Journal of Computer Applications in Archaeology

Underwater Drones as a Low-Cost, yet Powerful Tool for Underwater Archaeological Mapping: Case Studies from the Mediterranean

CASE STUDY

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ubiquity press

ABSTRACT

This paper investigates the transformative impact of micro-class Remote Operated Vehicles (ROVs), commonly known as underwater drones, on underwater archaeological mapping. With advancements in Unmanned Underwater Vehicles (UUVs) technology leading to increased capabilities and reduced costs, these compact and user-friendly drones are making underwater archaeological sites more accessible, reducing the need for human diving. The paper first highlights the advantages of ROVs, including their portability, maneuverability, and ability to perform semi-autonomous mapping with real-time data assessment, which enhances decision making and minimizes the need for site revisits. Second, it presents two case studies from the Phournoi archipelago in Greece, demonstrating the effective use of underwater drones in the photogrammetric mapping of a Late Roman shipwreck of amphora cargo, as well as the large-scale surveying of a historically significant anchorage site. The findings underscore the potential of this technology to revolutionize underwater archaeological documentation, akin to how terrestrial cultural heritage mapping has been highly benefited from aerial drone photogrammetry.

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KEYWORDS:
marine archaeology; underwater drones; ROV; shipwreck mapping; underwater cultural heritage; marine robotics; underwater photogrammetry; sensor fusion

TO CITE THIS ARTICLE:
Diamanti, E, Ødegård, Ø, Mentogiannis, V and Koutsouflakis, G. 2025. Underwater Drones as a Low-Cost, yet Powerful Tool for Underwater Archaeological Mapping: Case Studies from the Mediterranean. *Journal of Computer Applications in Archaeology,* 8(1): 10–24. DOI: https://doi.org/10.5334/jcaa.184

1. INTRODUCTION

Underwater photogrammetry has been massively applied as a remote sensing solution for mapping underwater archaeological and historical sites over the last decades. A basic reason for its popularity is the high amount of information that can be effortlessly collected in a short period of time. Together with the technological advances in underwater photography and photogrammetric software – especially since the release of user-friendly Structure from Motion (SfM) software – a few hundreds of underwater cultural heritage (UCH) sites have been 3D modelled and published. Although the majority of these 3D modelling works has been conducted through human diving (Drap, 2012; Yamafune et al, 2017; Gambin et al, 2023), whether on a research or commercial level, and at the wide depth range from 0 to 120 meters, the use of unmanned underwater vehicles (UUVs) in marine archaeological mapping is not something new (Drap et al, 2015; Johnson-Roberson et al, 2017; Pacheco-Ruiz et al, 2019; Mogstad et al, 2020; Diamanti et al, 2021). Autonomous Underwater Vehicles (AUVs), Work-class Remote Operated Vehicles (WROVs), bio-mimetic robots and their sophisticated technology have been recruited for shipwreck mapping, yielding interesting results. Diamanti and Ødegård (2024) provide a comprehensive review study on the use of marine robotic platforms for the optical-based mapping of marine archaeological sites since nearly the last decade.

In light of the remarkable advancements in UUVs technology, characterized by constantly increasing mapping capabilities and substantial cost reduction (Stein, 2023), this study aims to investigate the transformative impact of micro-class Remote Operated Vehicles (ROVs), commonly referred to as underwater drones, on underwater archaeological mapping. With the expanding accessibility of user-friendly and compact underwater drones that require no specialized technical or scientific expertise, our research seeks to explore the evolving dynamic wherein this affordable technology facilitates a democratization of underwater archaeological documentation, while reducing human diving significantly. The growing ratio of capabilities to cost in underwater archaeology is assessed akin to the paradigm shift observed over the last decade in aerial drone photogrammetry and cultural heritage mapping (Pepe et al, 2022).

In Section 2, the paper discusses the advantages of underwater drones in marine archaeology, highlighting their ever-increasing payload capacity, portability, maneuverability, user-friendliness and affordability to name a few properties, as well as the potential in performing semi-autonomous mapping missions, with full site coverage, obstacle avoidance and real-time data quality assessment. The combination of navigational and optical sensors offers capabilities for real-time computations, thus assisting the marine archaeologist to take on-site decisions, evaluate the mapping process, and avert the need for revisiting the site because of low data quality. The discussion extends beyond the inherent safety advantages of using ROVs over human diving and the apparent associated constraints such as depth and diving time and goes through a list of recent publications on the use of underwater drones in underwater cultural heritage projects.

Section 3 presents two case studies that demonstrate the integration of underwater drones into marine archeology. Both applications took place in the Phournoi archipelago, located in the North Aegean Sea, Greece, a region highly abundant in underwater archaeological findings. The first case study involves the photogrammetric mapping of a Late Roman shipwreck through the deployment of an underwater drone with a multi-sensor setup, whereas the second study deals with the large-scale surveying and documentation of an anchorage site of historical and archaeological significance. Both scenarios are examined through the utilized equipment, the selected methodological approaches and their final outcomes.

2. THE EVOLUTION OF UNDERWATER DRONES AND THEIR USE IN MARINE ARCHAEOLOGY

Cultural heritage entered a totally new era in documentation, analysis, and interpretation, when advanced remote-sensing technologies such as laser scanners, unmanned aerial vehicles (UAVs), and user-friendly Structure-from-Motion (SfM) software were introduced (Pepe et al., 2022). Archaeologists were able to survey extended areas in high accuracy and detail, and in a significantly reduced amount of time, with two key advantages: the new technology was affordable and required only a basic understanding of photogrammetry and SfM principles for effective use. UAV photogrammetry has been widely adopted in the documentation of archaeological excavations, historical buildings, monuments and cultural landscapes (Waagen, 2019; Adamopoulos and Rinaudo, 2020). Survey missions using aerial drones gained a high degree of autonomy, enabling the operator to program the parameters of the mission (coverage waypoints, flying height, image resolution, consecutive image overlap, neighboring transects overlap, flying pattern, battery percentage for end of mission etc.), perform the mission, retrieve the drone and download the data. The downscaling in size of the drones and their sensors made them comfortably manageable by a single operator, while the affordability of this technology resulted in a remarkable rise in the market. A wide budget variation in UAV technology does exist, however, and is depending on the drone type, the sensor payload, or the flight range (Campana, 2017). In operational terms, UAV systems allow for the surveying of areas up to 10 km^2, with a flying altitude range from 20 to 200 m, offering opportunities for covering cultural heritage sites that might be inaccessible for land surveying. Regarding their sensor payload, drones that are used for archaeological purposes are often equipped with high quality optical sensors (single, stereo or multiple cameras), hyperspectral imaging systems, high precision navigational and positioning systems, and other remote sensors like LiDAR (Light Detection and Ranging).

