Robotic Tools for Deep Water Archaeology: Surveying an Ancient Shipwreck with an Autonomous Underwater Vehicle

Brian Bingham
Department of Mechanical Engineering, University of Hawaii at Manoa, Honolulu, Hawaii 96822
e-mail: bsb@hawaii.edu

Brendan Foley, Hanumant Singh, and Richard Camilli
Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543
e-mail: bfoley@whoi.edu, hsingh@whoi.edu, rcamilli@whoi.edu

Katerina Delaporta
Hellenic Ministry of Culture, 105 55 Athens, Greece
e-mail: katerinadellaporta@yahoo.com

Ryan Eustice
Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, Michigan 48109
e-mail: eustice@umich.edu

Angelos Mallios
Department of Computer Engineering, University of Girona, CP 17071 Girona, Spain
e-mail: amallios@eia.udg.edu

David Mindell
Program in Science, Technology, and Society, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
e-mail: mindell@mit.edu

Christopher Roman
Department of Oceanography, University of Rhode Island, Narragansett, Rhode Island 02882
e-mail: cnr@gso.uri.edu

Dimitris Sakellariou
Institute of Oceanography, Hellenic Centre for Marine Research, 190 13 Anavyssos, Greece
e-mail: sakell@ath.hcmr.gr

Received 16 January 2010; accepted 2 May 2010

The goals of this article are twofold. First, we detail the operations and discuss the results of the 2005 Chios ancient shipwreck survey. This survey was conducted by an international team of engineers, archaeologists, and natural scientists off the Greek island of Chios in the northeastern Aegean Sea using an autonomous underwater vehicle (AUV) built specifically for high-resolution site inspection and characterization. Second, using the survey operations as context, we identify the specific challenges of adapting AUV technology for deep water archaeology and describe how our team addressed these challenges during the Chios expedition. After identifying the state of the art in robotic tools for deep water archaeology, we discuss opportunities in which new developments and research (e.g., AUV platforms, underwater imaging, remote sensing, and navigation techniques) will improve the rapid assessment of deep water archaeological sites. It is our hope that by reporting on the Chios field expedition we can both describe the opportunities that AUVs bring to fine-resolution seafloor site surveys and elucidate future opportunities for collaborations between roboticists and ocean scientists.

1. INTRODUCTION

Deep water archaeology is a compelling context for demonstrating current capabilities and future needs of autonomous underwater vehicle (AUVs). The process of underwater archaeological investigation through remote sensing is typically a nested process including wide-area survey, target identification, detailed site investigation, and (possible) excavation (Mindell & Bingham, 2001). This article focuses on the role of autonomous platforms for detailed site characterization through simultaneous sonar

Published online in Wiley InterScience (www.interscience.wiley.com). • DOI: 10.1002/rob.20350

bathymetry, photomosaic, and in situ chemical characterization. Archaeological applications demand the utmost in accuracy and precision to create data products of sufficient resolution for detailed interpretation.

Why are archaeological expeditions so important in the history of underwater autonomous robotics? We propose two reasons: archaeological survey is a surrogate for other applications, and new technology has a particularly large and immediate impact on archaeological investigations. This new application of autonomous robotics is analogous to many other scientific, military, and industrial missions. In fact, deep water archaeology is an important surrogate for these complementary missions because of the stringent requirements for documentation accuracy. To be consistent with the standards of land archaeology, deep water methods must supply fine-resolution observations, requiring positioning precision on the order of 10 cm (Holt, 2003). At the same time, the size of typical ancient shipwreck sites is extremely small by oceanographic standards (100–1,000 m^2), requiring absolute precision to ensure site coverage as opposed to less-specific, broad-area assessment. Furthermore, because of the inherently destructive nature and high cost of excavation, scientists must use remote (robotic) means to understand and interpret these cultural remains. Consequently, each technical advance translates into better interpretation at less cost for the users. Increasingly AUVs provide an ideal platform for hosting these remote sensors and collecting coregistered, precisely navigated data for archaeological interpretation. These advances, which improve deep water archaeology, are readily applicable to other scientific, military, and industrial missions.

The second reason for early applications in archaeology is that new technologies have an immediate impact on the methods of archaeology, allowing the scientist to find new answers and ask new questions. Remotely operated vehicles (ROVs) have allowed archaeologists to locate and investigate deep water shipwrecks but, previous to these discoveries, many scientists opposed even looking in deep water, standing by the theory that the vast majority of shipwrecks would be found in shallow coastal waters thought to be most heavily traveled and posing the greatest risks to mariners. Deep water shipwrecks, however, have shown that ancient people did indeed navigate the open seas, venturing far from sight of land. In addition, shipwrecks in the deep ocean have been shown to have been well preserved compared with their coastal contemporaries (Sakellariou, Georgiou, Mallios, Kapsimalis, Kourkoumelis, et al., 2007).

2. BACKGROUND AND CLOSELY RELATED WORK

2.1. Robotic Tools for Deep Sea Science

There are a variety of methods to investigate deep ocean environments including towed systems, human occupied vehicles (HOVs), ROVs, and AUVs. Each of these systems has capabilities for various operating conditions and observation types, but for archaeological site characterization AUVs have particular advantages. Deep-tow systems require large support vessels and operate with limited survey speed and precision. The hydrodynamics and limited control make it difficult to maintain a fixed altitude and often require maintaining large distances from the seafloor in dynamic terrain. Furthermore, depending on water depth, turns can take many hours, decreasing the survey efficiency dramatically (Chance, Kleiner, & Northcutt, 2000). HOVs have been used for deep sea science since the 1960s. With limited bottom time, low speeds, and human pilots, these platforms are better suited for direct observation and sampling than for large-area, fine-resolution surveys. ROVs, using telepresent operators at the surface, eliminate the constraint on bottom time but require a dynamically positioned support ship, which can cost tens of thousands of dollars per day. Furthermore, because of their tethered configuration, executing structured surveys can be a painstaking process of moving the robot and the surface ship in concert, limiting the overall efficiency and effectiveness of ROV surveys. In contrast to ROVs, deep-tow systems, and human-occupied submersibles, AUVs can operate from modest support ships (or from shore) and can survey large areas of seafloor for 24–72 h without returning to the surface.

2.2. Deep Water Archaeology

The practice of deep water archaeology is defined by a set of methods based on using technology to investigate the seafloor rather than relying on SCUBA-equipped archaeologists. This process has been discussed in other articles (Church & Warren, 2002; Foley & Mindell, 2002; Mindell & Bingham, 2001; Singh, Adams, Foley, & Mindell, 2000) and is described in the context of the Chios project in the companion scientific publication (Foley, DellaPorta, Sakellariou, Bingham, Camilli, et al., 2009). As the role of AUVs in this process of inquiry continues to expand, scientists are realizing the potential to efficiently investigate shipwreck sites and develop high-resolution coregistered data products for documentation and interpretation in far less time than previously possible.

The imperative to investigate shipwrecks below diver depth [O(50 m)] stems from the new views of ancient cultures they present. Beyond easy salvage depth and wave-induced disruptions, deep near-shore waters hold vast numbers of shipwrecks containing well-preserved artifacts (Ballard, Hiebert, Coleman, Ward, Smith, et al., 2001; Ballard, McCann, Yoerger, Whitcomb, Mindell, et al., 2000; Ballard, Stager, Master, Yoerger, Mindell, et al., 2002; McCann & Freed, 1994). Historical data indicate that the seafloor far offshore contains 20%–23% of all wrecks (Foley et al., 2009). In certain locations, with conducive oceanographic and geological conditions, a "relic bottom" exists that encourages preservation of shipwreck sites for thousands of years, effectively producing a time capsule on the seafloor (Bascomb, 1976). Robotic technology is the only way to explore these important cultural remains.

2.2.1. The Role of Robotics in Deep Water Archaeology

In 1989 one of the first scientific uses of the then-new Jason ROV was the archaeological investigation of a fourth-century A.D. merchant ship at a depth of roughly 800 m. The vessel went down in the Mediterranean Sea, between Carthage and Rome (Ballard, 1993). Despite the proven utility of submersible technology used by deep ocean scientists since the late 1960s such as Alvin and ROVs used by military and industrial users for an equally long time, scientists on the 1989 expedition were concerned about performing archaeology solely via telepresence, without actually "being there." In the event, Jason performed admirably, and since then ROVs have become standard tools for a variety of underwater sciences. Jason is now in its second incarnation (Jason II was put into service in 2002) as part of the National Deep Submergence Facility supporting a wide variety of scientific endeavors from mapping hydrothermal vents to sampling deep sea corals. A similar evolution is currently underway as scientists begin adopting AUV technology for seafloor mapping, and again archaeological applications are at the forefront.

Each development in deep submergence technology has been accompanied by a new archaeological investigation leveraging new capabilities. The Jason ROV system has been employed to investigate a variety of shipwreck sites. By investigating several wrecks discovered at the Skerki Bank site, scientists gained high-resolution access to a series of undisturbed artifact assemblages (McCann & Freed, 1994). As a group, the wrecks represent a longitudinal study of ancient Mediterranean seafaring never before available. The aggregate value of these finds is enormous, surpassing the sum of their significance as individual events (Adams, 2007).

