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Autonomous underwater vehicles as tools for deep-submergence archaeology

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Abstract: Marine archaeology beyond the capabilities of scuba divers is a technologically enabled field. The tool suite includes ship-based systems such as towed side-scan sonars and remotely operated vehicles, and more recently free-swimming autonomous underwater vehicles (AUVs). Each of these platforms has various imaging and mapping capabilities appropriate for specific scales and tasks. Broadly speaking, AUVs are becoming effective tools for locating, identifying, and surveying archaeological sites. This paper discusses the role of AUVs in this suite of tools, outlines some specific design criteria necessary to maximize their utility in the field, and presents directions for future developments. Results are presented for a recent joint AUV–towed system survey and a demonstration of current mine-hunting technologies applied to archaeology.

Keywords: autonomous underwater vehicles, deep-submergence archaeology, towed side-scan sonars, mine-hunting technologies

1 INTRODUCTION

The development of marine robotic systems, and in particular autonomous underwater vehicles (AUVs), has launched a revolution in oceanographic science and exploration. Improved battery technology and low-power electronics now allow vehicles to have dive times beyond 24 h, ranges greater than 100 km, and the ability to carry a vast array of acoustic, optical, and chemical sensors. Several commercial companies now build scientific-quality AUVs with high-field reliability and depth ratings to 6000 m.

Such assets have become viable tools for bottom surveying and bathymetric data collection as well as for environmental sensing in the water column. An AUV's proximity to the bottom allows for high-frequency sonars and imaging with centimetre-level resolution in deep water. Even in shallow water the superior handling of AUVs, with steady speed, minimal pitch and roll motions, constant altitude control, and efficient turns, makes them attractive platforms in comparison with tow bodies and hull-mounted systems on surface vessels. The data products are actively used in marine geology for topics ranging from submarine volcanoes to sand ripples [**1–8**], marine archaeology [**9–12**], oil exploration [**13**], habitat mapping [**14–16**], and sea ice mapping [**17–19**].

Within marine archaeology specifically, AUVs have utility for much of the data collection and investigative phases composing a complete field programme: large-area search, target identification, localized survey, and excavation [**20**]. The requirements for these phases utilize different aspects of AUV design, mission planning, and sensor selection.

The remainder of this paper discusses these phases in turn and highlights the relevant issues related to using AUVs in this expanding field. The data presented here are obtained from several AUV systems carrying specialized mapping sensors tested during the US National Oceanic and Atmospheric Administration (NOAA) and Office of Naval Research (ONR) AUVfest 2008 [**21**] demonstration of mine-hunting technologies for marine archaeology, a large transect survey performed with joint AUV–towed system operation, and a deep-water remotely operated vehicle (ROV)

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system that has been used extensively for small-scale wreck surveys. These data products highlight many of the desirable capabilities of AUV systems, indicate areas for future development, and demonstrate the growing links between the archaeological community and the scientific, military, and commercial enterprises interested in developing this technology.