Likewise, underwater drones have revolutionized marine archaeological research with a multitude of advantages that enhance both the efficiency and effectiveness of underwater exploration, mapping or intervention tasks:

- Their **payload capacity** allows for the integration of multiple sensors, including optical (multi-camera systems), acoustical (multibeam echosounders, side scan sonars, scanning imaging sonars), and navigational systems (Inertial Measurement Units (IMU), Doppler Velocity Loggers (DVL), underwater positioning systems), enabling comprehensive data fusion that enriches the quality and scope of archaeological findings. On a similar note with UAV systems, the sensor payload of underwater drones is defining also the level of budget of the sensor-carrying platform.
- Their **portability** and **maneuverability** eliminate the need for big research vessels and heavy equipment like cranes, reducing the number of personnel required, while at the same time minimizing the risk of entanglement underwater.
- Their ability to **dive deep**, execute **extended bottom-time missions**, and **cover vast areas** makes them critically important for accessing and surveying sites that were previously beyond reach. Their current dive rating is up to 500 meters, while the area extents depend on the battery capacity, the demands in resolution (a lower resolution requirement usually allows for longer surveys), the level of detail, and environmental factors like the existence of underwater currents that may cause additional drag forces to the underwater vehicle.
- Their **user friendliness** in terms of launching, operating, recovering and handling collected data, encourages their effective integration into marine archaeological projects by operators without a scientific or technical background in marine robotics. Underwater drones are now operated by compact devices like phones or tablets, through software interfaces with enhanced data displays and straightforward command controls.
- Their **affordability** has democratized advanced underwater research technologies, allowing for more widespread participation in marine archaeology. Low-cost ROVs have become accessible now to less funded underwater archaeological projects, boosting up the underwater exploration and documentation beyond the limits of human diving. It is not uncommon also for amateurs possessing inexpensive ROV equipment to come across new discoveries of underwater cultural heritage significance. Marine archaeological research is substantially benefited by crowdsourcing and citizen science, similarly to land archaeology, with a growing number of volunteers contributing to the gathering and processing of underwater historical and archaeological data (Scott-Ireton et al., 2023).
- The real-time video and data transmission to surface allow for **real-time data assessment**, applying visual techniques like Visual Simultaneous Localization and Mapping (VSLAM), increasing the pilot's operational awareness and perception and enabling control of site coverage, obstacle avoidance, and online decision making in general, providing immediate insights to the marine archaeologist, while reducing potential site revisit needs.

Beyond the clear safety advantages, the aforementioned features of underwater drones make them a more competitive option for the exploration and documentation of underwater cultural heritage as compared to traditional human diving. Although there is still a lot of progress to be made in order for robots to match a human-level intelligence in an underwater environment - particularly in how to perceive the 3D space, detect obstacles, get untangled, assess the importance of an underwater scene in an archaeological or historical context etc. - yet the integration of 'smart' sensors in ROVs can provide a higher level of objectivity and consistency in data collection, as compared to a diver. Attached DVLs, for example, allow ROVs to maintain a constant flying altitude over the site of survey, resulting in a uniform resolution in image acquisition. The real-time and fast data streaming, also, further contribute to this objectivity thanks to real-time computations and mapping results that enable an immediate assessment of survey coverage or detect gaps in data. High-precision navigational sensors allow for maintaining a stable, pre-defined path of the robot, thus preventing it from under-acquisition (gaps in data) or over-acquisition (unnecessary data) due to random, self-intuitive transects over the area of interest. On a parallel path with aerial drone mapping, underwater drone manufacturers like Blueye Robotics (Blueye Robotics, 2024) and DeepTrekker (Deep Trekker Inc, 2024) have recently developed mission planner software for their drone systems. A wreck survey mission can be pre-defined and executed semi-autonomously by adding waypoints to the area of interest, defining the vehicle's path, keeping a constant altitude from the seabed or wreck that allows for a uniform resolution on the collected data, or performing other control commands like end-the-mission or go-to-surface.

A few examples from recent literature highlight this rise in the use of underwater drones in underwater cultural heritage projects. The Laboratorio di Fotogrammetria of Iuav University of Venice used the open-source OpenROV, equipped with two additional GoPro cameras, for the photogrammetric documentation of a shallow wreck site in Puglia, Italy, comparing the ROV-based 3D models with diver-based photogrammetric data (Costa et al., 2018). The 3D reconstruction results of the Dolia shipwreck in the Tuscany archipelago were presented by Scaradozzi et al. (2013), who developed a micro ROV Assisted Guided System in a user-friendliness degree that could enable operators with limited experience to achieve all the goals of a ROV photogrammetric survey at an underwater archaeological site. The BlueROV2, a small and affordable ROV, was deployed for visual data acquisition and 3D reconstruction of an ancient wreck site in front of Cavtat in Croatia (Kapetanovic et al., 2020). The same robotic platform, BlueROV2, was used by Severino et al. (2023) in order to develop a low-cost system with an optical payload and acoustic localization system that provides real-time mapping results on underwater cultural heritage sites surveys. The Deep Trekker DTG2 underwater drone, equipped with a mini multibeam echosounder and an underwater positioning system, was employed for the exploration of a 75-meter deep wreck site at the challenging and murky waters of Lake Erie, at Great Lakes, in North America (Macdonald, 2017). A FIFISH V6 EXPERT underwater drone was deployed by the scientific team of KORSEAI Institute of Historical and Archaeological Research for the localization and documentation of amphorae in deep waters beyond human-diving reach, during the Phournoi archipelago underwater archaeological survey (KORSEAI, 2024). The Blueye underwater drone was selected as a photogrammetric acquisition platform for the 3D recording of M/S Helma schooner, 55 meters deep, in the dark waters of Trondheimsfjord in Norway (Diamanti et al., 2024).

The next section of the paper demonstrates the effective use of underwater drones within the framework of two archaeological sites in the Mediterranean. Both case studies are presented through the sequence "site description – data acquisition – processing – visualization of results". Similar to aerial or land archaeological surveying, an underwater archaeological survey (in this case through the use of underwater drones) encompasses three main stages: Planning, Mission and post-Mission. Figure 1 introduces an analytical timeline of all three stages, containing information and guidelines that could be adopted by a wide range of UCH surveying scenarios of high diversity.

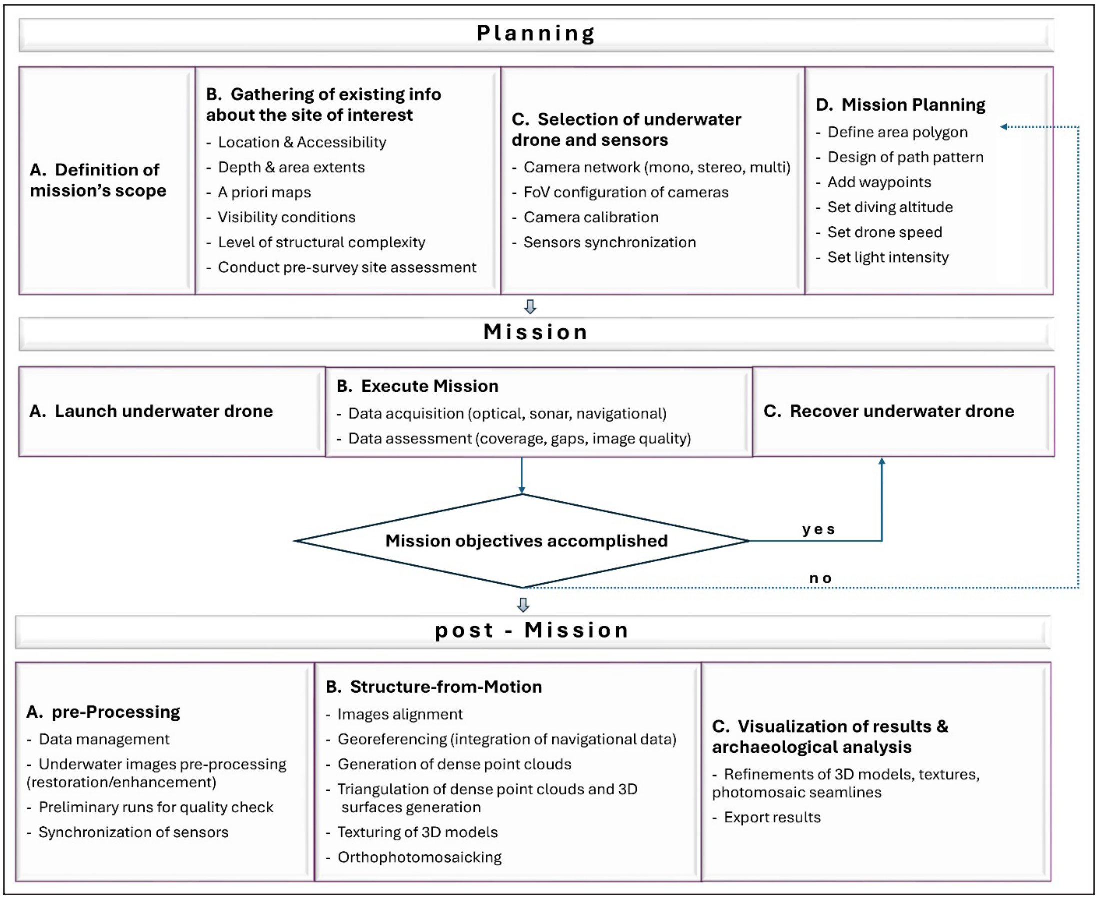

Figure 1 Flowchart illustrating the three main stages of surveying an underwater cultural heritage site using underwater drones.