For this work, ROVs immediately provided two critical archaeological capabilities: remote sensing for shipwreck site survey and manipulation dexterity to recover artifacts from the seafloor. The next step was to excavate, exposing what might be preserved beneath the seafloor. In 2003 the Hercules ROV was fitted with a specially designed excavation system to investigate a well-preserved ancient wreck in the anoxic depths of the Black Sea (Webster, 2008). Using complementary techniques, a Norwegian team excavated a historic North Sea wreck (likely from the 18th or 19th century A.D.) in preparation for pipeline installation in the Ormen Lange gas field (Alfsen, 2006; Soreide & Jasinski, 2005). In each case, robotic excavation was held to the same standards for documentation and precision set by significant prior experience within the archaeological community for land and shallow water site documentation.

2.2.2. Applications of AUVs to Archaeology

Archaeologists are just beginning to utilize AUVs to search for, identify, and survey shipwrecks (Mindell & Bingham, 2001). Some notable projects beyond those initiated by the coauthors of this article include an MIT team's deployment of the Caribou AUV to search for archaeological targets off the coast of Italy using side-scan sonar (Desset, Damus, Morash, & Bechaz, 2003) and the commercial use of AUVs by C&C Technologies for oil and gas pipeline surveys in the Gulf of Mexico. For pipeline surveys, AUVs provide a less-expensive alternative to deep-tow sonar surveys, and AUV data collected during the surveys revealed several historic shipwrecks (Warren, Church, & Eslinger, 2007). In both the MIT and C&C operations, the primary use of AUVs was as a sonar platform. However, the scientific demands of archaeology extend beyond target acquisition. Once sonar targets are located, they must be identified as natural or anthropogenic features.[1] If they are anthropogenic, they must be characterized (e.g., debris/jetsam, modern shipwreck, archaeological site) and assessed for significance. AUVs can be used for all of these tasks, and more.

In this section we do not attempt to provide a comprehensive background in AUV technology or archaeological methodology; instead we attempt to reach across scientific and engineering disciplines, to engage a broad audience in robotics as well as the sciences and humanities. Our intent is to inform engineers of opportunities to design the tools of scientific discovery through examples of archaeological fieldwork. At the same time, we aim to pique the interest of archaeologists and physical scientists, in the hope of stimulating future collaborations.

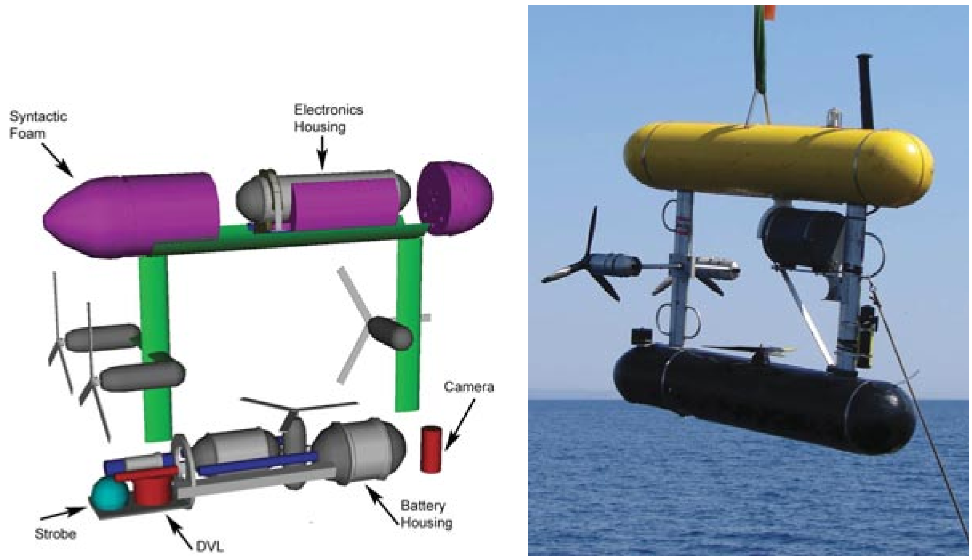
3. FIELD OPERATIONS: AUTONOMOUS INSPECTION OF A DEEP WATER SHIPWRECK

In this section we detail the experimental setup for an archaeological site survey by focusing on the configuration of an AUV system including the robotic platform itself, its onboard sensors, and internal and external navigation aids. The ability to survey a shipwreck autonomously in deep water is a consequence of innovations in component technologies and methods: vehicle design, image processing, bathymetric sonar, in situ chemical sensing, and underwater positioning. Although these individual technologies may not be novel, bringing them together for a field robotic survey of an ancient shipwreck is an important new application. Also, as indicated above, archaeological requirements are directly analogous to numerous scientific, industrial, and military applications.

3.1. Platform: An AUV for Inspection

The SeaBED AUV is a bottom-following, hover-capable, imaging research platform (Figure 1; Table I) (Singh,

[1] A thorough discussion on the capabilities and limitations of remote techniques in interpreting sonar targets and distinguishing between natural and anthropogenic features can be found in the literature (Sakellariou, 2007a, 2007b).



(a) Solid model (b) Vehicle being deployed in the Aegean

Figure 1. Solid model of SeaBED AUV as initially designed and photo of the vehicle as deployed on the Chios wreck site.

Armstrong, Gilbes, Eustice, Roman, et al., 2004; Singh, Can, Eustice, Lerner, McPhee, et al., 2004; Singh, Eustice, Roman, & Pizarro, 2002). As opposed to most typical single-hull, torpedo-shaped AUVs, the SeaBED vehicle was designed for imaging work close to the seafloor. The vehicle is of medium size (2 m in length) and weight (200 kg) with respect to the standard classes of AUVs (U.S. Navy, 2004). This allows it to be deployed from a wide variety of vessels, including small coastal craft or fishing boats. The robot's flotation foam and a buoyant instrument housing are mounted in an upper hull, and its batteries and other heavy components are mounted in the lower hull. The two hulls are connected by two vertical foil struts, to which two fore-and-aft thrusters mount on horizontal arms. The lower hull contains a vertical thruster mounted with the preferred thrust direction upward. This double-body arrangement

Table I. Specifications of the SeaBED AUV platform.

Specification		Value	Description
Vehicle	Depth rating	2,000 m	
	Size	2.0 (L) × 1.5 (H) × 1.5 (W) m	
	Mass	200 kg	
	Survey speed	0.15–1.0 m/s	
	Energy	2 kWh	Li-ion battery pack
	Propulsion	(3) 150 W	Brush-less dc thrusters
Navigation	Depth	0.01%	Paroscientific pressure sensor
	Velocity	±1–2 mm/s	RDI 1,200-kHz DVL
	Altitude	0.1 m	RDI (beam avg.)
	Heading	±0.1 deg	IXSEA OCTANS north-seeking FOG
	Pitch/roll	±0.01 deg	IXSEA OCTANS north-seeking FOG
	Absolute	1–3 m	Benthos LBL
Optical	Camera	1,280 × 1,024, 12 bit	Pixelfly CCD (B/W or color)
	Lighting	200 W · s	Incandescent strobe
Acoustic	Multibeam sonar	260 kHz	Imagenex 837 DeltaT
Chemical	Conductivity, temperature, depth (CTD)		Sea-Bird SBE 49
	Chlorophyll		Seapoint Sensors fluorometer
	CDOM		Seapoint Sensors ultraviolet fluorometer
	Aromatic hydrocarbons		Chelsea Technologies, AQUA tracka

separates the center of buoyancy from the center of gravity to create high passive pitch and roll stability. This stability, combined with precise control of multiple thrusters, allows for extremely slow motion operation.[2] Moving slowly allows for the collection of closely spaced remote observations, improving the measurement spatial resolution.

Three types of sensors were onboard the AUV during the 2005 survey: navigation sensors for positioning and guidance, optical and sonar sensors for mapping the seafloor and its features, and in situ chemical sensors for quantifying the oceanographic environment. A down-looking digital camera was mounted forward in the lower hull of the robot, and its single synchronized incandescent strobe light was positioned aft in the lower hull. This arrangement maximizes the camera-to-light separation to reduce optical backscatter in the digital images (Jaffe, 1990). A small, 240-kHz multibeam mapping sonar was mounted just aft of the camera. The Doppler velocity log (DVL) dead-reckoning navigation and altimetry sonar were fixed in the rear of the lower hull, and the fiber-optic gyro (FOG) was mounted to the forward strut. Chemical sensors mounted within the lower hull simultaneously measured salinity, temperature, chlorophyll, colored dissolved organic matter (CDOM), and aromatic hydrocarbons by using a common, actively pumped sample conduit. Because all of these sensors were incorporated into a single, passively stable, precisely navigated platform, the resulting data products can be correlated in space and time. This suite of sensors provides capabilities for examination of the wreck itself and numerous contextual measurements of the local environment.

3.2. Payload: Simultaneous Photographic, Bathymetric, and In Situ Chemical Sensing

3.2.1. Imaging Constraints of the Underwater Environment

The underwater environment places unique constraints on the ability to use and obtain visual information on an underwater robotic platform. The effects of scattering, attenuation, dynamic range, and field of view (FOV) must be considered to successfully collect images of sufficient quality to be used in many postprocessing techniques.

