradation. These conditions have motivated restoration strategies that exploit information already available in SfM–MVS pipelines, adapt to scene geometry and support both visual interpretation and photogrammetric robustness. Building on evidence that colour correction influences reconstruction quality (Vlachos et al. 2022b), the Self-Adaptive Colour Calibration framework integrates SfM–MVS-derived CoDs with learning-based correction, addressing key gaps between fully physical and purely data-driven approaches (Vlachos et al. 2025b).

### Colour restoration approach using DL

To overcome the limitations of physically based and traditional image-driven approaches under realistic underwater documentation constraints, a deep learning (DL)-based colour restoration framework, termed the Self-Adaptive Colour Calibration (SACC) pipeline, was developed for underwater photogrammetric datasets, where controlled calibration, environmental optical measurements and dedicated colour targets are typically unavailable.

The SACC pipeline restores colour by learning the relationship between image radiometry and scene geometry using a Feedforward Neural Network (FNN) (Vlachos and Skarlatos 2024). Rather than explicitly modelling underwater light propagation, the method learns a data-driven correction that accounts for distance-dependent colour degradation. A central assumption is that datasets acquired with artificial illumination include obser-

vations captured under favourable lighting conditions with minimal attenuation; these are treated as relative reference colours, enabling supervised learning without external ground truth. As a result, the pipeline is self-adaptive and trained on a per-dataset basis, adjusting to local water conditions and acquisition geometry (Vlachos and Skarlatos 2024; Vlachos et al. 2025a) (Fig. 4).

The pipeline is integrated within a standard SfM–MVS workflow and relies exclusively on data products routinely generated during 3D reconstruction, including multi-view imagery, sparse point correspondences and depth or camera-to-object distance (CoD) estimates. By exploiting this information, the network learns to map degraded colour observations to corrected values while remaining fully compatible with photogrammetric processing (Vlachos et al. 2025a).

Compared to fully physical models, the SACC pipeline does not require explicit estimation of absorption or backscatter coefficients, water optical properties or controlled acquisition protocols. By incorporating CoD information, it also overcomes the limitations of purely image-space DL approaches. Importantly, the correction is applied in a controlled manner that preserves image texture and avoids artefacts known to affect feature detection, feature matching and dense reconstruction quality in SfM–MVS workflows (Vlachos et al. 2022b; Vlachos et al. 2025b).

### 3.3 Applications to the *Mazotos* and *Nissia* shipwreck sites

The SACC pipeline was evaluated on underwater archaeological datasets from the *Mazotos* and *Nissia* shipwrecks, that represent realistic documentation scenarios with limited calibration opportunities. At *Mazotos* (–44 m), imagery was acquired at depths exceeding 40 m under exclusively artificial illumination, exhibiting strong distance-dependent colour attenuation. The SACC pipeline enabled dataset-wide colour restoration without physical colour charts, improving radiometric consistency and supporting more stable textured 3D recon-