3. CASE STUDIES

Since 2015, an interdisciplinary collaborative team from the Greek Ephorate of Underwater Antiquities, the RPM Nautical Foundation, the University of Thessaly, and the KORSEAI Institute of Historical and Archaeological Research have been conducting an underwater archaeological survey in the Phournoi archipelago, North Aegean Sea, Greece (Figure 2). More than 50 shipwrecks have been located in a depth range of 5 to 67 meters, with an approximate 50% coverage of the coastline being surveyed, making the archipelago of Phournoi the largest known concentration of shipwrecks in the Mediterranean (Campbell and Koutsouflakis, 2021). Since the underwater surveys were based solely on human diving, the deep-water zones (>60 meters) of the area remain uncharted, something that increases the potential for new discoveries after incorporating advanced remote sensing technologies underwater.

This section presents the results of the digital surveying of two selected sites in the Phournoi archipelago, documented for the first time through marine robotics. The main objective of both surveys was to experiment with two different sensor configurations of underwater drones on two sites of different mapping requirements as well as develop and establish a methodological basis for future marine surveying operations in the area and beyond.

3.1 PHOTOGRAMMETRIC SURVEY OF THE LATE ROMAN (EARLY BYZANTINE) WRECK

The first site of interest for underwater drone digital documentation was an ancient shipwreck located in the cape of "Aspros Kavos" or "Fygou" (trans. "White Cape" and "Escape") on the east coast of the main island of Phournoi. The wreck was discovered during the first survey campaign of the project in 2015 and since 2021 is undergoing excavation (Campbell and Koutsouflakis, 2021). It was initially dated to the 3rd-4th century CE (Koutsouflakis and Campbell, 2021) with its chronology revised recently according to new evidence in the last decades of the 5th ct. CE. The cargo consists of a large and quite varied number of mostly intact amphorae (Zeest 72, Zeest 104, Zeest 91b, Late Roman 1, Sinopean C1 and Kapitan 2 amphora types), covers an area of 25 by 15 meters and lies in a steep sandy seabed 38 to 50 meters deep. The wreck site was selected as an ideal object for sea trials because of the good prevailing underwater conditions, its low structural complexity as a 3D volume (low operational risks, such as tether entanglement or loss of equipment), the opportunity for multiple operations during the excavation season and finally, because of available and geometrically reliable a priori knowledge of the wreck's surface and bathymetry derived by a former photogrammetric mission, which served as ground truth.

3.1.1 The underwater drone photogrammetric setup

The underwater drone Blueye X3 (Blueye Robotics AS, 2024) was chosen as the sensor-carrying ROV for the documentation of the shipwreck. The lightweight (approximately 8 kg in air) and low-cost mini-class underwater vehicle is rated to a depth of 300 meters and can comfortably be handled by one person. It is actuated in four degrees of freedom (DoF), namely surge, sway, heave, and yaw, and has four thrusters (two in surge direction, one lateral, and one vertical). The

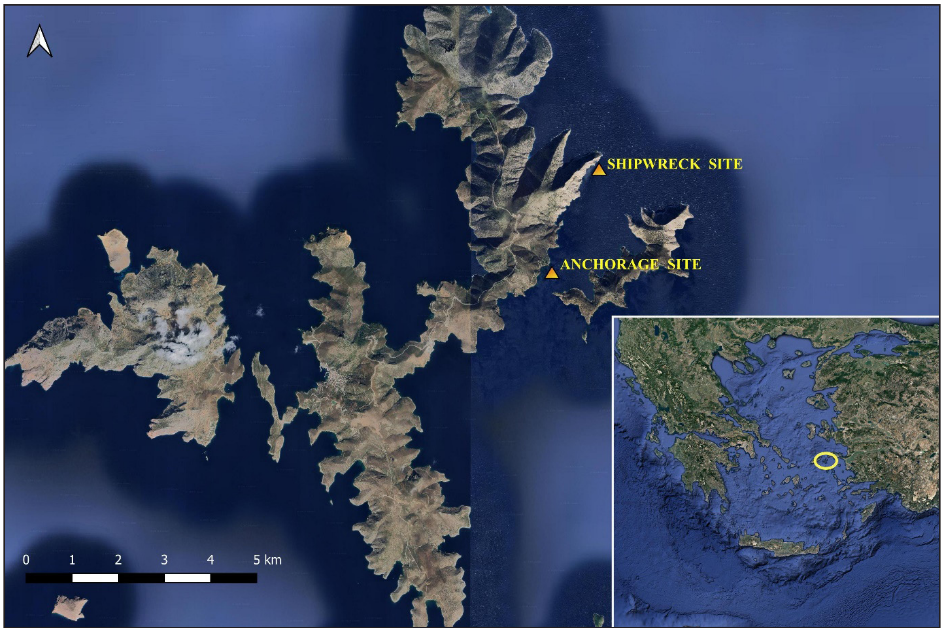

Figure 2 Map of the Phournoi archipelago, North Aegean Sea, Greece, and the locations of the two case studies (Late Roman shipwreck site and anchorage site) presented in the paper.

vehicle is equipped with an Inertial Measurement Unit (IMU) and a magnetometer for estimating the robot's orientation and a pressure sensor for depth. A Doppler Velocity Logger (DVL) was also attached to the bottom of the ROV, providing measurements that keep the diving altitude *h* – or flying height in aerial drone mapping terms – constant. In that way, the underwater drone follows the terrain of the site and the pixel size or ground sample distance (GSD) in images (resolution) is kept consistent. The combination of the DVL and IMU measurements provides the vehicle's estimated trajectory, which is then integrated into the photogrammetric software as initialization values for the camera poses. Regarding visual sensing, the ROV carries an integrated forward-looking, high-definition, 1080p/30fps, wide-lens camera (1/2.8-inch Exmor R CMOS) with a field of view of 115° and a mechanical tilt of –30° to +30°, and a light-emitting diode (LED) light of 3300 lumen.

In order to empower this payload for photogrammetric documentation purposes, a stereo-rig of two downward-looking GoPro Hero 9 cameras and a pair of external LED strobe lights of 4000 lumen each were mounted on the underwater drone (Figure 3). Finally, an Ultra-Short Baseline (USBL) transponder was attached to the drone, providing georeferencing and real-time tracking of the vehicle. This underwater positioning system has a nominal accuracy of approximately 2 cm.

The underwater drone is controlled through an application (Blueye App) that can be installed in any smart device and operated by personnel not specialized in marine robotics. The ROV is connected via an umbilical to a surface unit, which in turn is linked to the smart device through Wi-Fi. The operator has then access to the video stream of the ROV with low latency, reads telemetry data such as date and time, heading, orientation, depth, battery status, water temperature, and flying altitude, and sends commands for start and stop of recording, motion speed, camera tilting or LED lights intensity. An additional and simplified application (Blueye Observer App), without control commands, is available for multiple users to connect to the drone and view at the same time the video stream.