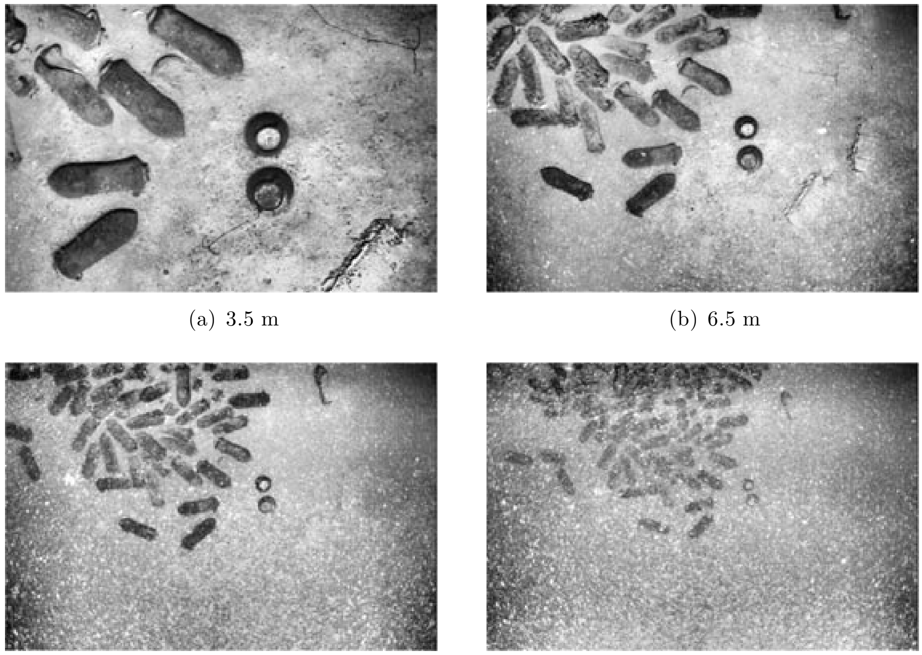
The absorption of light through seawater suffers from a wavelength-dependent exponential attenuation that shifts perceived color content toward the blue end of the spectrum (Duntley, 1963; McGlamery, 1975). Additionally, forward- and backscattering processes make it difficult to obtain high-contrast images unless careful engineering consideration is made between illumination power and physical camera-to-light separation. Within this realm, the work of Jaffe (1990) showed that large horizontal camera-to-light separations are desirable to reduce backscatter—the principal cause being the reduction of common volume between the camera FOV and volume of projected light. More recently, Singh, Howland, and Pizarro (2004) showed that there are theoretical limits to the benefits of large camera-to-light separation as applied to practical vehicle configurations. Figure 2 demonstrates the range over which backscatter has an effect for a fixed camera and light geometry.

In conjunction with the constraint of minimizing backscatter, the rapid attenuation of light through water imposes additional challenges when collecting underwater imagery. Light attenuation limits the altitude at which a vehicle can fly from the seafloor and collect imagery. The design of deep sea vehicles that carry their own light sources must trade off the desire for high-altitude imaging, which reduces parallax effects over three-dimensional (3D) scenes, and imaging close enough to supply ample lighting with reduced backscatter. In practice the typical altitudes for imaging are between 3 and 10 m (Singh, Howland, et al., 2004). In addition, moving the light source with the vehicle leads to nonuniform illumination and moving shadows—both of which pose additional challenges during image registration and postprocessing. As a result of these constraints, vehicles are forced to fly close to the seafloor, where terrain relief may be comparable to the imaging distance, which induces gross perspective changes. The reduced FOV of underwater images requires that multi-images be registered and mosaicked together to create a scene-wide rendering.

Unfortunately, image registration can also be more difficult with underwater imagery than with terrestrially acquired imagery. Unstructured surveys by vehicles with low-resolution navigation and heading inaccuracies are common. This results in imagery with gross motions between temporal frames, often with minimum overlap (Bradley, Feezor, Singh, & Sorrell, 2001). In addition, the types of imaged scenery can be vastly different, ranging from highly 3D coral reefs (Singh et al., 2002) to featureless muddy bottoms (Singh & Howland, 1999). Man-made features such as edges, corners, and parallel lines, prominent in land-based images and exploited in many processing techniques, cannot be reliably expected to occur in underwater imagery. Furthermore, the images must be color corrected as illustrated in Figure 3.

Power budget limitations of AUVs are also an important consideration in the design of imaging systems. The amount of energy expended in illuminating the scene will reduce the endurance of these battery-powered vehicles (Bradley et al., 2001). Typically, AUVs cannot afford the continuous lighting needed for video frame rates because it would come at the sacrifice of precious bottom time. Rather, strobed lighting is often used to conserve power (Singh et al., 2002; Singh, Weyer, Howland, Duester, & Bradley, 1999). Additionally, the low amount of image overlap afforded by this illumination scheme precludes

[2]Typical speeds for the Chios missions were 0.25 and 0.20 m/s.



(a) 3.5 m (b) 6.5 m

(c) 9.5 m (d) 12.5 m

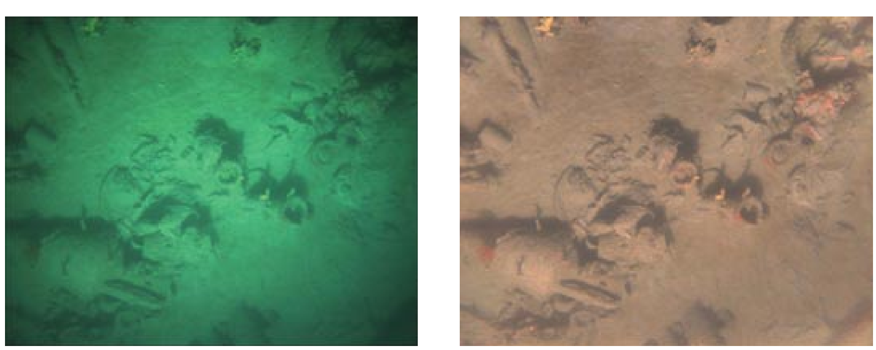
Figure 2. A demonstration of underwater backscatter using data collected by the Jason ROV (Singh, Howland, et al., 2004). In this example, a sequence of images is shown over an incremental range of altitudes to demonstrate the significance of backscatter. Note that backscatter reduces the effective altitude at which an underwater vehicle can clearly image the scene.

optical-flow image registration methods such as those of Negahdaripour, Xu, and Jin (1999) and Negahdaripour and Xun (2002a). Hence, the unique energy constraints of AUVs are a major driver for the development of mosaicking and image registration techniques that can handle low overlap imagery (i.e., 15%–35% temporal overlap).

3.2.2. Sonar Imaging

Multibeam sonar systems collect bathymetric data in a fan-shaped swath that is wide in the across-track direction and narrow in the along-track direction. These sonar systems are capable of providing dense data sets of 3D bathymetric soundings to quantify the fine-scale characteristics of objects on the seafloor and the seafloor itself. Bathymetric maps are generated through the use of high-precision navigation to merge the sonar returns into a spatially consistent 3D point cloud, which is then fitted with a surface estimating the seafloor topology.

AUVs have proven their utility as stable, controlled, near-bottom survey platforms able to make efficient use



(a) Uncorrected (b) Color corrected

Figure 3. Original color imagery (left) and its color-compensated counterpart (right). The methodology is based on the estimated reflectance image to achieve color fidelity that is independent of the camera, lighting system, and distance between camera and object (Singh, Roman, Pizarro, Eustice, & Can, 2007).

of advances in currently available sonar systems. For any given sensor, a number of variables affect the resolution of a multibeam sonar system, including sound frequency, pulse duration, beam pattern of the sonar as dictated by the transducer design, seafloor roughness, and range to the bottom. The size of the acoustic footprint on the seafloor can greatly affect the resolution of the final map product, as a large acoustic footprint over fine-scale complex seafloor terrain will not resolve the details of the seafloor but will reveal broader bathymetric patterns. AUV platforms are capable of flying precisely controlled fixed-altitude survey lines, making full use of the sonar resolution.

Additional variables that affect the resolution of a final map product are dependent on data acquisition protocols. For example, the along-track spatial density of bathymetric soundings is dependent on ping rate, vehicle speed, and vehicle altitude. The across-track data density is dependent on characteristics of the multibeam system (e.g., swath width) and distance from the seafloor and the prescribed trackline spacing.

3.3. Navigation: Accuracy and Precision for an Archaeological Investigation

Navigation provides the common reference for overlaying observations from multiple sensors into coregistered maps. This transforms otherwise purely observational exploration into systematic scientific investigation. Our goal is to meet or exceed the standards for precision and accuracy obtained by archaeologists working on land or in shallow water by scientists equipped with SCUBA. Underwater positioning precision and accuracy for AUVs must enable archaeological interpretation, aid site preservation, and guarantee accurate documentation. The survey of the Chios wreck provides a venue for discussing the general requirements of underwater navigation in support of deep water archaeology.

Positioning and navigation of the AUV must address the following:

1. The real-time positioning must be sufficiently accurate in a global frame to locate the survey above the site.
2. The real-time navigation must be sufficiently precise, in a relative frame, to ensure the desired overlap of sensor observations both along track and across track.
3. The postprocessed positioning, derived from numerous constituent navigational and environmental sensor measurements, must be sufficiently precise to take advantage of payload sensor resolution for making maps of the site.

Below we discuss how we addressed each of these functional requirements for the Chios AUV survey.

