

Return to Antikythera: Multi-session SLAM Based AUV Mapping of a First Century B.C. Wreck Site

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Abstract This paper describes an expedition to map a first century B.C. ship wreck off the coast of the Greek island of Antikythera using an Autonomous Underwater Vehicle (AUV) equipped with a high-resolution stereo imaging system. The wreck, first discovered in 1900, has yielded a wealth of important historical artefacts from two previous interventions, including the renowned Antikythera mechanism. The deployments described in this paper aimed to map the current state of the wreck site prior to further excavation. Over the course of 10 days of operation, the AUV completed multiple dives over the main wreck site and other nearby targets of interest. This paper describes the motivation for returning to the wreck and producing a detailed map, gives an overview of the techniques used for multi-session Simultaneous Localisation and Mapping (SLAM) to stitch data from two dives into a single, composite map of the site and presents preliminary results of the mapping exercise.

1 Introduction

In September 2014 an expedition was mounted to revisit the site of a first century BC shipwreck off the coast of the Greek island of Antikythera. The project began in 2013 with multibeam mapping and diver-based search of the site of the Antikythera shipwreck in preparation for further excavation. The objective of this second phase of the project was to produce a high-resolution, 3D map of the site using the Autonomous Underwater Vehicle (AUV) Sirius operated by the University of Sydney's Australian

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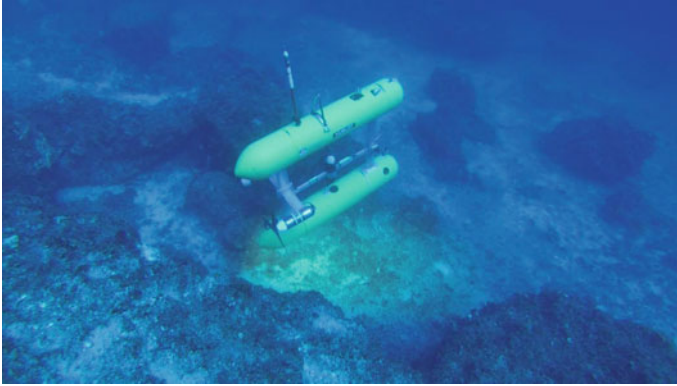


Fig. 1 The AUV Sirius conducting surveys over the wreck site on the coast of Antikythera, Greece. This frame, extracted from a video (<http://tinyurl.com/q7erkcv>) of the vehicle surveying the wreck, shows the footprint of the strobe on the seafloor as it travels *down* the slope *above* the wreck site (credit: Phil Short)

Centre for Field Robotics (ACFR). Figure 1 shows the vehicle at work during one of the deployments over the wreck site.

This paper outlines the AUV based mapping of the site. We describe the technical challenges that were addressed in order to facilitate this work and examine the rationale for preliminary mapping of the site, showing how robotic systems are well suited to the task of collecting data that can facilitate the documentation of the site as a historical record prior to the commencement of excavation. We also present preliminary outcomes of the surveys and examine how the resulting maps were used to facilitate subsequent diving operations.

The remainder of this paper is organised as follows. Section 2 provides background and an overview of the historical significance of the wreck site while Sect. 3 describes the tools used to deliver geo-referenced benthic imagery and associated data products. Section 4 presents results of the surveys conducted over a 10 day period during the 2014 field season and Sect. 5 presents concluding remarks and future directions for this project.