All three cameras of the system were calibrated prior to the mission in the controlled environment of a tank, with the use of a typical checkerboard pattern (with dimensions 800 × 600 mm, Figure 4). The calibration data were processed in the Matlab "Camera Calibrator" App (Bouguet, 2020) for the estimation of the intrinsic and extrinsic parameters, and distortion coefficients of the GoPro cameras and the drone's internal camera.

3.1.2 Data acquisition

Since there was no option at the time of the experiments for executing an autonomous photogrammetric mission on the wreck site, comparable to aerial drone mapping where the path pattern, overlap and flying height can be predefined and imported in the mission planer application, the ROV was manually piloted for the acquisition of photogrammetric data. The ROV operator performed an approximate lawnmower pattern route over the shipwreck, starting with the stern-bow direction, and then moving perpendicularly, recording a few additional flyovers for data redundancy. Despite the manual control of the piloting, the photogrammetric mission featured a certain degree of autonomy thanks to the availability of two sensors. First, the underwater positioning system provided real-time tracking of the ROV's position and trajectories, ensuring a full coverage of the site. Second, the DVL sensor allowed for a fixed flying altitude of 1 meter above the wreck site (Figure 5). This ensured a consistent image resolution during the

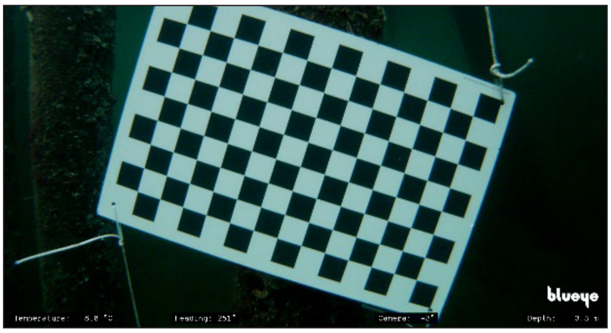

Figure 4 Calibration data from the underwater drone's internal camera.

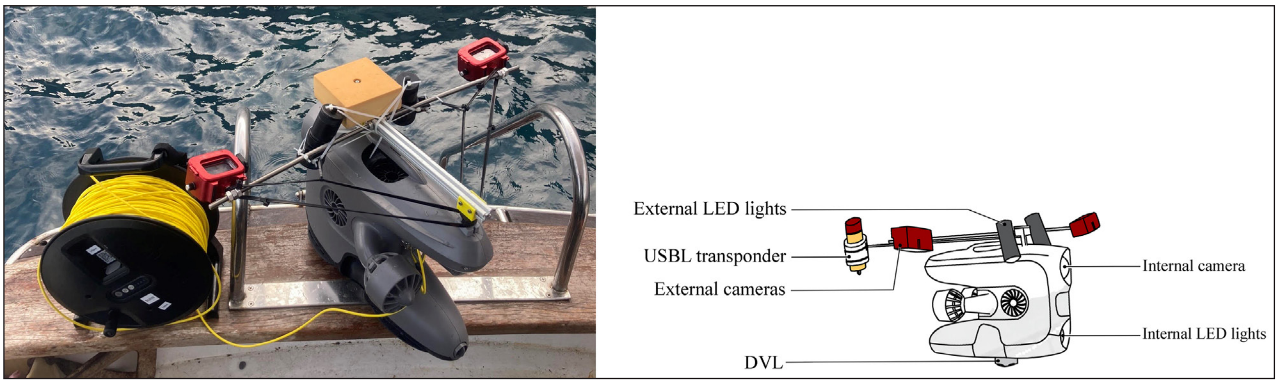

Figure 3 Left: The underwater drone Blueye X3 ready for deployment. Right: The underwater drone's full photogrammetric setup.

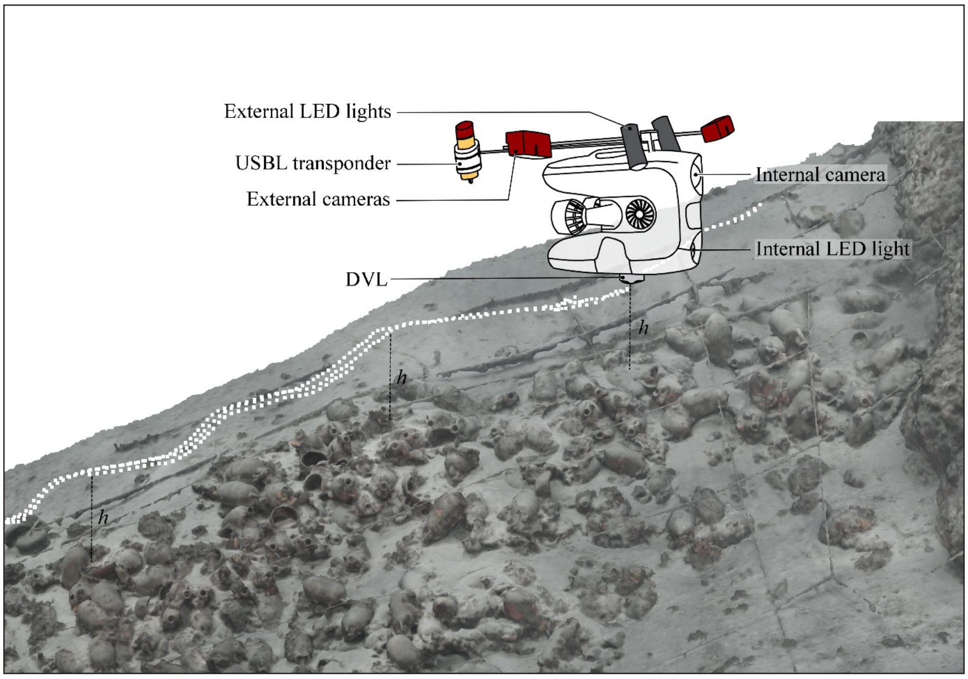

Figure 5 The underwater drone's trajectories over the wreck site. The white dashed line shows the path of the vehicle, which follows the terrain of the site, while keeping a constant altitude ***h*** thanks to the DVL sensor. The dimensions of the robot with respect to the wreck site are distorted for visualization purposes.

whole mission, which is particularly advantageous for a photogrammetric survey of a wreck situated on a sloping seabed with depth variations over 10 meters.

The underwater drone completed a full site coverage photogrammetric mission within a 30 minutes (recording time) dive (Figure 6). The GoPro cameras were scheduled to start recording simultaneously with the drone's camera, so that all video recordings could be synchronized at the data processing phase. The vehicle's battery life ranges from 2 to 5 hours depending on the task. For this wreck's survey, a 60% of battery was used, given a comfortable launch and recovery process and no underwater currents.

Another aspect of turning the photogrammetric mission into semi-autonomous mode was the implementation of a Visual Simultaneous Localization and Mapping (VSLAM) algorithm, using the footage from the underwater drone's internal camera as input. The ORB-SLAM3 algorithm, developed by Campos et al. (2021), was applied to provide the camera transects, while at the same time create and update an incremental 3D point cloud (Figure 7). Although using data from only one camera was not sufficient for a full control of the site's coverage, the algorithm's performance did offer valuable information on the quality of the visual data collected on site. The quality parameters are the coverage of the surveyed area, the distance from the camera to the target underwater scene, as well as the overlap of the consecutive ROV transects. In this way, besides the manual piloting of the underwater vehicle, the operator's perception was significantly increased.