3.3.1. Absolute Positioning

Absolute localization was accomplished by long baseline (LBL) acoustic positioning (Hunt, Marquet, Moller, Peal, Smith, et al., 1974). The team installed a network of acoustic transponders moored to the seafloor in the geometry illustrated in Figure 4. Once deployed, the transponders were surveyed from a surface ship to determine their 3D positions and localize the acoustic network relative to global positioning system (GPS) geodetic coordinates (the Earth-centered, Earth-fixed coordinate system affixed to the WGS-84 reference ellipsoid). The quality of this estimate is indicated by the root-mean-squared (RMS) error between the final prediction and the measurements. For the three transponders shown in Figure 4, the RMS error for the beacon locations was between 1.5 and 2.1 m.

Unlike some other applications of AUV survey techniques that rely solely on dead reckoning, absolute positioning is an important part of the navigation requirement. The Chios wreck was extremely small by oceanographic standards, roughly 21 m long, and the survey geometry was fine grained to produce high-resolution optical, sonar, and chemical maps. Having a fixed reference allowed the team to do repeated surveys on separate missions and directly overlay information from each successive mission to the final data product. For example, a photographic survey completed during the first survey was referenced directly to a later chemical survey to generate consistent, layered visual representations for comparative analysis.

3.3.2. Dead Reckoning

Precise dead reckoning complements the absolute positioning. The LBL system enables the vehicle to initiate the survey at the wreck site. Once initiated, the survey was conducted using real-time, dead-reckoning navigation, relying on the onboard DVL for odometry and the FOG for heading reference. On the basis of the specifications of these instruments and previously published uncertainty models (Bingham, 2009), we estimate the maximum positioning uncertainty between parallel tracklines of the Chios surveys to be 0.187 m (standard deviation) or 0.31% of distance traveled. This, coupled with the absolute reference, is sufficient to ensure sensor overlap for the survey shown in Figure 5 with 1.25-m trackline spacing.

3.3.3. Navigation Sensor Fusion

The final step in navigating the AUV is completed offline, using an acausal Kalman smoother to refine the localization record (Jakuba & Yoerger, 2003). This step allows the absolute LBL observations to constrain the drift of the dead-reckoning estimate. The algorithm discards acoustic positioning outliers, combining the LBL range data with the velocity information from the DVL and attitude measurement from the inertial navigation system. The results of this

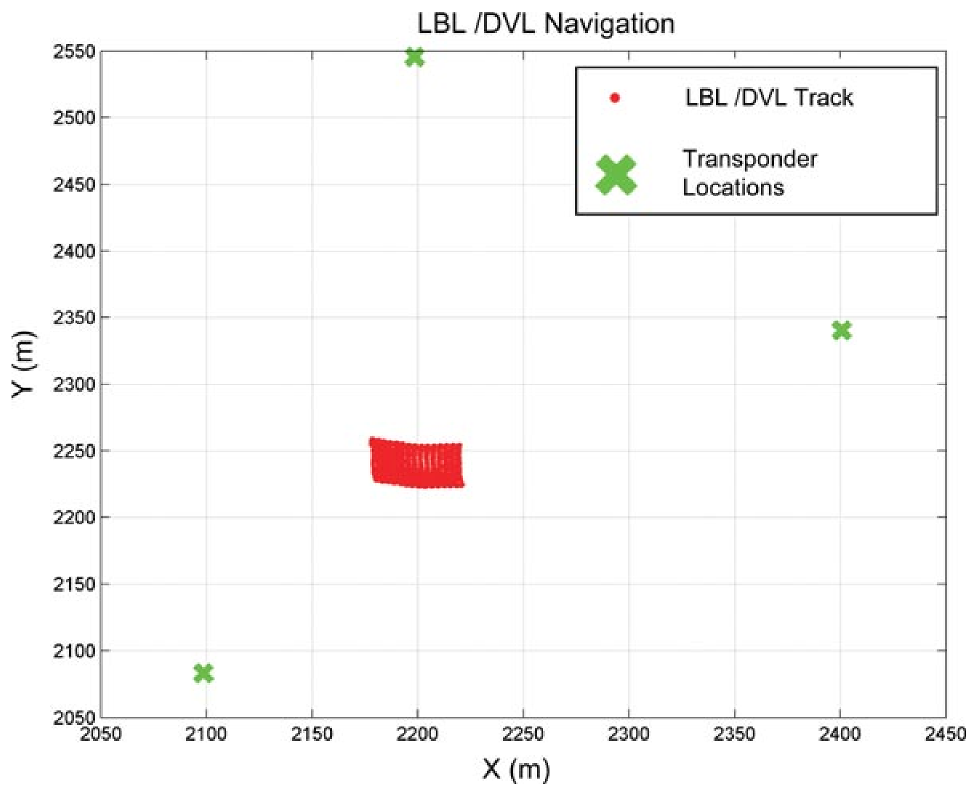


Figure 4. The LBL transponder locations are shown in two dimensions along with the postprocessed positioning estimates for a single pass over the Chios shipwreck site.

sensor fusion are shown in Figure 5. This postprocessing is necessary in order to provide positioning that is commensurate with the sensor resolution; the resolution of the final bathymetry and chemistry maps is often limited by the underwater positioning precision, not the sensor performance (Roman & Singh, 2007).

3.4. Survey: Evolution of the Chios 2006 Field Operations

The 2005 Chios survey was designed to provide quantified data products, images of the shipwreck site collected over a sequence of SeaBED missions[3] using a collection of optical, acoustic, and chemical remote sensing. The design, execution, and postprocessing of the survey operations focused on creating images suitable for archaeological interpretation. The Chios wreck site was discovered 1 year prior to the AUV investigations by researchers from Hellenic Ephorate of Underwater Antiquities (EUA) and the Hellenic Centre for Marine Research (HCMR) (Sakellariou et al., 2007). The initial target was identified during a geophysical survey of the Chios Strait using side-scan and subbottom sonar. The target was verified as an ancient shipwreck using the HCMR Super Achilles ROV, which collected video images.

The following year, an international team of scientists and engineers returned to the site to execute the AUV survey discussed here. The full survey consisted of three AUV missions (see Table II), each adding more information for interpreting the archaeological evidence. Repeatable absolute positioning within a stable reference frame provided a common coordinate space among missions. As the team's

Table II. Mission durations for the Chios AUV survey.

Mission number	Duration (HH:MM)
2	02:42
3	02:19
4	01:23

[3]Typically submersible operations are called "dives," ROV operations are called "lowerings," and AUV operations are called "missions."

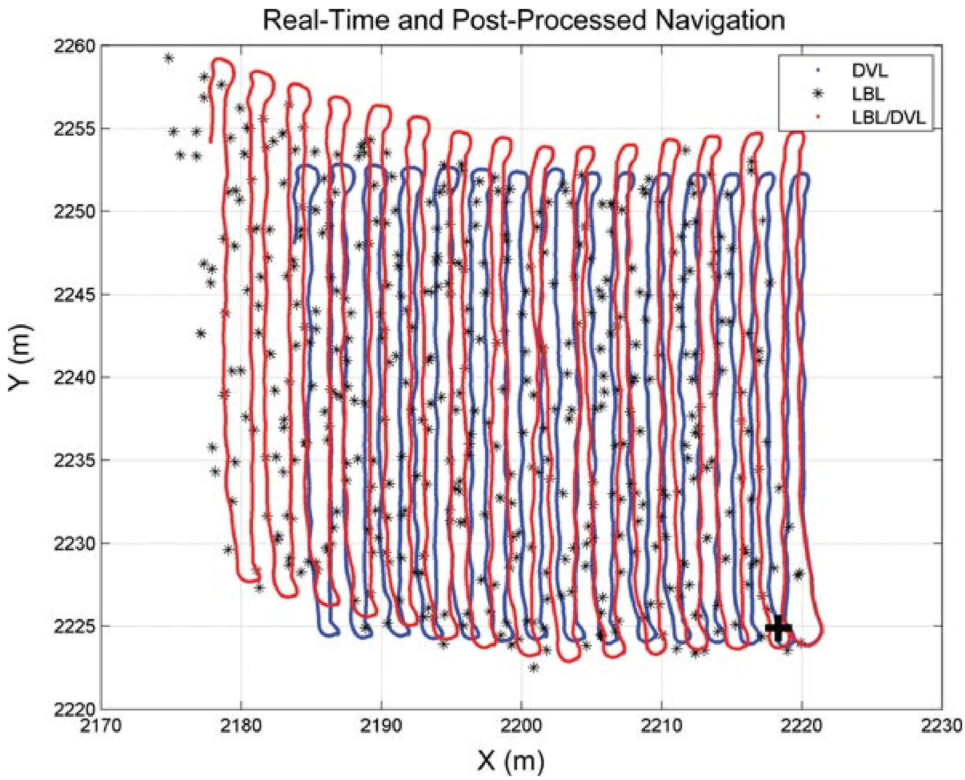


Figure 5. Illustration of the final fine-resolution SeaBED mission over the Chios wreck site. The plot illustrates the dead-reckoning navigation (DVL) and acoustic positioning (LBL) records along with the results of the Kalman smoother acausal estimate of position (LBL/DVL). The black marker (+) in the lower right corner signifies the beginning of the survey. The nominal trackline spacing is 1.25 m.

understanding of the site improved, efforts focused on increasingly finer scale surveys to generate new awareness and knowledge of the site. For example, bathymetry measurements from the first survey informed subsequent surveys, allowing for a gradual increase in the resolution of the investigation. Chemical and optical data collected in later surveys could be overlaid on early bathymetric maps because the positioning was consistent between each of the missions.