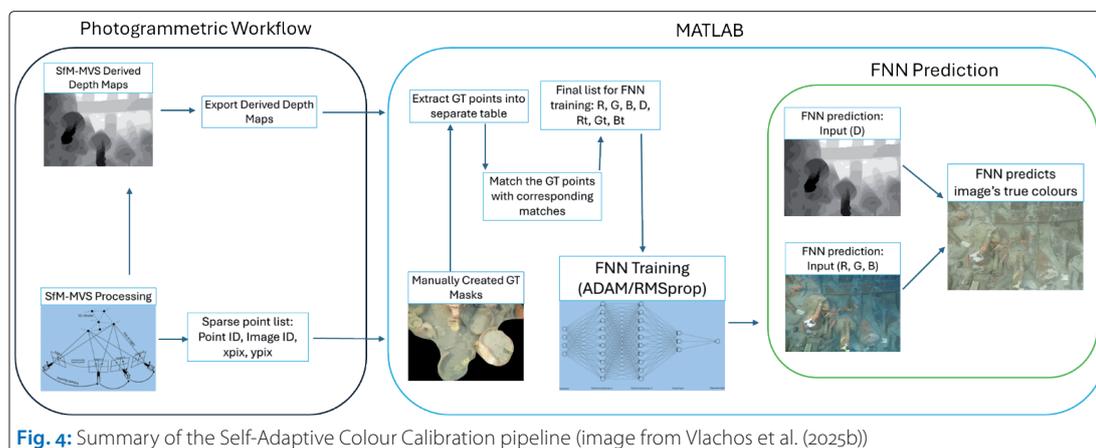
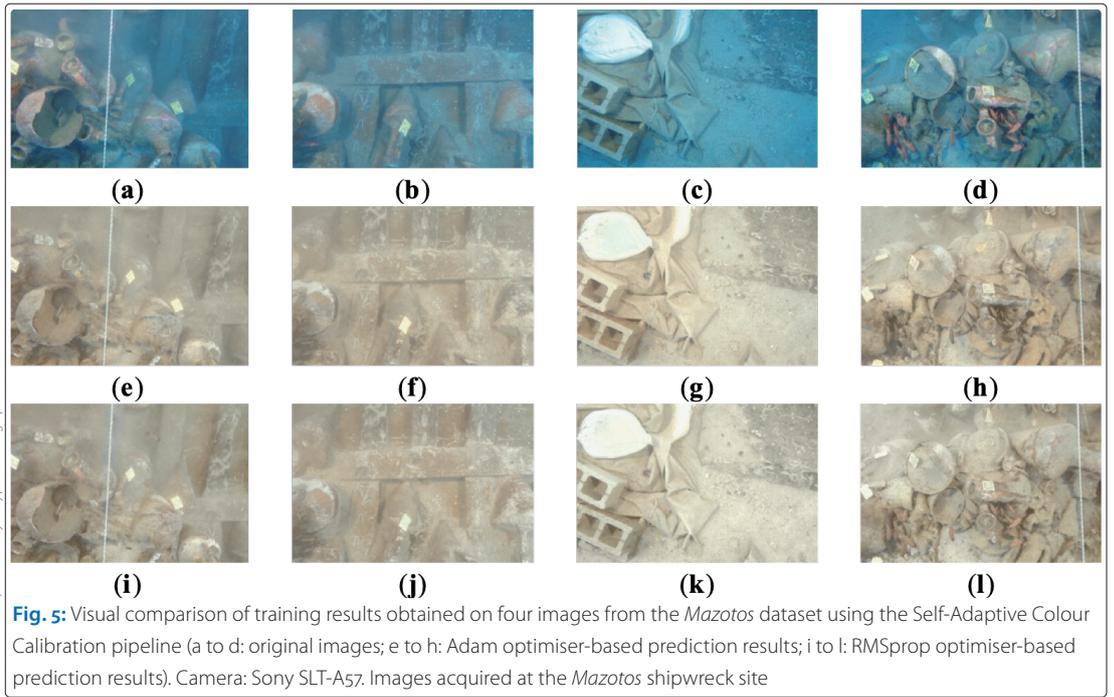


Fig. 4: Summary of the Self-Adaptive Colour Calibration pipeline (image from Vlachos et al. (2025b))



Credits: MA-RELab, © University of Cyprus. Photographer: Massimiliano Secci

**Fig. 5:** Visual comparison of training results obtained on four images from the *Mazotos* dataset using the Self-Adaptive Colour Calibration pipeline (a to d: original images; e to h: Adam optimiser-based prediction results; i to l: RMSprop optimiser-based prediction results). Camera: Sony SLT-A57. Images acquired at the *Mazotos* shipwreck site