3.1.3 Processing & Results

The 30-minute video recordings from the three cameras were converted into 6,500 frames using the open-source library ffmpeg (Tomar, 2006). The synchronization of the three cameras was approximate and was estimated by the internal clock of each camera. The IMU data from the underwater drone were corresponded to the frames of the drone's internal camera. The navigational data were then synchronized and assigned to the IMU data. Given the assumption that all three cameras were moving as a rigid body in 3D space, the same navigational data were assigned to the GoPro dataset at the first processing step and in order to speed up image alignment.

The Structure-from-Motion software Agisoft Metashape (Agisoft, 2024) was used for the photogrammetric processing. Two separate image groups (chunks) were created, one for the drone's camera and one for the GoPro stereo rig, and processed separately for the orientation of image frames of each chunk. The camera calibration results were also imported for the three cameras and taken into account during the alignment process. Next, five characteristic features (markers) distributed along the shipwreck, were tagged on images of both chunks, for the chunks to be aligned and merged. In this step, the navigational data that were assigned to the GoPro data were disregarded. Finally, all images of the entire dataset of the trifocal camera system of the underwater drone were oriented after a final bundle adjustment, and georeferenced thanks to the navigational data of the drone's camera. The final root mean square (RMS) error (in X, Y, Z) resulted as 0.04 m. A Multi-View-Stereo (MVS) step was then executed for

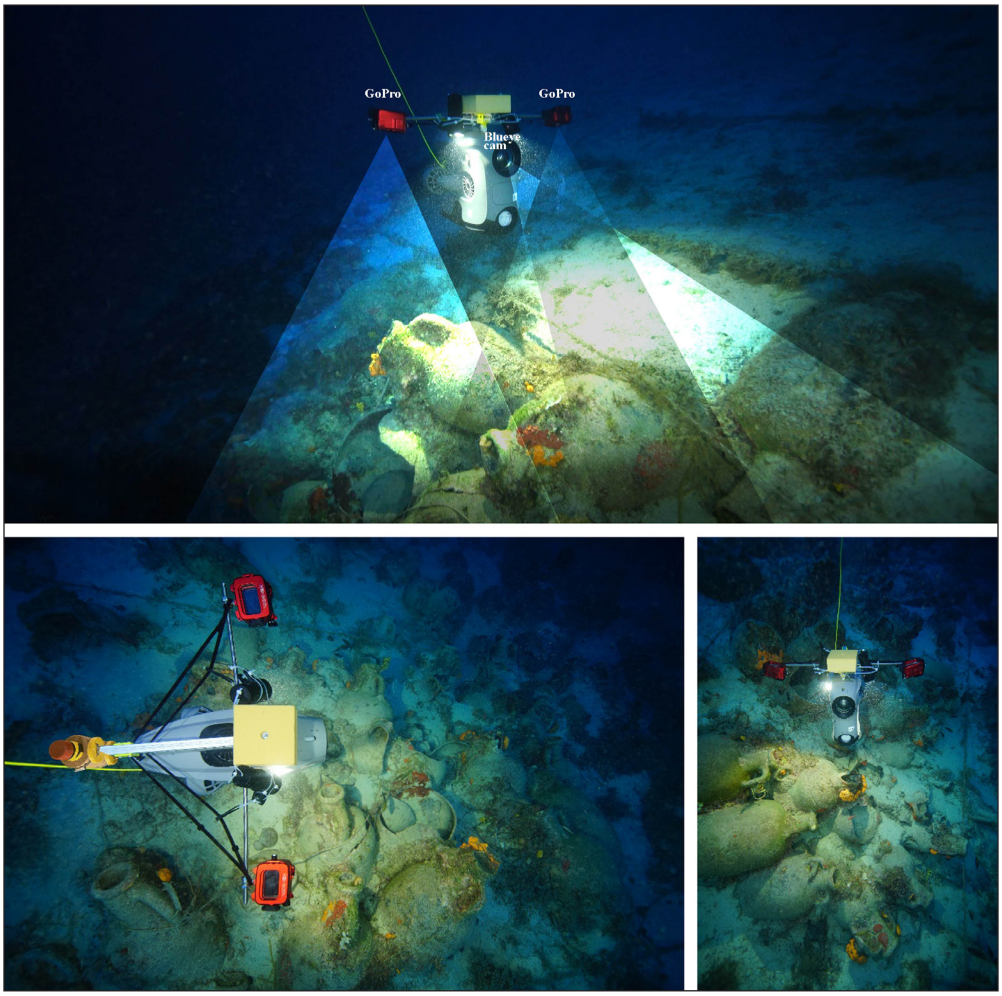

Figure 6 Up: The field of view of the three cameras of the photogrammetric setup. Down: Snapshots from the photogrammetric recording of the byzantine wreck by the underwater drone.

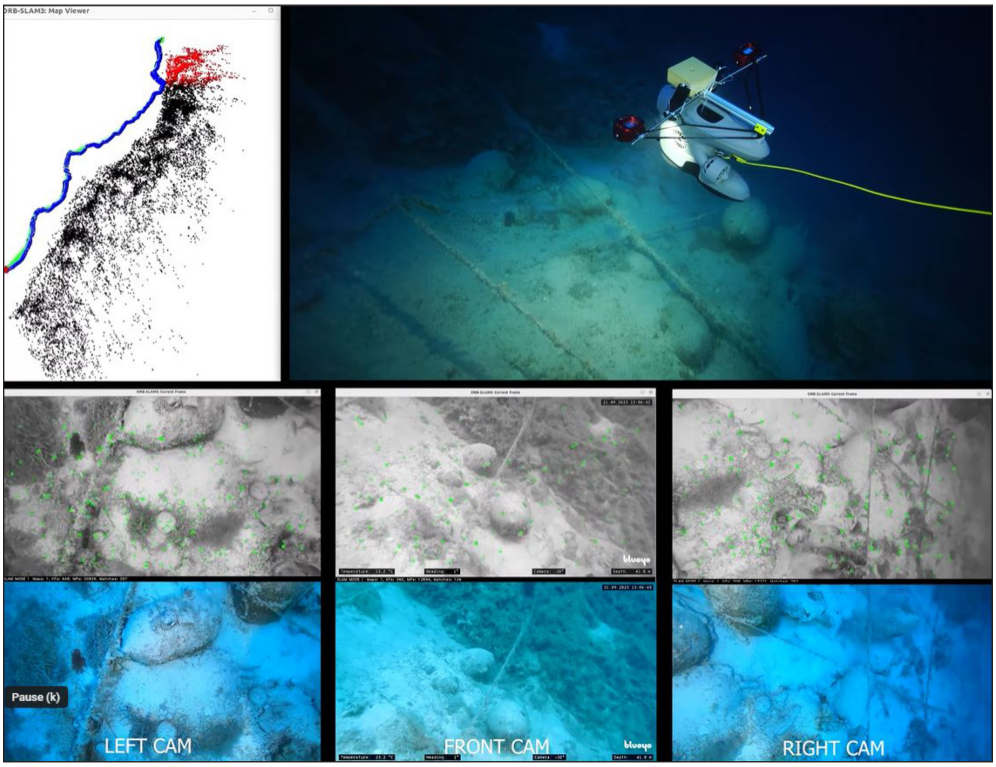

Figure 7 Up: Real-time map creation of the wreck through ORB-SLAM3 implementation. Down: Synchronized footage from the trifocal camera system of the underwater drone.

the computation of the shipwreck's dense point cloud, which was then triangulated for the creation of the final 3D model (Figure 8).