After relocating the site with a small ROV and deploying seafloor transponders from the ship, the team initiated the first AUV mission: a large-area reconnaissance to document the wreck's environmental context. During this coarse investigation the AUV collected photographic, bathymetric, and chemical observations over an area of 50 × 100 m with 5-m trackline spacing at a speed of 0.25 m/s. The second and third missions consisted of fine-resolution survey patterns, at an altitude of 2.5 m, to produce comprehensive digital imaging, multibeam sonar, and chemical maps of the wreck and the seafloor immediately surrounding it. These surveys covered 30 × 45 m of seafloor centered on the wreck site at a constant speed of 0.20 m/s (0.39 kt) and trackline spacing of 1.5 and 1.25 m. The AUV's camera collected images every 3 s, synchronized with its strobe light. At 2.5-m altitude, the camera footprint on the seafloor was approximately 1.50 m along track × 1.85 m across track. This altitude, image collection rate, and speed over ground resulted in approximately 60% overlap along track in successive images. Adjacent tracklines were spaced 1.5 m apart, theoretically providing at least 20% image overlap in parallel tracks. The multibeam sonar collected data continuously throughout the mission, with an average swath width of 5 m providing more than 50% overlap between adjacent tracks. Onboard environmental sensors measured water temperature, salinity, aromatic hydrocarbons, concentrations of dissolved organic matter, and chlorophyll levels.

These successive survey missions resulted in more than 7,000 high-resolution digital images of the wreck and surrounding seafloor. After color correcting and histogram equalizing the raw digital images, the team assembled photomosaic strips of the wreck site. Partial mosaics of the wreck were in the hands of the archaeologists within hours of data collection. At the same time, the engineering team

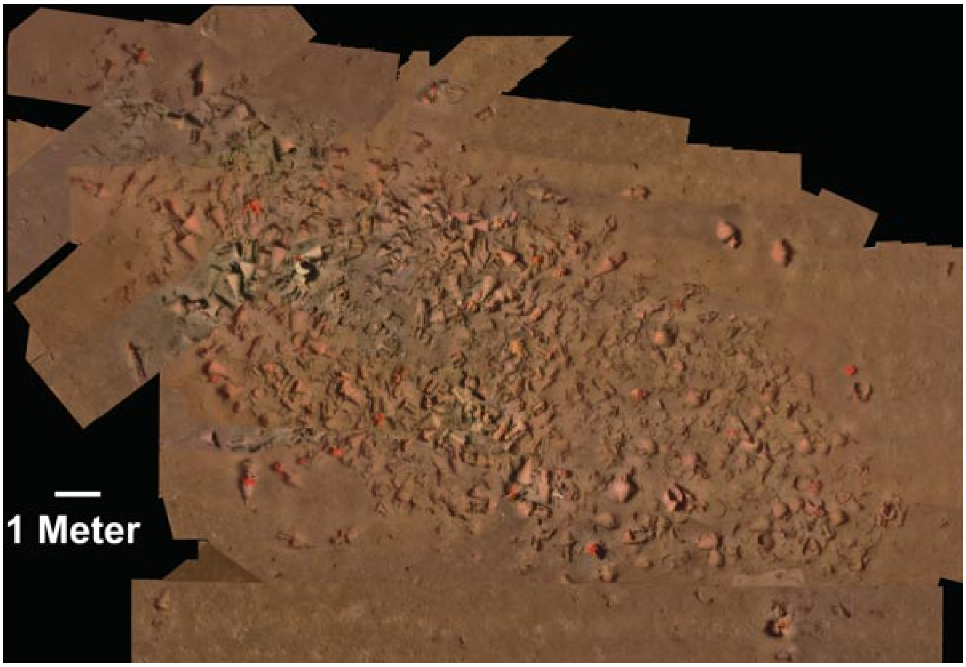


Figure 6. Photomosaic created from a subset of the more than 7,000 images resulting from three AUV missions, providing an otherwise impossible view of the Chios shipwreck.

generated preliminary bathymetric maps of the wreck site. The following section outlines how these data products were refined to enable archaeological interpretation of this fourth-century B.C. shipwreck.

4. SCIENTIFIC RESULTS: DATA PRODUCTS

The wreck carried more than 350 amphoras of two distinct types. The morphology of one of these amphora types is well studied, providing important clues for determining the origin, date, cargo, and historical context of the vessel. Beyond interpretation, these results were used to select particular artifacts for recovery and further physical analysis [see Foley et al. (2009) for details].

4.1. Photomosaic

Probably the most important individual data product for archaeological interpretation is the large-area photomosaic shown in Figure 6. Most common algorithms for automated mosaicking make use of techniques adapted from the field of simultaneous localization and mapping (SLAM), augmented with techniques from computer vision and photogrammetry, to create a self-consistent set of image transformations that merge the images yet minimize accumulated error (Gracias & Santos-Victor, 1998; Pizarro, Eustice, & Singh, 2009; Singh et al., 2000; Xu & Negahdaripour, 2001). These techniques enable automated generation of strip mosaics, using data association between sequential images to produce a composite image of a single pass over the site. Extending automated mosaicking for multiple transects makes it possible to constrain the growth of positioning uncertainty through the use of vision-based constraints (Eustice, Pizarro, & Singh, 2008; Gracias, van der Zwaan, Bernardino, & Santos-Victor, 2003; Negahdaripour & Xun, 2002b). Numerous problems related to 3D effects, scaling, and registration, however, still exist when producing mosaics, and this remains an active area of research.[4]

4.2. 3D Optical Reconstruction

In parallel with generation of the qualitative two-dimensional photomosaic, the team also applied techniques for large-area 3D reconstruction (Pizarro et al., 2009) and visually augmented navigation (VAN) (Eustice et al., 2008). These techniques extract 3D bathymetry estimates for the entire site based on only the collected images (Figure 7). The VAN method employs camera-derived, relative-pose measurements to provide spatial constraints, which enforce trajectory consistency and also serve as

[4]The tool set used to generate the results presented here is discussed by Singh et al. (2007).

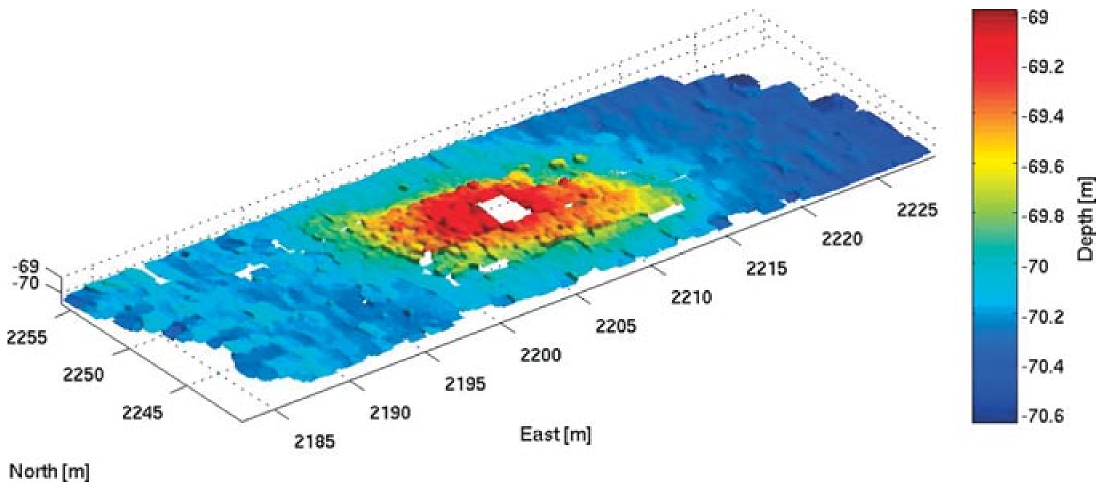


Figure 7. 3D bathymetry derived from still imagery, gridded at 5-cm resolution.

a mechanism for loop closure. This vision-based SLAM framework makes use of the relative navigation information between successive images to arrive at both a vehicle trajectory with bounded uncertainty and, simultaneously, an estimate of the bathymetry of the imaged seafloor derived from the triangulation of features apparent in multiple images.

Figures 7 and 8 illustrate the potential of this approach. On the basis of the imagery and relative positioning alone, we are able to extract a quantifiable map of the wreck site, as shown in Figure 7. This data product complements the photomosaic by providing a dimensionally accurate 3D representation of the site not available in the mosaic alone. Archaeologist can make use of this map to measure aspects of the site and record the relative location of artifacts. Figure 8 combines this quantitative map with the qualitative visual information in the photomosaic as a dimensionally accurate representation of the site, eliminating distortions due to perspective and lighting effects. In digital form, this data product enables the scientist to explore the site at various levels of detail from a variety of vantage points. There are sections of the survey where there was insufficient overlap to produce this vision-only bathymetry. The areas of this sparse reconstruction are evident in the missing surface data in Figures 7 and 8. The texturing process projects the image texture only over areas where there is a high enough density of surface points.