2 The Antikythera Wreck

The Antikythera Shipwreck (circa 60–80 B.C.) is one of the richest ancient wrecks ever discovered [1]. Greek sponge divers located the wreck on a rocky shelf at the base of a cliff in a depth of approximately 55 m of water on the NE coast of the island of Antikythera in 1900. They spent a year salvaging its treasures, with the help of the Hellenic Navy, in the process recovering hundred of works of art including bronze and marble statues that now fill galleries at the National Archaeological Museum

in Athens. The wreck also yielded the Antikythera Mechanism, a geared device designed to calculate and display celestial information, including phases of the sun and a luni-solar calendar [2]. This mechanism has fascinated historians for the quality of the workmanship and the sophistication of the mechanism design which had to capture the retro-grade motion of the planets and sun resulting from the fact that the earth was considered to be the centre of the solar system at the time. Numerous projects have sought to reproduce the workings of the mechanism over the years [3, 4] to get a better understanding of this previously unknown mechanical system, which has been described as one of the first known examples of an analog computer.

Undersea explorer Jacques Cousteau and the Calypso crew worked at the Antikythera wreck site for several weeks in 1976, with the approval of the Ministry of Culture. Cousteau and his team recovered numerous artefacts while documenting their excavation as part of a television program following their expedition. As part of their work, the team dredged a section of the wreck to reveal more artefacts for the cameras.

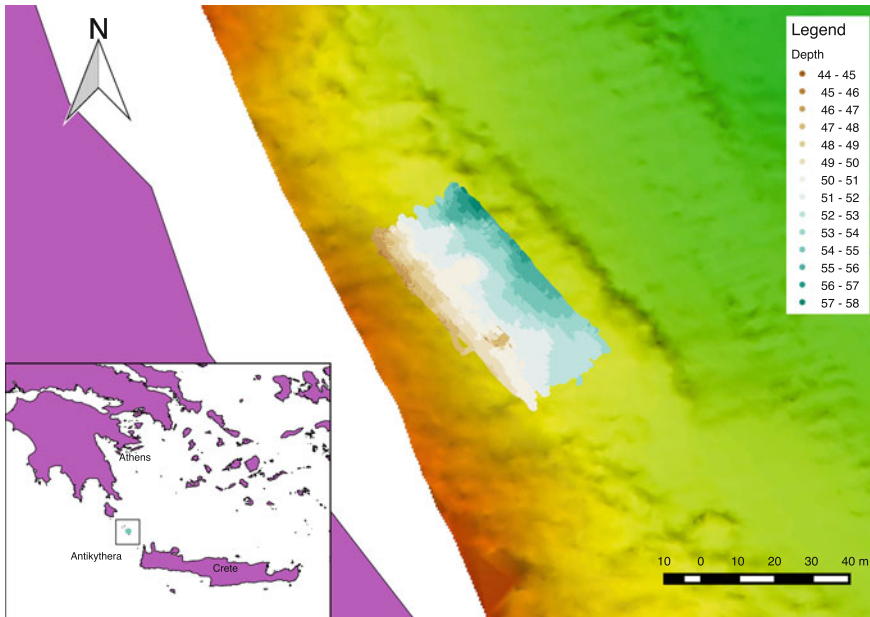


Fig. 2 The location of the AUV based visual survey of the Antikythera wreck. The small island of Antikythera is located between the larger islands of Crete to the SW and Kythira to the NW. The AUV mission covered an area of approximately 70 m × 50 m at depths of 44–58 m on a shelf adjacent to the coastline. The vehicle’s estimated trajectory during two dives is shown with the location of each pose coloured by seafloor depth based on the vehicle’s depth sensor and altimeter measurements. The underlying bathymetric map of the site was produced using ship-borne multibeam collected during the 2013 field season

In 2013 a team from the Hellenic Ministry of Culture and Sports, the Ephorate of Underwater Antiquities and the Woods Hole Oceanographic Institution (WHOI) returned to Antikythera to survey the island and map the site of the wreck. As part of the expedition, divers conducted visual census of the site, in the process uncovering what was thought to be a second, previously unknown wreck to the south of the main wreck site. Figure 2 shows the location of the island in the Greek archipelago and features a portion of the ship-borne multibeam map and the path of the AUV used in this work to map the site. The decision was made to seek funding to support further fieldwork in order to produce detailed maps of the wreck site and to conduct excavation operations.