In order to compare the geometric accuracy of the underwater drone-based 3D reconstruction with the existing diver-based 3D reconstruction, a network of seven control points that were visible in both models was measured. The diver-based 3D model was aligned to the georeferenced drone-based model and the final RMS of the alignment yielded a result of 2 cm, demonstrating a robustness in the geometric accuracy of both 3D models. Regarding processing time, the drone-based reconstruction was three times faster than the diver-based one, mostly thanks to the existence of navigational data (combination of USBL and IMU data), which was used as initial values before image orientation. A downside of the ROV 3D model was the radiometric inconsistencies that were observed at the texturing and orthophotomosaicking step, mainly due to shadows or over-exposed areas occurred by the overlapping lights configuration. Despite the inconsistencies in lighting conditions, the geometric accuracy of the drone-based photogrammetric model was high, with the reprojection error remaining sub-pixel after the bundle adjustment. The main parameters that resulted in a low reprojection error were the optimal camera network (bundle adjustment leveraged triangulation from different viewpoints), the redundancy in homologous points within overlapping images (each estimated 3D point was projected in at least 5 images), the existence of calibration data (all cameras were pre-calibrated for the estimation of their intrinsic parameters), as well as the geometric constraints from the navigational data.

As far as the data acquisition methods are concerned, the underwater drone equipped with navigational sensors and underwater positioning system enabled a controlled navigation over the wreck site (control of the vehicle's transects and fixed diving altitude) as well as online data assessment thanks to the vehicle's position tracking and the implementation of VSLAM. On the other side, the high quality of the diver-based photogrammetric results can be largely attributed to the high quality of the underwater camera (Sony ILCE-7RM3), as well as the comfortably diveable depth and the relatively flat and simple terrain of the shipwreck. A favorable topography facilitates easier navigation and image acquisition, leading to the collection of adequate datasets and thereby accurate 3D reconstructions. However, the

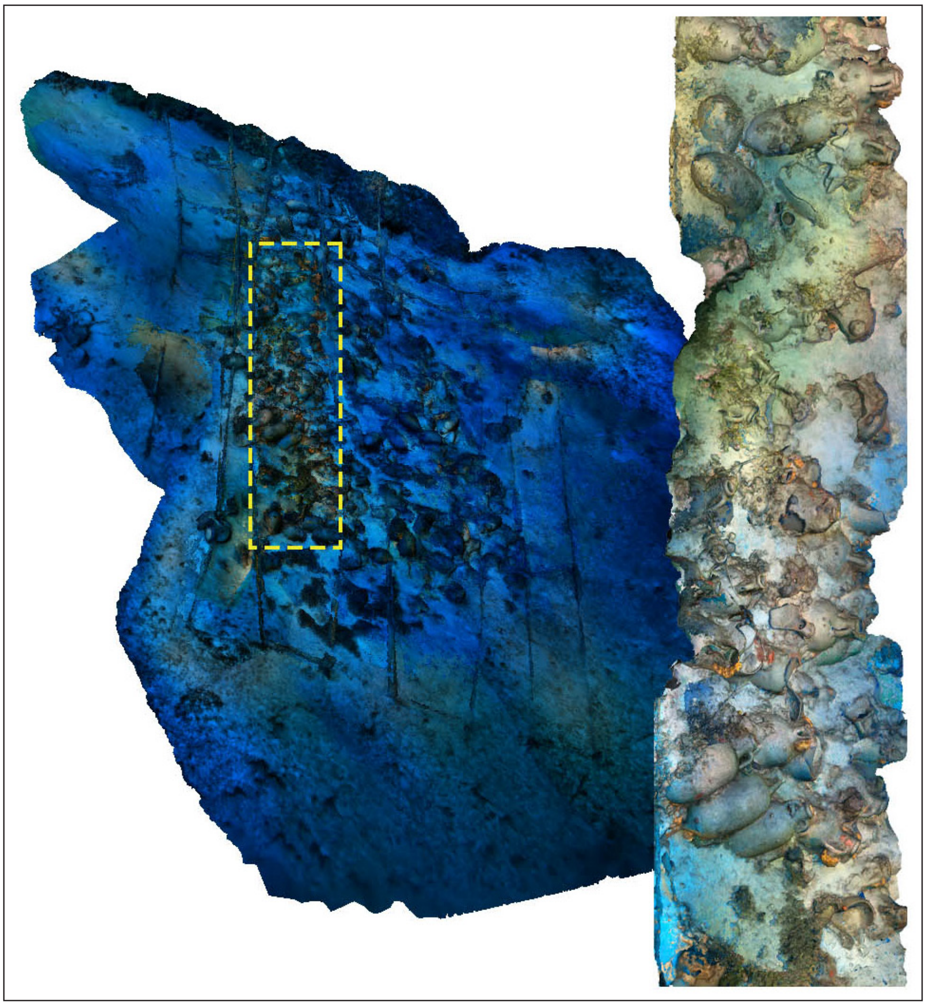

Figure 8 Results of the 3D reconstruction of the byzantine Late Roman wreck (in overview and detail).

complexity of an underwater photogrammetric mission would be significantly amplified if the object of interest was a shipwreck characterized by a more intricate 3D structure or extruding volumes, such as those found in modern shipwrecks.

3.2 SURVEYING THE ANCHORAGE SITE OF KAMARI

In the framework of the same underwater archaeological project in the Phournoi archipelago, the scientific team came across an extended distribution of anchors that date from the Roman period through to the Early Modern period at the bay of Kamari on the east coast of Phournoi main island (Campbell and Koutsouflakis, 2021). The underwater archaeological survey, primarily conducted by diving groups, located more than 20 anchors composed of iron, lead and stone (Figure 9), in an area of approximately 25,000 square meters and at a depth range from 10 to 55 meters, indicating the use of the bay of Kamari as a major anchorage. The integration of state-of-the-art marine remote sensing technology is anticipated to increase significantly the number of known anchors in the area. The finds also indicate the maritime connectivity between the entirety of the Mediterranean and reveal trade and technological changes along the different periods.

3.2.1 Equipment

The localization, mapping and documentation of the anchors' distribution was a collaborative effort between divers and an underwater drone. The drone that was deployed during the anchorage site documentation surveys was a DTX2 ROV (Figure 10), manufactured by Deep Trekker (Deep Trekker, 2024). The vehicle is depth-rated to 200 meters, weighs about 8.5 kg in air and has a nominal battery life up to 8 hours depending on the task. It carries an integrated forward-looking 4K camera with a 270° rotating head and dimmable LED lights up to 4000 lumens. The ROV comes with its own handheld controller with all control commands and a 7-inch viewing screen for real-time video and telemetry data (date, time, heading, pitch, roll, depth, camera tilt, battery percentage) display (Figure 10). Additionally, a MicronNav100 USBL system (Tritech, 2024) was mounted on top of the underwater drone, providing the vehicle's relative position in real-time, as well as a recorded tracking of its trajectories. The utilized underwater positioning system has a range accuracy of 20 cm and a bearing accuracy of 3°, while the software suite Seanet Pro was used for real-time visualization of the ROV's position, allowing for satellite and bathymetric maps overlays.