4.3. Multibeam Sonar Bathymetry

In addition to digital images, multibeam sonar data were collected during the Chios survey. The resulting bathymetry map, gridded at 5-cm resolution, is shown in Figure 9. This resolution is sufficient to reveal the detailed characteristics of the wreckage and the surrounding seafloor. The wreck itself is bathymetrically complex, but, even in the initial sonar maps, individual amphoras spatially isolated (horizontally or vertically) from the wreckage

Figure 8. Quantitatively accurate 3D photomosaic derived from fusing digital imagery and the gridded surfaces shown in Figure 7.

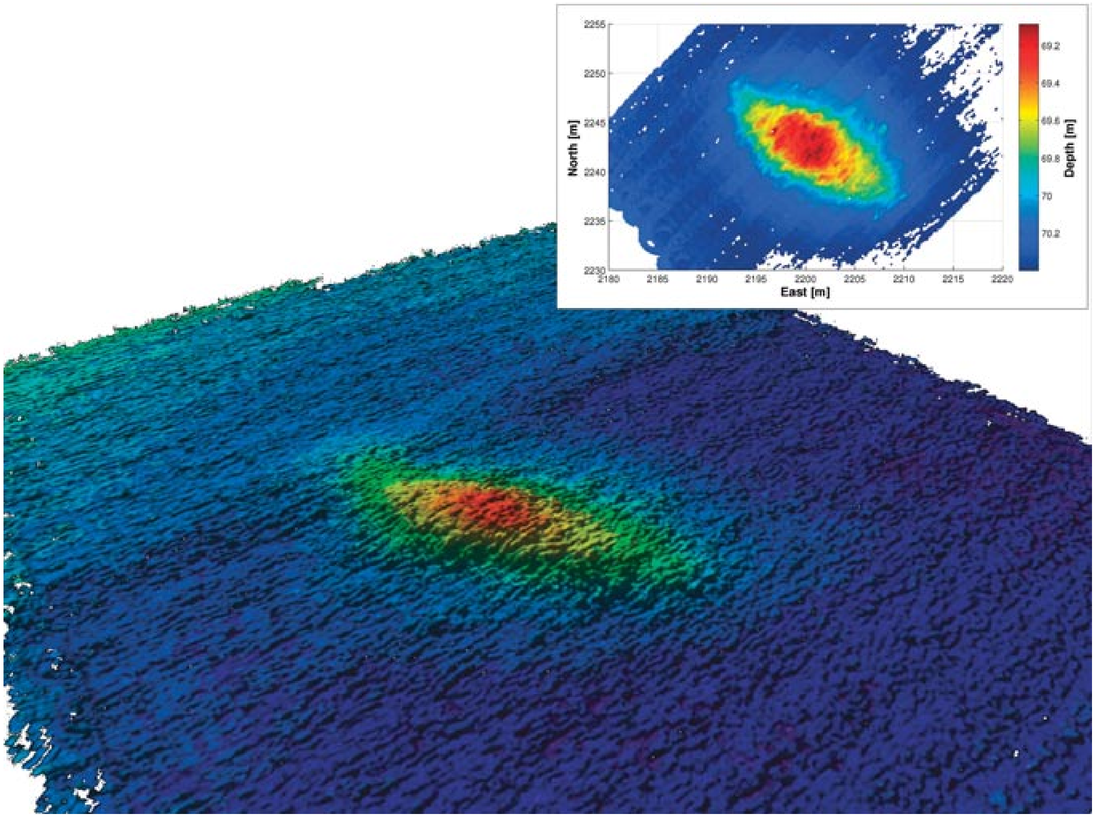


Figure 9. Multibeam bathymetry of the Chios shipwreck site. The total relief of the amphora mound is approximately 1 m above the surrounding seafloor.

were identified. With postprocessing of the sonar data based on research by the authors (Roman & Singh, 2005, 2007), individual artifacts within the amphora mound can be discerned (Figure 9 inset).

4.4. Fused Photographic and Sonar Maps

A data product that has proven to be particularly useful for archaeological interpretation is texture-mapped bathymetry, as shown in Figure 10. This product combines the qualitative, fine-resolution imagery of the photomosaic from Figure 6 with the quantitative, 3D relief from the bathymetry in Figure 9. Presenting these data as a rendered solid object allowed the archaeologists to interact with the site in three dimensions, exploring the details of the site with all the complexity of the seafloor topology. Such a data product, which shows the distribution of volume and associated object-specific information, will be particularly useful when considering excavation of such sites.

4.5. In Situ Chemistry

Concurrent with the photographic and bathymetric surveys, the team also used the AUV as a platform for in situ chemical measurement in an effort to characterize the oceanographic context of the wreck site. The onboard suite of sensors was used to measure salinity and temperature, chlorophyll, CDOM, and aromatic hydrocarbons (see Table I for sensor models). The spatial distribution of these parameters is illustrated in Figure 11 in the same coordinate frame as the photomosaic and bathymetry discussed above.

Describing the physical environment of the wreck site is an important part of the archaeological process. The in situ chemical measurements allowed the science team to describe and document the oceanographic and geographical context. Quantifying the oceanographic environment—including water chemistry, benthic currents, temperature, and salinity—provided the science team with the data to make recommendations on the stability of the site and how best to manage its preservation. Similar site descriptions are typical of historically significant wreck sites as part of the overarching responsibility to manage these important cultural resources (Ballard et al., 2000; Herdendorf, Thompson, & Evans, 1995; Lenihan, 1989). The combination of AUV platforms and emerging scientific instrumentation makes it possible to simultaneously collect various modes of evidence about the surrounding ocean, the wreck site morphology, and individual artifacts.

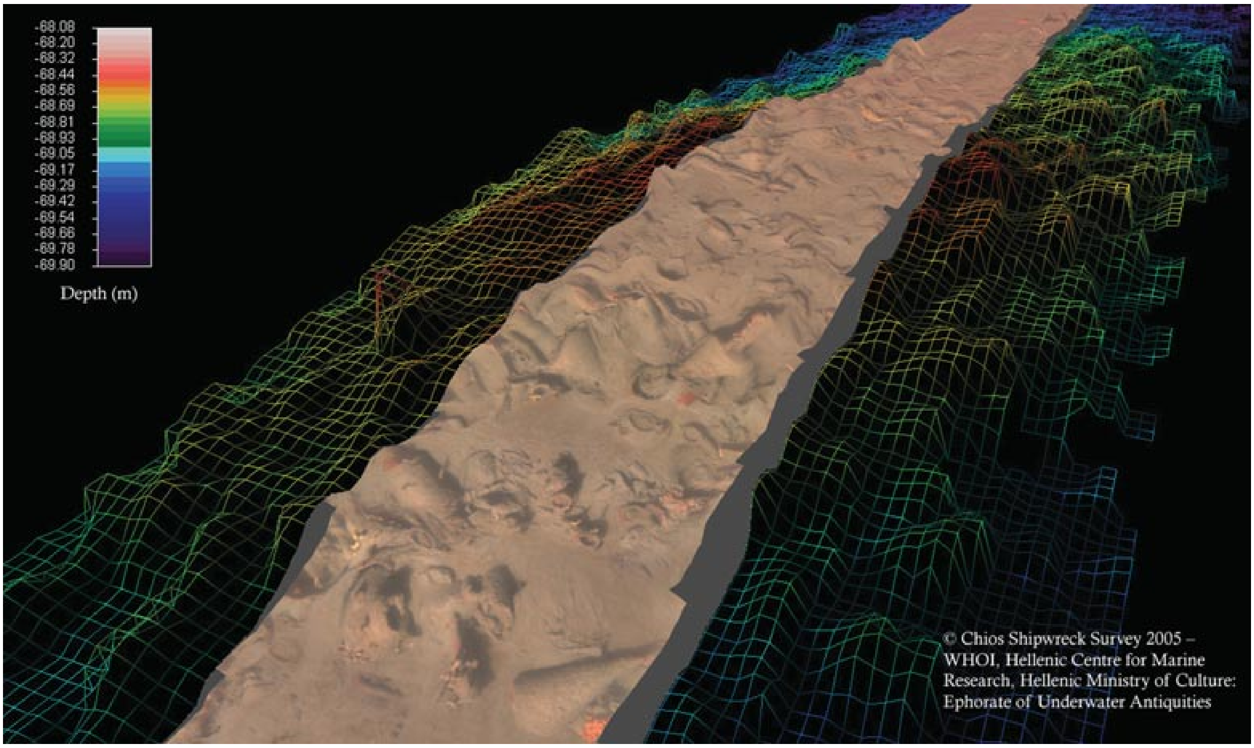


Figure 10. A portion of the photomosaic from Figure 6 draped over the multibeam bathymetry from Figure 9.