3 Wreck Survey Tools and Design

3.1 *Autonomous Underwater Vehicles*

AUVs have recently begun to play an increasingly important role in modern oceanographic research. Tasks for which AUVs are suited range from deep water exploration [5, 6] and monitoring of oceanographic phenomena to high-resolution optical imaging [7–10] and multibeam surveying in deepwater applications [11, 12]. AUVs are also being used to support a number of archaeological operations. Recent work has demonstrated how AUVs equipped with imaging and multibeam systems can be used to document wreck sites [13–15]. High-resolution imaging missions such as that used by this work are typically flown at a relatively low altitude above the seafloor, requiring hundreds or thousands of images to cover a site.

Our recent work has demonstrated the ability of benthic imaging AUVs to rapidly and cost-effectively deliver high-resolution, accurately geo-referenced, and precisely targeted optical and acoustic imagery [16–18]. We employ a visual Simultaneous Localisation and Mapping (SLAM) algorithm to identify the loop closures and to refine the vehicle’s estimated trajectory [19]. The estimated vehicle trajectory is then used to generate a detailed, three dimensional, texture-mapped surface model of the survey site [20].

3.2 *The Sirius AUV*

The primary requirement of this expedition was to produce a high-resolution, 3D model of the wreck site prior to the diving operations. We operate an ocean going AUV called *Sirius* capable of undertaking the required high-resolution, geo-referenced survey work [18]. This platform is a modified version of a mid-size robotic vehicle called *SeaBED* built at the Woods Hole Oceanographic Institution [21]. This class of AUV has been designed specifically for relatively low speed, high-resolution imaging and is passively stable in pitch and roll. The submersible is equipped with

a full suite of oceanographic sensors, including a high-resolution stereo imaging system (2 x Prosilica GC1380 cameras) with synchronised LED strobes, multibeam sonar, CTD, fluorometers and a comprehensive navigation suite [18].

3.2.1 Realtime Navigation

Our vehicle is equipped with a single band GPS receiver, a Doppler velocity log (DVL), a depth sensor, a magnetic compass with integrated roll and pitch sensors and an Ultra Short Baseline (USBL) Acoustic positioning system deployed by the support vessel. The observations of velocity provided by the DVL are fused with observations of attitude and depth using an Extended Kalman Filter [22]. The USBL observations, consisting of range and bearing measurements between the vessel and the vehicle, are collected on the surface and are sent together with the ship's position and attitude to the vehicle using the USBL's acoustic modem. These observations are received by the vehicle and fused into its onboard navigation filter. The heading reference used is sensitive to the magnetic signature of the rest of the vehicle [23], which can introduce distortions of several degrees into the heading estimate. Even when soft and hard iron calibration are performed, persistent heading-dependent errors of $O(1 \text{ deg})$ are possible. While adequate to perform linear transects or broader acoustic surveys (particularly when aided by acoustic positioning from LBL or USBL), the magnitude of these errors makes an intended dense 'mow the lawn' pattern with reciprocal, closely spaced, parallel tracklines difficult for the vehicle to complete. We have recently shown that it is possible to derive a heading-dependent correction to the magnetic compass using visual data and that this correction can enable a compass-equipped AUV to perform dense visual coverage of a seafloor patch of approximately $50 \text{ m} \times 75 \text{ m}$ with 50 parallel tracklines [24]. This has resulted in a navigation suite that is capable of meeting the requirements for full coverage survey with narrow track spacing.

3.3 Simultaneous Localisation and Mapping

In order to generate accurate models of the seafloor, it is important that the estimated vehicle trajectory is self-consistent with respect to the data being collected during each survey. We employ visual Simultaneous Localisation and Mapping (SLAM) to optimally fuse uncertain navigation estimates and visual observations [19, 25]. This allows us to further refine the estimated vehicle trajectory using the environmental data, including high-resolution imagery and multibeam sonar, collected during the survey. Stereo cameras are capable of high-resolution observations such that if the same scene is imaged from different positions, it is possible to determine the relative poses of the cameras using observations of features in the scene. These constraints are fused into the vehicle's navigation solution to further refine the vehicle's estimated trajectory.