3.2.2 Data acquisition

Most of the anchors were located by divers during a systematic underwater survey at the bay of Kamari between 2016–2018. Each anchor was labeled, photographed and tagged with a buoy by the diving group that first encountered it (Figure 9). The ROV documentation of the anchorage site was done in 2018. The underwater drone DTX2 surveyed the area where the anchors were found in two different missions: a large-scale survey and a close-up photogrammetric documentation. The goal of the first mission was to re-locate the anchors that were first discovered by divers, and georeference them on a common map. For this purpose, the ROV proceeded to a flyover survey

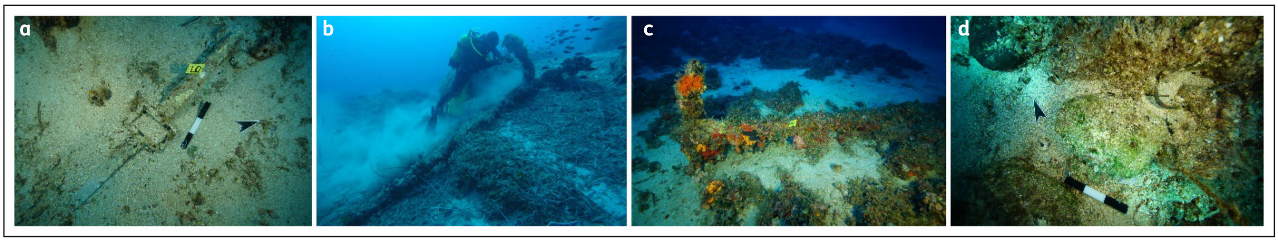

Figure 9 Four different anchor types found at the bay of Kamari. From left to right: **a)** lead stock of a Roman anchor, **b)** grapnel anchor of the Ottoman period, **c)** admiralty type anchor (18th–19th century), **d)** composite stone anchor (prehistoric).

Figure 10 The DTX2 underwater drone surveying the Kamari anchorage site.

at a fixed altitude of 5 meters above the sloping sea bottom and with its camera at a 45° forward-looking tilt, following the bathymetric contours from deep to shallow (Figure 11). For the ROV's path planning, we used an existing bathymetric model of 1 meter resolution of the entire gulf between the main island of Phournoi and Agios Minas island, available from a previous multibeam echosounder (MBES) survey conducted by the RPM Nautical Foundation in 2016 (Figure 11). During the first mission, 21 anchors were re-located and georeferenced thanks to the USBL system of the ROV.

The second mission of the underwater drone focused on the full photogrammetric documentation of a route that connected all the anchors, so that their relative positions could be visualized in a single orthophotomosaic. The results from the ROV's first mission (X, Y, depth for each find) were used for the path planning of the second mission. A down-looking GoPro camera was mounted on the ROV for the photogrammetric data acquisition and a set of 1-meter scalebars were placed next to five anchors for extra topographic constraints at the processing phase. The drone flew over the anchorage site on an approximate altitude of 2–3 meters from the seabed, covering an area of 5,000 square meters with a total video time of 20 minutes.

3.2.3 Processing & Results

Images extracted from the 20 minutes video was imported into Agisoft Metashape software on a rate of 0.5 frames per second, along with USBL data at the same rate. Due to the relatively low accuracy (>20 cm) of the USBL positioning system for photogrammetric processing, the accuracy of the camera poses was set to 50 cm, so that it could not affect the alignment of images significantly. The scalebars were used as extra constraints during the final bundle adjustment in order to increase the geometric accuracy of the photogrammetric model. A final georeferenced orthophotomosaic of 3.3 mm resolution was created for the Kamari anchorage site (Figure 12). An additional disparity map was generated for the typology of the anchors, their chronological identification (Archaic, Hellenistic, Roman, Byzantine etc.), their material and their depth (Figure 13).

4. DISCUSSION & FUTURE WORK

The successful application of two different mapping setups of underwater drones in the two case studies from the Phournoi archipelago demonstrates their capacity to deliver high-quality, comprehensive data, which can rival traditional diver-based data acquisition methods. One of the key advantages highlighted in this study is the capability of compact ROVs to perform semi-autonomous mapping missions, significantly enhancing both the efficiency and safety of underwater archaeological surveys. The integration of advanced multi-sensor technology, including optical, acoustical and navigational systems, not only enables real-time data processing and assessment, but also enhances the archaeologist's situational awareness, allowing for immediate on-site decision making. Implementing visual Simultaneous Localization and Mapping (VSLAM) techniques on the collected data in real time provides valuable feedback on the site coverage status, the quality of visual data (fail of loop closing for example can be indicative of featureless areas that require additional transects of the ROV and path re-planning), as well as the detection of obstacles. Such capabilities reduce the need for multiple site visits, thereby conserving resources and minimizing risks associated with human diving.

Although computer vision methods like VSLAM or Visual Odometry can provide real-time results, the underwater environment poses several challenges in real-time visual 3D reconstructions, often due to effects like rapid light attenuation, high turbidity or presence of floating particles (Gracias et al., 2017). Coupling visual with navigational sensors can address the loss of tracking

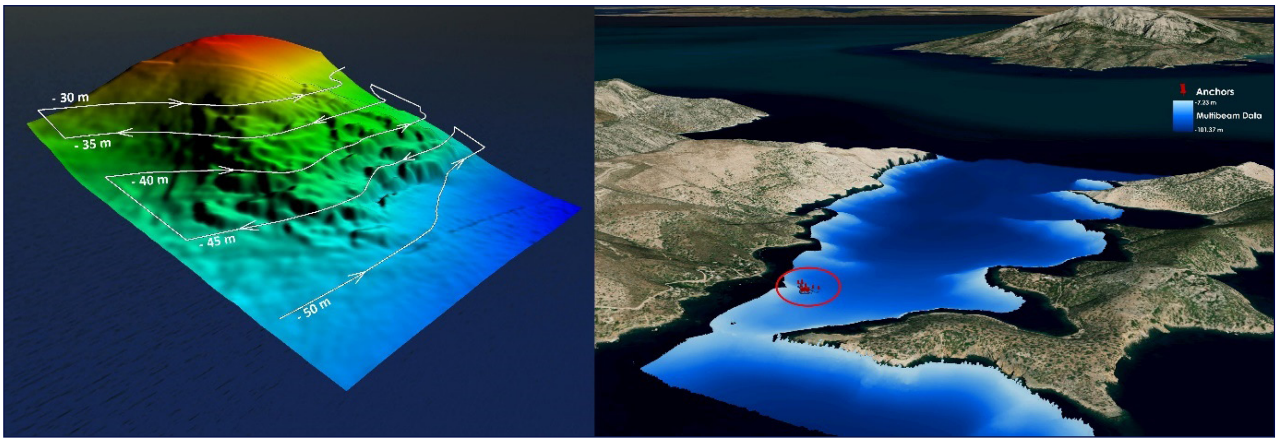

Figure 11 Left: the transects of the underwater drone following the bathymetry of the anchorage area, at a constant diving altitude of 5 meters above the seabed. Right: the localization of the 21 anchors off the shore of the bay of Kamari and the existing bathymetric model provided by RPM Nautical Foundation.

of the vehicle's position on one hand, but, on the other hand, it is important to acknowledge that high-accuracy underwater positioning systems come with a substantial increase in cost, which can be a limiting factor for many marine archaeological projects. Affordable underwater positioning systems have an increased risk of losing track of the vehicle or provide poor data. Therefore, a combination of IMU, USBL and VSLAM (proprioceptive