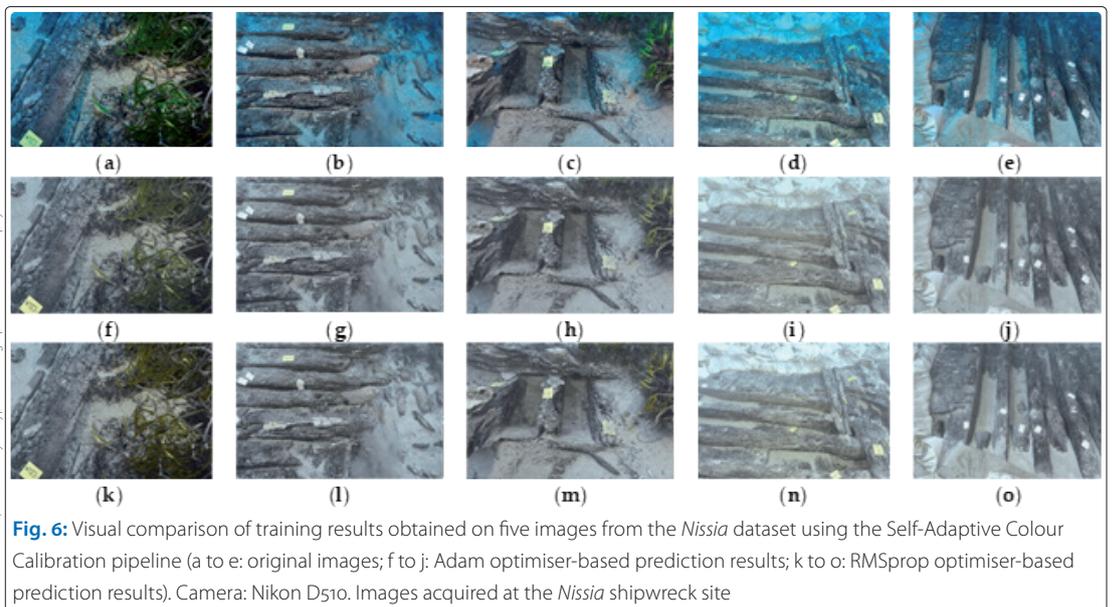
structions in a complex excavation environment (Vlachos and Skarlatos 2024). Fig. 5 presents four images from the 2019 field season at *Mazotos*, together with their colour-corrected counterparts produced using predictors trained with different optimisers.

At *Nissia* (–27 m), a more controlled evaluation scenario was available, with the inclusion of colour reference targets, which enable quantitative assessment of restoration accuracy. Results showed improved agreement between restored and reference colours, particularly in the red and green channels, while highlighting remaining challenges in blue channel recovery. The *Nissia* case study also enabled systematic evaluation of the pipeline's impact on feature matching and reconstruction

robustness (Vlachos et al. 2025b). Fig. 6 presents five images from the dataset acquired during the 2024 field season at *Nissia*, alongside their colour-corrected counterparts produced using predictors trained with the Adam and RMSprop optimisers.

### 3.4 Summary

The Self-Adaptive Colour Calibration (SACC) pipeline is a deep learning-based, geometry-aware colour restoration strategy for underwater photogrammetric documentation. By exploiting SfM-MVS-derived depth information and dataset-internal reference colours, it bridges the gap between physically grounded and purely image-based methods. Its application to the *Mazotos* and *Nissia* shipwrecks demonstrates its suitability for



Credits: MARELab, © University of Cyprus. Photographer: Andonis Neophytou

**Fig. 6:** Visual comparison of training results obtained on five images from the *Nissia* dataset using the Self-Adaptive Colour Calibration pipeline (a to e: original images; f to j: Adam optimiser-based prediction results; k to o: RMSprop optimiser-based prediction results). Camera: Nikon D510. Images acquired at the *Nissia* shipwreck site

underwater archaeological datasets, supporting the use of colour as evaluative information rather than purely visual enhancement.