Recently, a number of authors have considered the problem of multi-session SLAM, in which data from multiple deployments of one or more robotic platforms must be registered and fused together to produce a final map of the environment. This has included multi-session SLAM work in terrestrial [26, 27], aerial [28] and underwater [29, 30] environments. In cases where there is little change in the environment between deployments, it may be sufficient to simply re-initialise the estimated vehicle location and to match features across deployments to allow this data to be fused. In other cases in which there are more significant changes, such as one might expect from deployments in different seasons or over longer periods of time, more sophisticated methods have been proposed for robust place recognition [31].

In the case considered here, deployments were completed within a period of approximately 10 days and results are shown from two dives completed two days apart. Given the small amount of time between dives, standard feature-based visual recognition was sufficient to identify matching features between subsequent dives using techniques similar to those reported in [17].

3.4 Seafloor 3D Reconstruction and Visualization

Although SLAM recovers consistent estimates of the vehicle trajectory, the estimated vehicle poses themselves do not provide a representation of the environment suitable for human interpretation. A typical dive will yield several thousand geo-referenced overlapping stereo pairs. While useful in themselves, single images make it difficult to appreciate spatial features and patterns at larger scales. We have developed a suite of tools to combine the SLAM trajectory estimates with the stereo image pairs to generate 3D meshes and place them in a common reference frame [20]. These meshes are generated once the vehicle is recovered and take on the order of the same amount of time to compute as the length of the dive allowing dive outcomes to be examined while still at a site. The resulting composite mesh allows a user to quickly and easily interact with the data while choosing the scale and viewpoint suitable for the investigation. In contrast to more conventional photomosaicking approaches [32, 33], the full three dimensional spatial relationships within the data are preserved and users can move from a high level view of the environment down to very detailed investigation of individual images and features of interest within them. This is a useful data exploration tool for the end user to examine the survey area.

3.5 Survey Design

As outlined above, the objective of the missions reported on in this paper were to produce a full coverage, texture-mapped 3D map of the wreck site using the vehicle's high-resolution stereo imaging system. Bathymetric data from the 2013 campaign and markers surveyed in by divers provided information with which to plan the dives

over the wreck site. The AUV, which is capable of hovering and turning on the spot using a pair of lateral thrusters at the rear of the vehicle, was programmed with a mission consisting of four legs across the site spaced approximately 12.5 m apart followed by a dense grid survey consisting of 51 parallel tracklines, each 70 m long, spaced by 1.0 m covering the site. The initial track lines serve as candidate across-track loop closure points while the trackline spacing of the dense grid is selected to yield sufficient overlap between adjacent legs to ensure along-track loop closures are also found.

4 Results

During the Antikythera dives presented here, the vehicle completed 2 full coverage dives over the site from which data was used to generate the final site maps. The estimated pose of each stereo pair is plotted in Fig. 2, with the symbols coloured by estimated seafloor depth based on combining the vehicle's depth sensor and altimeter measurements. The underlying multibeam map shows the complex structure of the site and the proximity of the dives to the coastline.

For this particular survey, we employed two dives completed over the main wreck site. The site is at the base of a steep cliff in approximately 50 m of water, extending out across a 60 m wide shelf which then drops down to 75 m of water depth. There are a number of large boulders in the middle of the site and the north west side of the survey area comprised a dense boulder field at the base of a cliff, presenting a challenging environment in which to conduct near-bottom survey operations. During the first deployment the vehicle was programmed to maintain an altitude of 2 m above the seafloor while travelling at a speed of 0.5 m/s and capturing stereo images at 1 Hz. With a field of view of approximately 42×34 degrees, this yields an image footprint of approximately 1.5×1.2 m and ensures an overlap of approximately $2/3$ between frames along track and $1/3$ across track.