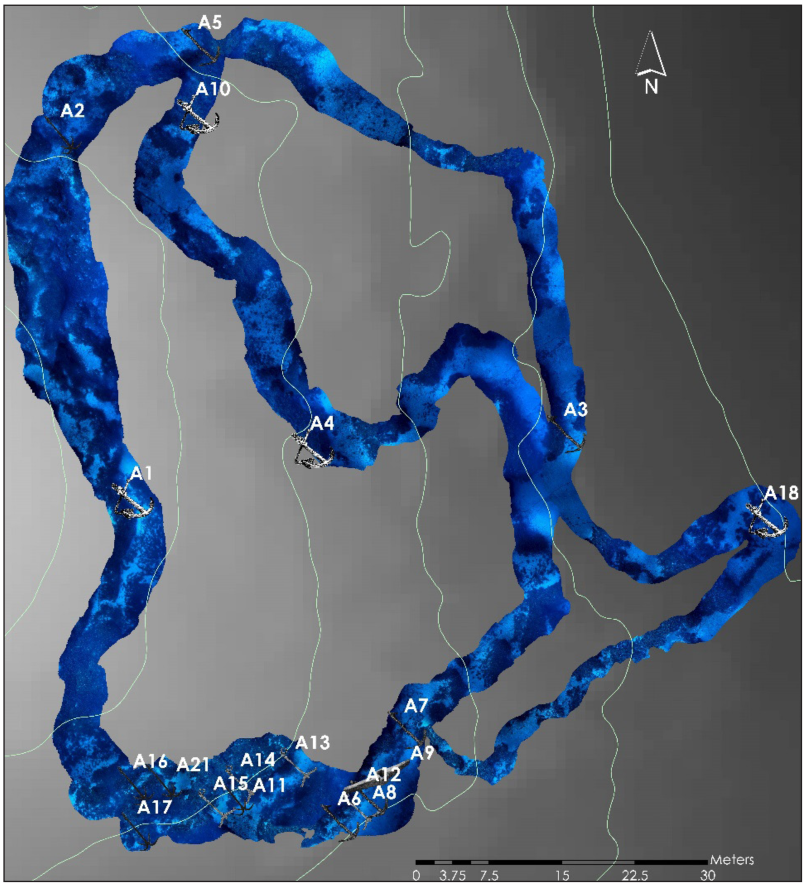

Figure 12 Georeferenced orthophotomosaic of the anchorage site of Kamari.

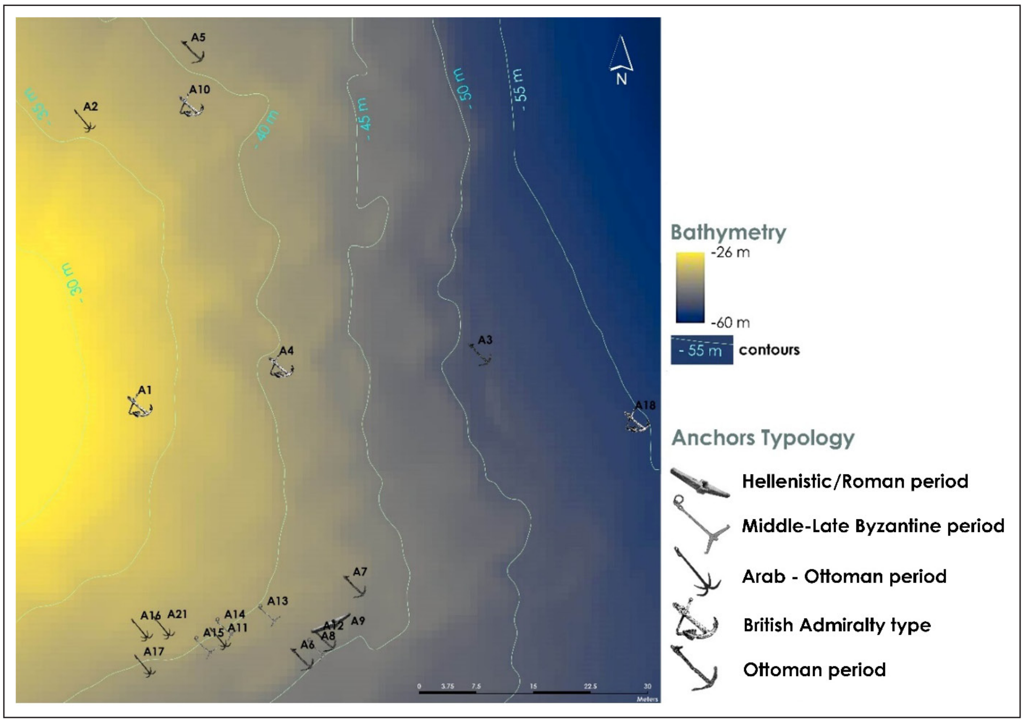

Figure 13 Anchors distribution map at the Kamari bay.

and exteroceptive sensors) is a way to mitigate this problem without extreme increase in cost.

Situational awareness is a growing area of research within mobile robotics in all environments (Bavle et al., 2023), critical for good decision making towards obtaining mission objectives. In the two case studies presented in this paper, we will argue that the benefits of applying underwater robotics to marine archaeological surveying and mapping beyond merely relieving a diver from dull, dirty or dangerous work are emerging. Multimodal perception enables the robot to offload some cognitive tasks from the archaeologist (e.g. maintaining constant altitude, consistent navigation along planned transects) to ensure sensor data coverage and quality. Using for instance VSLAM and georeferenced visualisations enables the archaeologist to consider and better comprehend the progress of a mission at different spatial and temporal scales during operations, improving the basis for replanning and decision making to achieve goals and objectives. Simultaneous access to the FOV of the different sensors used for data acquisition and a bird's-eye view of the whole site/area provides the archaeologist with an extended situational awareness not only relevant for navigation and operations but also a sense and understanding of underwater "landscape", surrounding environment and cultural contexts. This capability of zooming in and out between different levels of information gives a flexibility that is traditionally hard to obtain in traditional diver-based marine archaeology. As situational awareness in underwater robotics is highly contextual, determined by the properties of site, environment and mission objectives, archaeologists as domain experts can also provide valuable and unique input to further technological development. As technology end users with specific and often idiosyncratic objectives and requirements, marine archaeologists must dare to adopt and integrate enabling technologies like robotics and machine intelligence to reveal their full potential as tools for the discipline.

5. CONCLUSIONS

This paper underscores the considerable impact of modern, cost-effective, underwater robotic platforms, commonly known as underwater drones, on marine archaeological documentation. Alongside a literature review on the evolution of compact ROV platforms in this field, our study presents two real-world scenarios of integrated underwater photogrammetric surveys. The two case studies include detailed descriptions of sensor configuration and synchronization, data collection and real-time quality assessment, as well as data post-processing, final visualization, and the evaluation of results based on geometrical accuracy, site coverage, color consistency, and computational efficiency. As marine technology continues to advance, the incorporation of affordable marine robotic solutions into the underwater archaeological surveys like that of the Phournoi archipelago is poised to significantly enhance the exploration of uncharted areas, offering archaeologists a more comprehensive understanding of the maritime history of the region under investigation. We anticipate that the increasing availability of these accessible, compact, and robust underwater platforms will soon lead to a marked rise in the use of robotic 3D archaeological recording techniques.

ACKNOWLEDGEMENTS

The authors wish to thank the engineers of NTNU AUR-Lab for their help during the equipment preparations, as well as the researchers of KORSEAI Institute for their help during the on-site operations. Special acknowledgements are attributed to Dr. Kotaro Yamafune for providing the diver-based photogrammetric results. Special acknow-ledgements are attributed to Dr. Kotaro Yamafune for providing the diver-based photogrammetric results, and the RPM Nautical Foundation for providing the MBES data.

FUNDING INFORMATION

The Research Council of Norway (RCN) is acknowledged as the main sponsor of this work through the Autonomous Robots for Ocean Sustainability (AROS) project (RCN project number 304667) and the RCN-funded Center of Excellence, Autonomous Marine Operations and System (AMOS) (RCN project number 223254).

COMPETING INTERESTS

The authors have no competing interests to declare.

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TO CITE THIS ARTICLE:
Diamanti, E, Ødegård, Ø, Mentogiannis, V and Koutsouflakis, G. 2025. Underwater Drones as a Low-Cost, yet Powerful Tool for Underwater Archaeological Mapping: Case Studies from the Mediterranean. *Journal of Computer Applications in Archaeology,* 8(1): 10–24. DOI: https://doi.org/10.5334/jcaa.184

Submitted: 07 November 2024 **Accepted:** 19 November 2024 **Published:** 24 January 2025