## 4 Coastal sites and drone mapping

### 4.1 Motivation

Mapping coastal sites is essential for a range of engineering and archaeological applications. While established methodologies exist for terrestrial zones (e.g., drones, LiDAR) and the seabed (e.g. echo sounders), achieving a seamless, unified model across the land-sea boundary remains a significant challenge.

While echo sounders typically generate point clouds lacking visual colour information, which is critical for identifying specific archaeological features, unmanned surface vehicles (USVs) equipped with multibeam echo sounders (MBES) and underwater nadir cameras allow for detailed 3D and visual documentation. The use of underwater cameras facilitates direct application of SfM and MVS photogrammetry, as water refraction effects can be effectively absorbed during camera self-calibration.

Aerial drones equipped with bathymetric LiDAR offer another potential solution for seamless surface modelling, but generating seamless orthophotomosaics from such data requires specific water refraction corrections. Aerial drone photogrammetry represents an affordable and effective solution in regions with high water clarity, such as the Eastern Mediterranean. This approach is particularly valuable in very shallow waters, where unmanned surface vehicles (USV) or swimmers cannot operate safely. The application of through-water aerial photogrammetry, however, is currently limited because standard commercial software fails to account for air-water refraction, a phenomenon that introduces significant geometric errors regardless of water depth or flight altitude (Skarlatos and Agrafiotis 2018). Applying unified mapping techniques was critical for mapping numerous coastal sites, including the Amathus harbour, Cyprus (Empereur and Verlinden 1987), Pavlopetri (Harding et al. 1969) and Epidaurus (Davide Petriaggi et al. 2020), Greece, and Caesarea, Israel (Hohlfelder et al. 1983). These sites require a holistic approach that seamlessly connects underwater and terrestrial remains.

For example, the late 4th century BC harbour of Amathus, Cyprus, is a very good example of a shallow site, with extensive architectural remains on land and under the sea, that can only be studied through accurate mapping and documentation within a unified, seamless spatial reference system. Firstly, close examination of the moles and breakwaters is hindered by the very shallow depth and the rich marine flora, so aerial photography is the only way to understand the architectural layout.

Moreover, the Amathus harbour works are organically connected with coastal monuments of the ancient city, from which they are now detached, due to coastal erosion; and at the same time, submerged terrestrial structures within its basin should be recorded with accuracy, so that other phenomena of coastal changes can be documented.

### 4.2 Through-water photogrammetric documentation

There are three primary justifications for employing through-water aerial surveys: 1) the extensive size of the survey area, 2) the requirement for a seamless visual survey encompassing both terrestrial and underwater structures, and 3) extremely shallow water depths (Alexandrou et al. 2024) that preclude the use of underwater photography. It is important to note that while a combined approach utilising an aerial drone for land and a USV equipped with MBES and a hull-mounted camera yields superior image resolution, it invariably results in a data void within the surf zone. In cases of underwater or harbour structures, this zone can contain critical information.

The principal impediment to aerial photogrammetric mapping in this context is water refraction, which violates the fundamental collinearity assumption (straight visual line) of photogrammetry. Accurate geometric results require two-media photogrammetry, a capability currently absent in standard commercial software, thereby limiting the widespread adoption of this methodology.

To address this, a solution employing ML to correct the erroneous bathymetric point clouds generated by standard SfM–MVS processes that neglect refraction has been proposed in Agrafiotis et al. (2024) and in Agrafiotis et al. (2021). The Support Vector Machine (SVM) model was trained using reference LiDAR bathymetric data (Agrafiotis et al. 2024) and synthetic bathymetric and imagery datasets (Agrafiotis et al. 2021). Following the depth correction of underwater points, all corresponding images undergo differential rectification based on the corrected depths to ensure accurate orthorectification and mosaicking. This method has been successfully validated at several sites, including the ancient harbour of Amathus, Paphos harbour and Agia Napa marina (Fig. 7).