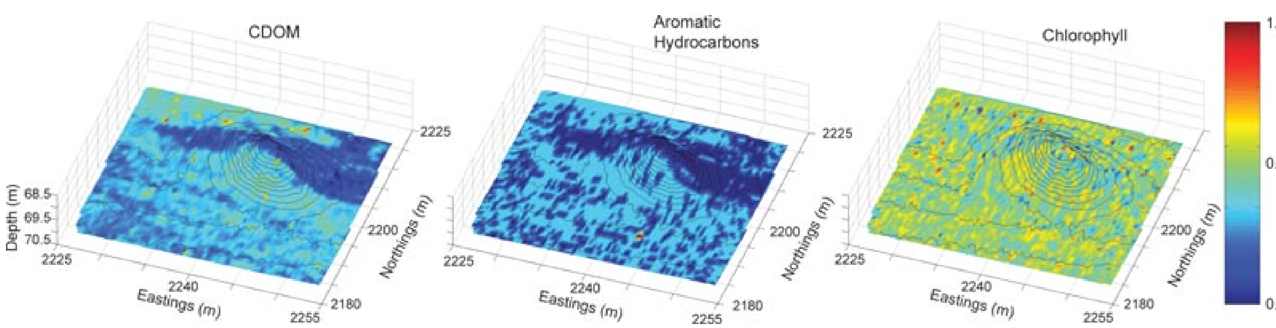


Figure 11. In situ chemistry maps of the Chios wreck site, correlated with the seafloor bathymetry, shown with 10-cm contour intervals. The color map represents a normalized concentration of each measurement over the site. CDOM, aromatic hydrocarbon observations, and chlorophyll are important parameters for quantifying the thermal and kinetic energy inputs and the level of biological and anthropogenic activity at the site.

5. SUMMARY AND CONCLUSIONS

This article details the results of an AUV survey of a fourth-century B.C. shipwreck near the island of Chios, Greece. We believe that this set of AUV missions, totaling 6 h, 25 min over three deployments, represents the state of the art in deep water archaeology using autonomous field robotic technology. This expedition made use of a mature platform for high-resolution seafloor imaging, the SeaBED AUV. In addition, the data products from the survey illustrate the convergence of platform maturity, payload instrumentation, and data processing to efficiently produce high-fidelity, interactive representations of the seafloor for scientific interpretation.

Over the course of 3 days, these surveys produced qualitative and quantitative data products documenting the state of the ancient shipwreck. Because of the navigation accuracy, the archaeologists were able to discern wreck dimensions and amphora pile height, leading to an estimate of the total cargo. Only a few Classical Greek shipwrecks are known, and only rarely are they undisturbed. These important measurements, made possible by the AUV platform, sensors, and processing techniques, provided sufficient precision to enable interpretation of the cargo type and capacity, critical information for determining the role of seafaring in ancient trade. Furthermore, the overall site plan, created in just three missions, was interpreted on site to guide the careful selection of key artifacts for collection by Greek scientists.

The scope of this article is intentionally broad—touching on a diverse set of topics in robotics, remote sensing, navigation, instrumentation, image processing, and archaeology. Each of these topics is a distinct area of research; this project leveraged the authors' research in these topics as well as current research in the literature. The Chios surveys brought together each of these components into an expedition highlighting how field robotics can benefit scientific and cultural discovery.

6. FUTURE DIRECTIONS

The use of AUVs in particular, and underwater robotics in general, is still evolving as research continues to advance our ability to ask new scientific questions. At the same time, deep water archaeology continues to offer challenges to the underwater robotics and instrumentation community. The historical interplay between archaeological science and marine systems has demonstrated that addressing these technical challenges offers many synergistic opportunities for complementary scientific, military, and industrial applications.

As a platform for gathering scientific, military, and industrial data, AUVs continue to mature and evolve. Whereas the basic, propeller-driven, long-duration platform is increasingly a commodity item, new classes of vehicles continue to emerge, enabling novel types of investigations. For example, new hover-capable platforms are addressing the need to inspect ship hulls (Vaganay, Elkins, Esposito, O'Halloran, Hover, et al., 2006), hybrid AUV gliders are extending the possible endurance of data-gathering missions (Claus, 2009), and new propulsion techniques such as flapping foils promise to enable new missions (Licht, Wibawa, Hover, & Triantafyllou, 2009).

The challenges of localization continue to limit many applications. Archaeology, as a representative application, necessitates both accuracy and precision to satisfy both the operational needs and the requirements for site documentation. Current research promises not only to decrease the uncertainty in underwater navigation but also to remove the necessity of deploying seafloor-mounted transponders. For example, range-only SLAM offers the advantage of eliminating the time required to survey acoustic transponders but does not afford a truly accurate solution because the final map is unconstrained in translation and rotation (and possibly reflection) (Olson, Leonard, & Teller, 2006). Single-transponder navigation methods may decrease the setup time but do not eliminate the need to deploy and survey these moored instruments (Hartsfield, 2005; LaPointe, 2006). Recent research has demonstrated the ability of a surface ship to support absolute positioning, removing the requirement for transponders but requiring constant acoustic ranging and communication (Eustice, Whitcomb, Singh, & Grund, 2007). Visual navigation methods make it possible to completely eliminate all such external references, relying solely on the optical imagery to internally constrain the growth in uncertainty due to dead reckoning (Eustice, et al., 2008). Similar sonar-based approaches have shown promise, especially in areas of low visibility (Barkby, Williams, Pizarro, & Jakuba, 2009; Mallios, Ridao, Hernandez, Ribas, Maurelli, et al., 2009; Roman & Singh, 2005). Despite these advances, the deep water archaeology application still requires a traditional approach of combining absolute acoustic positioning and dead reckoning to satisfy the requirements for both accuracy and precision.

Finally, possibly the most important lesson from the Chios AUV survey for continued research comes from the computer science adage, "Simple things should be simple, complex things should be possible."[5] As research in vehicle platforms, navigation, imaging, and sonar and in situ instrumentation continue to advance, applying these new tools to the multidisciplinary endeavor of field robotics for scientific discovery demands that we make trade-offs between capabilities and complexity. The accomplishments of this field expedition illustrate that we can transition robotics research to field deployments, but to justify the added complexity each new capability must add value for the scientific users, enabling them to ask new questions in new ways.

ACKNOWLEDGMENTS

The authors wish to thank the Hellenic Ministry of Culture, the Hellenic Centre for Marine Research, the U.S. National Science Foundation (NSF), George Chronis and Vangelis Papathanassiou of HCMR, and the captain and crew of R/V AEGAEO. We would also like to recognize the hard work of the archaeology team including Dimitris Kourkoumelis, Theotokis Theodhoulou, Dionysis Evangelistis, and Paraskevi Micha. The SeaBED AUV and the efforts of its team were funded by the Censsis Engineering Research Center under NSF grant EEC9986821. We express our sincere appreciation to sponsors Susan and Robert Bishop, Jane and James Orr, and others, whose generosity made this project possible.

REFERENCES

Adams, J. (2007). Alchemy or science? Compromising archaeology in the deep sea. Journal of Maritime Archaeology, 2(1), 1557–2285.

[5]Often attributed to Alan Kay.