The rough terrain and large obstacles caused the vehicle's altitude controller to struggle to maintain a constant height above the seafloor throughout the dive, despite it slowing down as forward obstacles were approached. This resulted in gaps in some portions of the vehicle's trajectory as a lower altitude results in a narrower image footprint on the ground. The tuning of the altitude controller was adjusted and subsequent missions were flown at a higher altitude of 3 m to ensure full coverage of the survey site, thereby increasing the footprint of the images and facilitating obstacle avoidance over the rough terrain and large boulders in the survey site. The image framerate was also increased to 1.5 Hz to increase the along track overlap between images. This increased altitude and imaging rate increased the overlap both along and across track, resulting in significantly more loop closures as shown below.

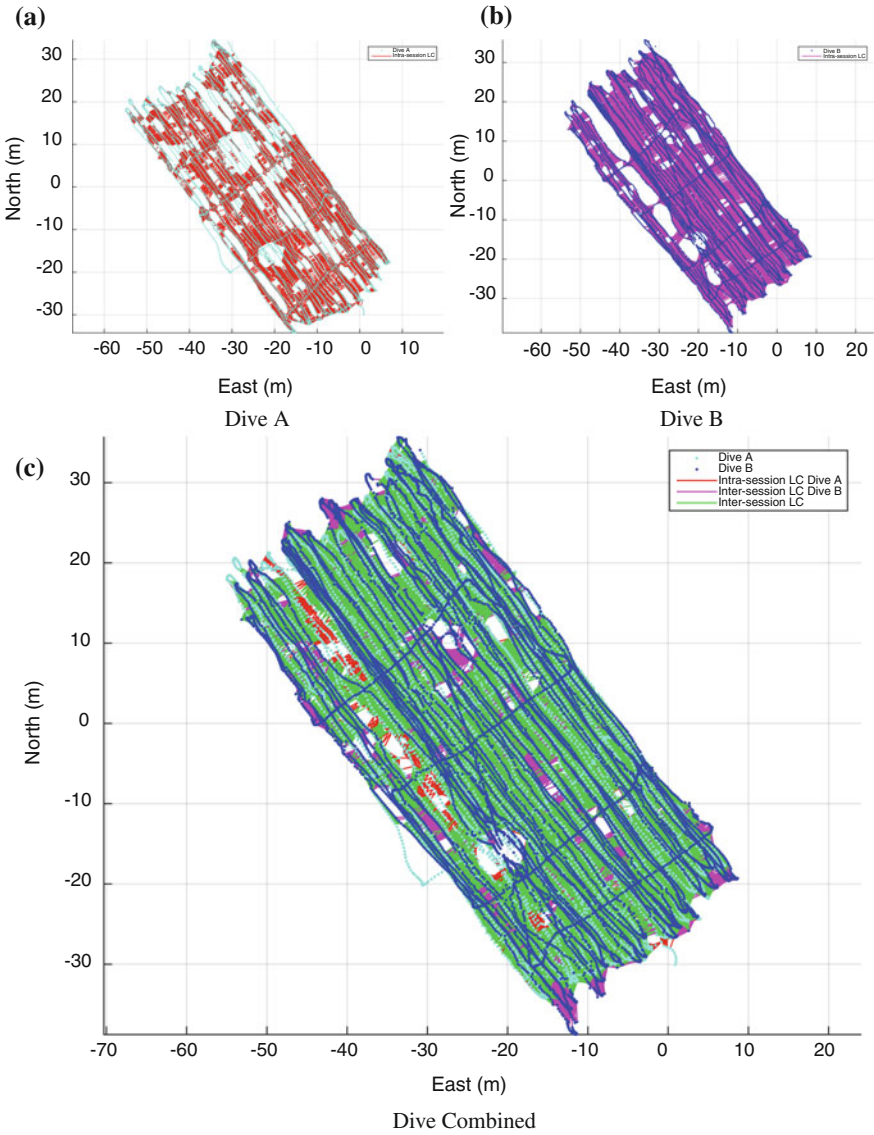


Fig. 3 Multi-session SLAM result. **a** The Dive A solution, showing estimated camera locations and intra-session loop closures **b** Dive B solution, showing estimated camera locations and intra-session loop closures **c** Multi-session SLAM solution. Loop closure links are shown in *red* and *magenta* for intra-session loop-closures and in *green* for inter-session links. Over 340,000 loop closures were identified in total to produce this model

4.1 Multi-session SLAM

In order to produce a complete map of the area, the two surveys were combined using our multi-session SLAM tool. Each dive is initialised independently using the GPS and USBL data available to the vehicle. This is sufficient to georeference the mission data to within 2–3 m between dives. However, finescale registration requires matching features between dives to co-register the dives. This step is