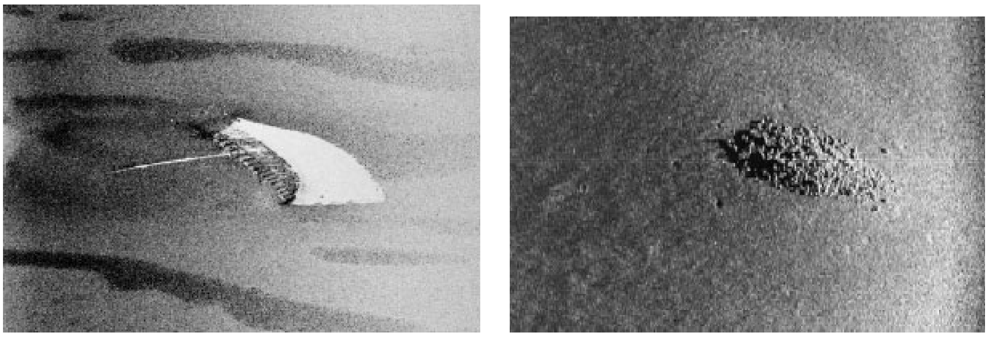
2 LARGE-AREA SEARCHES

In general, advances in underwater archaeological survey theory have lagged behind comparable developments on land [**22–25**]. While land-based surveys have moved towards statistical and structured models that foster the understanding of site distributions, the density of sites, and/or the human use of inter-site zones, most underwater archaeological surveys remain centred on finding uniquely important, frequently well-bounded sites. This is often referred to as archaeological prospecting [**26**]. The most common targets for these investigations are discrete shipwrecks. Underwater archaeologists have used both visual survey techniques and an array of geophysical tools such as towed side-scan sonars, multi-beam bathymetry, and magnetometers to locate these kinds of site and have done so with some success. Combining these geophysical instruments with AUV platforms offers the prospect of greatly increased efficiency of shipwreck archaeological prospecting, which seeks to maximize coverage while minimizing the occurrence of false positives. The same amalgamation of technologies, however, can also be used to survey the broader cultural landscape in a more systematic manner, i.e. an approach that is designed to generate statistically reliable estimates of the number, density, and distribution of sites across a region or, in other words, a survey strategy more closely aligned with recent advances in archaeological survey method and theory on land. Under this scenario, the survey objectives would probably be diachronic and designed to understand long-term changes in human use, navigation, fishing, trade, warfare, and communication in a region. Such a strategy would require that data be gathered evenly throughout the marine landscape running ‘across the grain of environmental variability’ [**27**].

AUVs offer great flexibility in this regard to achieve broad but yet high-resolution results beyond the capabilities of towed systems which in general suffer from a number of drawbacks that compromise both their data quality and their efficient practical use. Independent of the choice of operating frequency, side-scan sonar data are quickly degraded by extraneous motions of the tow fish [**28**]. Towed systems are primarily affected by ship heave coupling through the tow cable that introduces pitch, roll, and yaw motions at the fish. Depending on the tow configuration and the possible use of an intermediate clump weight, this coupling still inevitably increases with increased ship motion. The steady motion of AUVs separated from surface effects is a distinct advantage in most situations when looking for small targets, such as scattered artefacts away from a wreck or lone ancient amphora, potentially indicating areas of past shipping traffic, which even in ideal conditions are only visible in a small number of sonar pings.

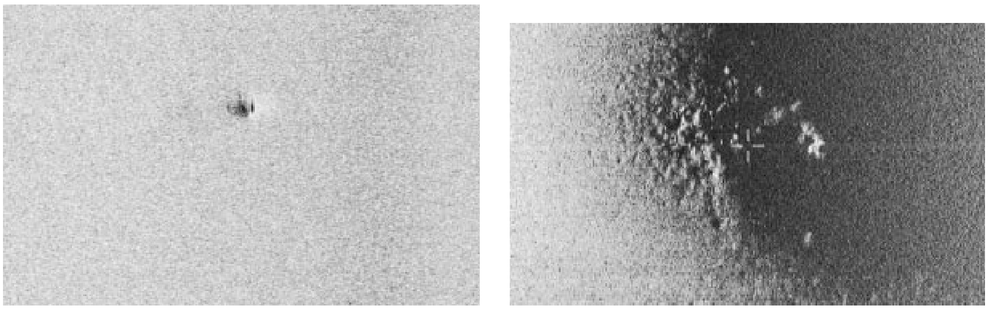
In deep water the layback, or the sonar’s distance behind the ship, creates additional problems. A layback of several kilometres is not uncommon in water depths of several thousand metres, even for ships towing as slowly as 2 kn. Such situations restrict the ship’s ability to perform efficient turns, make following the bottom at a desired altitude difficult, and compromise any ability to stop quickly and to investigate a target without time-consuming ship handling. Safely making manoeuvres in deep water often requires lifting towed systems off the bottom and sacrificing data as the speed and tow angle vary in a turn. The tight fast turns of an AUV allow efficient surveying by reducing the time requirements of large ship turns and maximizing the coverage of a new area [**29**].