Alfsen, M. (2006). Digging deep. Archaeology, 59(3).
Ballard, R. D. (1993). The JASON remotely operated vehicle system (Tech. Rep. WHOI-93-34). Woods Hole Oceanographic Institution.
Ballard, R. D., Hiebert, F. T., Coleman, D. F., Ward, C., Smith, J. S., Willis, K., Foley, B., Croff, K., Major, C., & Torre, F. (2001). Deepwater archaeology of the Black Sea: The 2000 season at Sinop, Turkey. American Journal of Archaeology, 105(4), 607–623.
Ballard, R. D., McCann, A., Yoerger, D., Whitcomb, L., Mindell, D., Oleson, J., Singh, H., Foley, B., Adams, J., & Picheota, D. (2000). The discovery of ancient history in the deep sea using advanced deep submergence technology. Deep-Sea Research, 47(9), 1591–1620.
Ballard, R. D., Stager, L. E., Master, D., Yoerger, D., Mindell, D., Whitcomb, L. L., Singh, H., & Piechota, D. (2002). Iron age shipwrecks in deep water off Ashkelon, Israel. American Journal of Archaeology, 106(2), 151–168.
Barkby, S., Williams, S., Pizarro, O., & Jakuba, M. (2009, October). An efficient approach to bathymetric SLAM. In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), St. Louis, MO.
Bascomb, W. (1976). Deep water, ancient ships. Garden City, NY: Doubleday and Company, Inc.
Bingham, B. (2009, September). An analytical framework for predicting the performance of autonomous underwater vehicle positioning. In Proceedings of the Unmanned Untethered Submersible Technology Conference, Durham, NH.
Bradley, A., Feezor, M., Singh, H., & Sorrell, F. (2001). Power systems for autonomous underwater vehicles. IEEE Journal of Oceanic Engineering, 26(4), 526–538.
Chance, T., Kleiner, A., & Northcutt, J. (2000). The autonomous underwater vehicle (AUV): A cost-effective alternative to deep-towed technology. Integrated Coastal Zone Management, 2(7), 65–69.
Church, R., & Warren, D. (2002). Autonomous underwater vehicles: The latest tool for archaeological investigations. Marine Technology Society Journal, 36, 3.
Claus, B. (2009, September). Hybrid glider propulsion module implementation and characterization. In Proceedings International Symposium on Unmanned Untethered Submersible Technology, Durham, NH.
Desset, S., Damus, R., Morash, J., & Bechaz, C. (2003). Use of GIBs in AUVs for underwater archaeology. Sea Technology, 44(12), 22–27.
Duntley, S. (1963). Light in the sea. Journal of the Optical Society of America, 53(2), 214–233.
Eustice, R., Pizarro, O., & Singh, H. (2008). Visually augmented navigation for autonomous underwater vehicles. IEEE Journal of Oceanic Engineering, 33(2), 103–122.
Eustice, R., Whitcomb, L., Singh, H., & Grund, M. (2007, April). Experimental results in synchronous-clock one-way-travel-time acoustic navigation for autonomous underwater vehicles. In 2007 IEEE International Conference on Robotics and Automation, Rome, Italy (pp. 4257–4264).
Foley, B., DellaPorta, K., Sakellariou, D., Bingham, B., Camilli, R., Eustice, R., Evagelistis, D., Ferrini, V., Katsaros, M. H. K., Kourkoumelis, D., Mallios, A., Micha, P., Mindell, D., Roman, C., Singh, H., Switzer, D., & Theodoulou, T. (2009). The 2005 Chios ancient shipwreck survey: New methods for underwater archaeology. Hesperia, 78(2), 269–305.
Foley, B., & Mindell, D. (2002). Precision survey and archaeological methodology in deep water. ENALIA: The Journal of the Hellenic Institute of Marine Archaeology, VI, 49–56.
Gracias, N., & Santos-Victor, J. (1998, September–October). Automatic mosaic creation of the ocean floor. In Proceedings IEEE/MTS OCEANS Conference and Exhibition, Nice, France (vol. 1, pp. 257–262).
Gracias, N., van der Zwaan, S., Bernardino, A., & Santos-Victor, J. (2003). Mosaic based navigation for autonomous underwater vehicles. IEEE Journal of Oceanic Engineering, 28(4), 609–624.
Hartsfield, J. C. (2005). Single transponder range only navigation geometry (STRONG) applied to REMUS autonomous under water vehicles. Master's thesis, Massachusetts Institute of Technology and Woods Hole Oceanographic Institution.
Herdendorf, C. E., Thompson, T. G., & Evans, R. D. (1995). Science on a deep-ocean shipwreck. Ohio Journal of Science, 95(1), 4–225.
Holt, P. (2003). An assessment of quality in underwater archaeological surveys using tape measures. International Journal of Nautical Archaeology, 32(2), 246–251.
Hunt, M., Marquet, W., Moller, D., Peal, K., Smith, W., & Spindel, R. (1974). An acoustic navigation system (Tech. Rep. WHOI-74-6). Woods Hole Oceanographic Institution.
Jaffe, J. (1990). Computer modeling and the design of optimal underwater imaging systems. IEEE Journal of Oceanic Engineering, 15(2), 101–111.
Jakuba, M. V., & Yoerger, D. R. (2003, September). High-resolution multibeam sonar mapping with the Autonomous Benthic Explorer (ABE). In Thirteenth International Symposium on Unmanned Untethered Submersible Technology (UUST03), Durham, NH.
LaPointe, C. (2006). Virtual long baseline (VLBL) autonomous underwater vehicle navigation using a single transponder. Master's thesis, Massachusetts Institute of Technology.
Lenihan, D. J. (1989). USS Arizona Memorial and Pearl Harbor National Historic Landmark. Southwest Cultural Resources Center Professional Papers.
Licht, S., Wibawa, M., Hover, F., & Triantafyllou, M. (2009, September). Toward amphibious robots: Asymmetric flapping foil motion underwater produces large thrust efficiently. In Proceedings of the International Symposium on Unmanned Untethered Submersible Technology, Durham, NH.
Mallios, A., Ridao, P., Hernandez, E., Ribas, D., Maurelli, F., & Petillot, Y. (2009, May). Pose-based SLAM with probabilistic scan matching algorithm using a mechanical scanned imaging sonar. In Proceedings of the MTS/IEEE Oceans Conference (Europe), Bremen, Germany.
McCann, A. M., & Freed, J. (1994). Deep water archaeology: A late Roman ship from Carthage and an ancient trade route

near Skerki Bank off northwest Sicily. Journal of Roman Archaeology, Supplementary Series, 13.

McGlamery, B. (1975). Computer analysis and simulation of underwater camera system performance (Tech. Rep. SIO Ref. 75-2). Scripps Institution of Oceanography.

Mindell, D. A., & Bingham, B. (2001, November). New archaeological uses of autonomous undersea vehicles. In Proceedings of the MTS/IIEEE Oceans Conference, Honolulu, HI.

Negahdaripour, S., Xu, X., & Jin, L. (1999). Direct estimation of motion from sea floor images for automatic station-keeping of submersible platforms. IEEE Journal of Oceanic Engineering, 24(3), 370–382.

Negahdaripour, S., & Xun, X. (2002a). Mosaic-based positioning and improved motion-estimation methods for automatic navigation of submersible vehicles. IEEE Journal of Oceanic Engineering, 27(1), 79–99.

Negahdaripour, S., & Xun, X. (2002b). Mosaic-based positioning and improved motion-estimation methods for automatic navigation of submersible vehicles. IEEE Journal of Oceanic Engineering, 27(1), 79–99.

Olson, E., Leonard, J. J., & Teller, S. (2006). Robust range-only beacon localization. IEEE Journal of Oceanic Engineering, 31(4), 949–958.

Pizarro, O., Eustice, R., & Singh, H. (2009). Large area 3-D reconstructions from underwater optical surveys. IEEE Journal of Oceanic Engineering, 34(2), 150–169.

Roman, C., & Singh, H. (2005, August). Improved vehicle based multibeam bathymetry using sub-maps and SLAM. In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Edmonton, Alberta, Canada.

Roman, C., & Singh, H. (2007). A self-consistent bathymetric mapping algorithm. Journal of Field Robotics, 24, 23–50.

Sakellariou, D. (2007a). Integration of sub-bottom profiling and side scan sonar data in deep water archaeological research: Site formation and interpretation of geophysical recordings. SKYLLIS, 2007/08, 155–164.

Sakellariou, D. (2007b). Remote sensing techniques in the search for ancient shipwrecks: How to distinguish a wreck from a rock in geophysical recordings. Bulletin of the Geological Society of Greece, XXXVII(4), 1845–1856.

Sakellariou, D., Georgiou, P., Mallios, A., Kapsimalis, V., Kourkoumelis, D., Micha, P., Theodoulou, T., & Dellaporta, K. (2007). Searching for ancient shipwrecks in the Aegean Sea: The discovery of Chios and Kythnos Hellenistic wrecks with the use of marine geological–geophysical methods. International Journal of Nautical Archaeology, 36, 365–381.

Singh, H., Adams, J., Foley, B., & Mindell, D. (2000). Imaging for underwater archaeology. American Journal of Field Archaeology, 27(3), 25–35.

Singh, H., Armstrong, R., Gilbes, F., Eustice, R. M., Roman, C., Pizarro, O., & Torres, J. (2004). Imaging coral I: Imaging coral habitats with the SeaBED AUV. Journal of Subsurface Sensing Technologies and Applications, 5(1), 25–42.

Singh, H., Can, A., Eustice, R. M., Lerner, S., McPhee, N., Pizarro, O., & Roman, C. (2004). SeaBED AUV offers new platform for high-resolution imaging. EOS, Transactions of the American Geophysical Union, 85(31), 289, 294–295.

Singh, H., Eustice, R. M., Roman, C., & Pizarro, O. (2002, September). The SeaBED AUV: A platform for high resolution imaging. In Unmanned Underwater Vehicle Showcase, Southampton, UK.

Singh, H., & Howland, J. (1999). A forensic analysis of the remains of flight EA990. Poster, Woods Hole Oceanographic Institution.

Singh, H., Howland, J., & Pizarro, O. (2004). Advances in large-area photomosaicking underwater. IEEE Journal of Oceanic Engineering, 29(3), 872–886.

Singh, H., Roman, C., Pizarro, O., Eustice, R., & Can, A. (2007). Towards high-resolution imaging from underwater vehicles. International Journal of Robotics Research, 26(1), 55–74.

Singh, H., Weyer, F., Howland, J., Duester, A., & Bradley, A. (1999, October). Quantitative stereo imaging from the Autonomous Benthic Explorer (ABE). In Proceedings IEEE/MTS OCEANS Conference and Exhibitions, Seattle, WA (vol. 1, pp. 52–57).

Soreide, F., & Jasinski, M. (2005, September). Ormen Lange: Investigation and excavation of a shipwreck in 170 m depth. In Proceedings of the MTS/IEEE Oceans Conference, Washington, DC (vol. 3, pp. 2334–2338).

U.S. Navy (2004). The Navy unmanned undersea vehicle (UUV) master planning (Tech. Rep.). Department of the Navy. Available at http://www.navy.mil/navydata/technology/uuvmp.pdf.

Vaganay, J., Elkins, M., Esposito, D., O'Halloran, W., Hover, F., & Kokko, M. (2006, September). Ship hull inspection with the HAUV: US Navy and NATO demonstrations results. In Proceedings of the MTS/IEEE OCEANS Conference, Boston, MA.

Warren, D. J., Church, R. A., & Eslinger, K. L. (2007, May). Deepwater archaeology with autonomous underwater vehicle technology. In Offshore Technology Conference, Houston, TX.

Webster, S. (2008). The development of excavation technology for remotely operated vehicles. In R. D. Ballard (Ed.), Archaeological oceanography (pp. 41–65). Princeton, NJ: Princeton University Press.

Xu, X., & Negahdaripour, S. (2001, May). Application of extended covariance intersection principle for mosaic-based optical positioning and navigation of underwater vehicles. In Proceedings IEEE International Conference on Robotics and Automation, Seoul, South Korea (vol. 3, pp. 2759–2766).