performed automatically by matching SIFT features in a manner identical to that used for identifying loop closures from within a single dive. Figure 3 shows the result of the use of multi-session SLAM to fuse data from two dives completed over the wreck site. The figure shows the estimated vehicle trajectories for the two dives, as well as the combined estimates of the two dives. We use the terminology adopted from [27], designating loop closures from a single dive as ‘intra-session’ loop closures and loop closures between dives as ‘inter-session’ loop closures.

Table 1 presents statistics of the two dives, including the dive times, number of individual stereo pairs and loop closures identified within and between dives. As can be seen, both dives took just under two hours to complete. The second dive, completed at a higher altitude and with a higher framerate, resulted in significantly more loop closures and, as can be seen, there are a large number of inter-session loop closures that serve to co-register the dives.

4.2 Three Dimensional Surface Model

Sample reconstructions produced using data collected during the AUV surveys conducted on the Antikythera site are shown in Fig. 4. While it is possible to examine the individual images that were used to generate these 3D surface models, the spatial structure of the site is more evident in the composite mesh. Figure 5 shows examples of details from the 3D surface model, highlighting historical artefacts of interest that were visible in the model.

Table 1 Multi-session Dive statistics

Mission time Dive A	1:49
Mission time Dive B	1:57
Dive A stereo pairs	6,565
Dive B stereo pairs	10,554
Total stereo pairs	17,119
Dive A intra-session loop closures	32,098
Dive B intra-session loop closures	162,778
Inter-session loop closures	149,386
Total loop closures	344,262