Despite the high bathymetric accuracy achieved, the methodology is subject to specific limitations. Flight altitudes must generally exceed 30 metres to mitigate the impact of dynamic wave patterns on SfM feature matching. Additionally, caustic patterns in very shallow water and turbidity can hinder the process. Furthermore, the use of an RTK-enabled drone is strongly recommended to ensure geometric stability. Perhaps the most



**Fig. 7:** This aerial orthophotomosaic of Amathounta harbour has a resolution of 2.5 cm and has been produced by drone aerial photos, after water refraction correction. For scale reference, visible south jetty is approximately 170 m long

significant constraint is the assumption of a planar water surface. This simplification affects both LiDAR and photogrammetric approaches, as the scientific community continues to seek viable solutions for real-time wave modelling to accurately define surface normals for the rigorous application of Snell's law.

## 5 The way forward

The adoption of machine learning is primarily justified in cases where the precise physical formulas governing a phenomenon are unknown or too complicated to estimate; the model cannot be calibrated due to missing information; not all variables can be determined due to equipment limitations. Given the complex physical formulae of light propagation, the constantly changing underwater environmental parameters affecting light propagation and the limited environmental data, machine learning offers a significant potential. As mentioned above, ML has been utilised in underwater colour restoration and bathymetric evaluation, bypassing the full physical models.

The use of 3D Gaussian splatting (3DGS) in underwater 3D reconstruction, seems to offer distinct

advantages over traditional structure-from-motion (SfM) and multi-view stereo (MVS) pipelines. Where MVS approaches struggle in aquatic environments due to featureless textures, light flickering and significant scattering, 3DGS leverages differentiable rasterisation to achieve near real-time rendering in speeds that far exceed those of MVS. At the same time 3DGS represents scenes as explicit point clouds with Gaussians splatted onto the image plane, providing a balance between the explicit geometry of MVS and the photorealistic rendering.

A critical advantage of most recent 3DGS frameworks (Li et al. 2025; Yang et al. 2025; Liu et al. 2024), is their capacity to integrate the physical Image Formation Models (IFMs). In MVS, the water medium's effects such as wavelength attenuation and backscatter are baked into the texture, resulting in colour cast models. Conversely, physics-aware 3DGS manage to model these optical interactions, allowing the disentanglement of the scene's true albedo from the participating medium. This capability facilitates simultaneous 3D reconstruction and colour restoration, effectively »removing« the water to present the scene as it would appear in air.

Regarding the later, the promise of 3DGS as a tool to merge 3D reconstruction, 3D representation and colour restoration, becomes an attractive potential. Being able to combine, in a single solution water refraction correction, geometry recovery and colour restoration into a fast holistic tool, seems like the holy grail of underwater photogrammetry.

Such tool would ultimately be able to utilise aerial photos for correct geometric reconstruction of sea bottom and land removing the effect of water altogether, creating a seamless true colour orthophoto mosaic and corresponding digital surface model over the mapping area.

However, the application of 3DGS in underwater domains is not without limitations. The framework relies on SfM algorithms for camera pose estimation and point cloud initialisation. This creates a significant dependency on photogrammetry, with all current limitations in turbid or texture-poor underwater scenes where point operators fails to identify sufficient feature matches. Problems with suspended particles and floaters in the photos, degrading the geometric fidelity of the resulting reconstruction and representation, seems to have been dealt successfully (Li et al. 2025; Yang et al. 2025; Liu et al. 2024; Wang et al. 2025), but issues with marine life and moving seaweeds, still remain. In terms of point density and detail in geometric accuracy, 3DGS are still behind traditional SfM-MVS, without any tangible signs of how they could bridge the gap.

Consequently, while 3DGS provides superior visual presentation and restoration capabilities, the resulting point density and geometric connectivity may require further refinement to match the

metrological precision of dense MVS meshes. Nevertheless, the potential of ML in underwater applications for archaeology and marine and ocean sciences is undoubtable. //

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