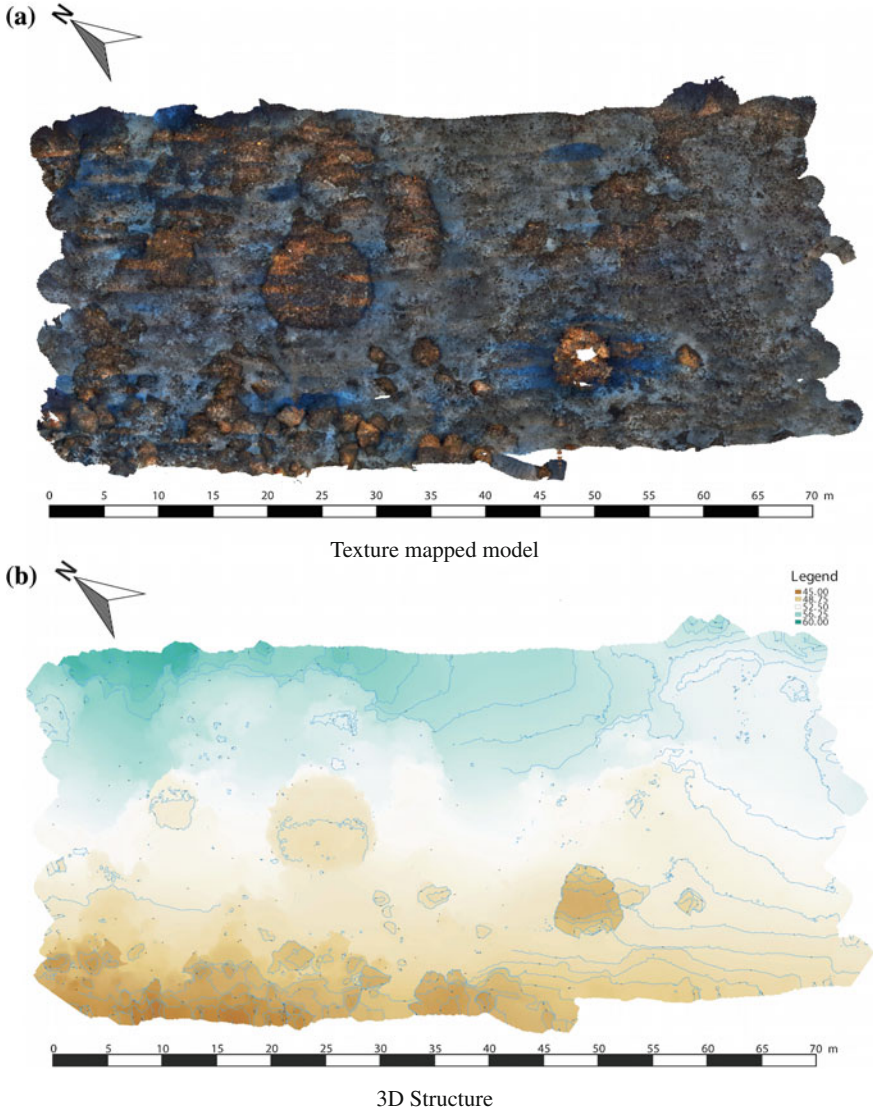


Fig. 4 **a** The final texture mapped model of the site is generated by blending the imagery collected by the vehicle to produce a seamless texturemap which is draped over the 3D surface model. **b** The underlying 3D structure of the site reveals the base of the cliff to the SW and several large boulders around which artefacts, including the ship’s anchor, amphorae, pottery sherds and a 2 m long bronze spear, were located

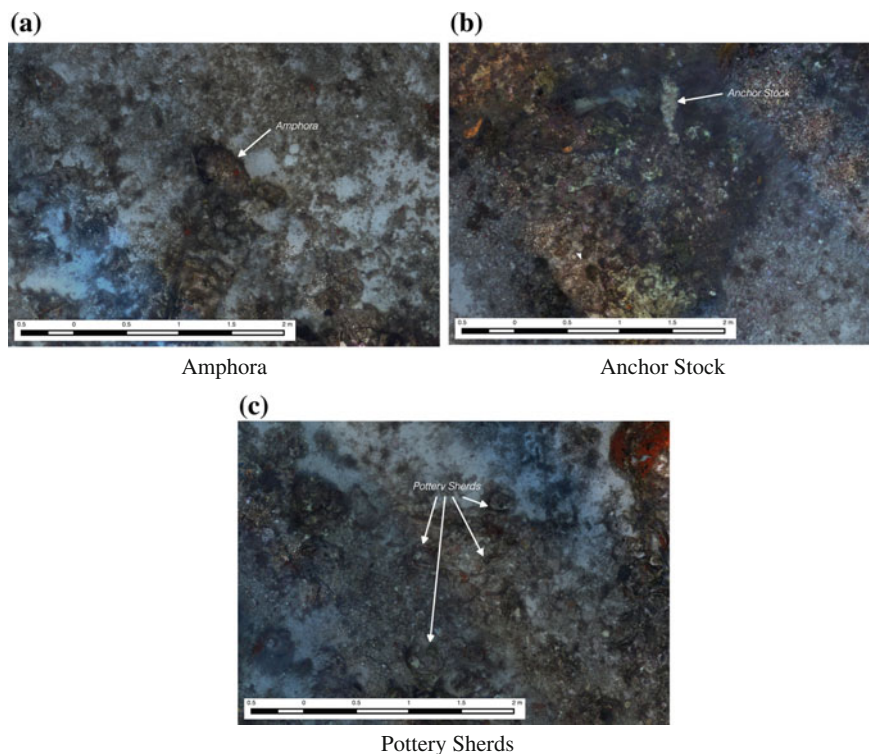


Fig. 5 Examples of the detail of the 3D texture mapped surface model including **a** an Amphora, **b** one of the ship's lead anchor stocks and **c** pottery sherds, possibly left after the Cousteau excavation in 1976

4.3 Diver Aiding

Many remaining artefacts from the wreck are thought to be buried under sediment. As part of the 2014 expedition, divers conducted surveys of the site using underwater metal detectors to identify buried metal objects. Figure 6 shows the project team (a) using a 3 m × 2 m printout of the AUV derived maps to plan dives and (b) on-site with the metal detectors and recovered artefacts. They used laminated copies of the AUV generated maps to help with in situ identification of the location of potential excavation sites. During the 2014 field season, the vessel's anchor stock, a number of small artefacts and a 2 m bronze spear were recovered.

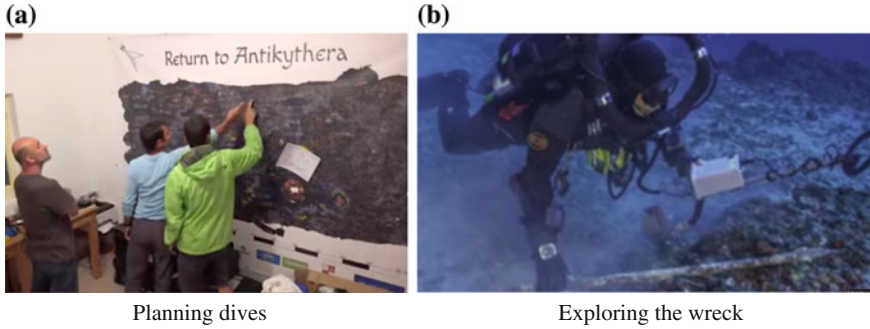


Fig. 6 **a** The AUV based maps were used to plan dives using both a large, wall-mounted printout as well as GIS systems. **b** Divers carried small versions of the map to orient themselves on the site. They conducted a visual census and used metal detectors to search for buried artefacts

5 Conclusions and Future Work

This paper has described an expedition to document the site of a first century B.C. wreck on the coast of the island of Antikythera, Greece. We conducted multiple dives using an AUV to collect tens of thousands of stereo images with which to build a detailed model of the wreck site prior to the commencement of excavation. A multi-session SLAM technique was used to fuse data from multiple dives into a single, detailed model of the site. The resulting maps were used by divers to help with in situ survey of the site and to document the resulting finds.

The ability to quickly and automatically generate detailed, texture-mapped 3D models of the site were instrumental in assessing the quality of the maps while in the field and in facilitating subsequent diving operations. Combining data from multiple dives allowed us to generate a full coverage site map. We were also able to update the vehicle's obstacle avoidance behaviour and mission parameters, including standoff altitude and imaging rate, to ensure full coverage and to avoid some of the more challenging areas of the terrain.

While this first year of AUV surveys was a success, with the production of a detailed site map and exploration of a number of other areas of interest, adverse weather limited the number of days for the archaeological dive team. However, the surveying they were able to complete revealed prospective targets both within the extent of the area surveyed by the AUV as well as immediately to the south. A potential second wreck site was also confirmed a few hundred metres to the south. Future expeditions will seek to map areas to the south of the mapped area and to conduct a more systematic metal detection survey to help identify prospective excavation targets. More extensive excavation operations are also planned for the 2015 field season.

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