The effectiveness of large-area searches and the identification of archaeological sites can be measured to some degree by the number of targets that require additional investigation for classification. When searching for a specific item, obviously the ideal number of targets is one. However, when exploring for previously unknown sites, the exact number and signature of valid targets are not known *a priori*. In this case, it is often more challenging to separate out false positives. Figure 1 shows example sonar signatures of several wreck sites taken with different side-scan sonar systems. Larger, more modern wrecks (Fig. 1(a)) are fairly obvious. Ancient wrecks, however, are more difficult to identify and classify as non-geological in nature when completing a large-area survey [**30**, **31**]. Field experience searching for early modern and ancient wrecks, which are typically less than 15 m in length with less than a metre of relief, has demonstrated the need for sonars at frequencies of 300 kHz and greater. Conventional side scans below 300 kHz have significant difficulty in resolving such wrecks to the degree that subsequent investigation is not needed. The obvious downside of using higher frequencies, however, is the reduced range and increased time required to search any given area.



(a) Grand banks wreck, 900 kHz

(b) Large ancient wreck, 600 kHz

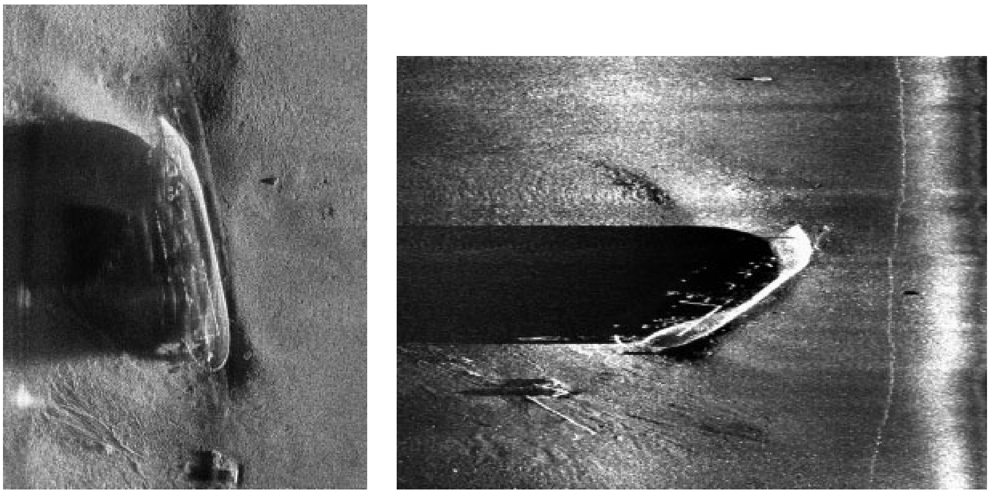


(c) Trawled ancient wreck, 100 kHz

(d) Cluster of rocks, 300 kHz

Fig. 1 Sample side-scan sonar images of small wrecks: (a) an approximately 15 m boat found on the Grand Banks AUV survey described in section 4; (b) the ancient wreck shown in detail in Fig. 6; (c) a small ancient wreck consisting of only a few amphora and a collection of ballast stones that was probably trawled; (d) a geological outcrop that looks very similar to the typical size and shape of ancient wrecks

Beyond conventional side-scan sonars, synthetic aperture, focused, chirp and multi-ping systems have tremendous potential for archaeological work on AUVs. Synthetic aperture sonar (SAS) systems use coherent signal processing to combine separate pings to create high-resolution images which have range-independent along-track resolution [**32**, **33**]. To achieve this precision, platform navigation measurements are required. AUVs with inherently steady motion and high-performance inertial navigation sensors are ideal platforms for SAS systems and are starting to become commercially available for survey work. Figure 2 shows a comparison between a 900 kHz conventional side scan and data collected using the



(a) SAS12 image

(b) Conventional 900 kHzside scan

Fig. 2 Comparison between an SAS system image and a conventional side scan collected during AUVfest 2008. The wreck's beam is approximately 7 m

180 kHz SAS12 system [**34**] during the AUVfest 2008 trials. The SAS12 system has a nominal resolution of 2.5 cm×2.5 cm and was designed as a mine-hunting tool for proud and partially buried objects. The obvious advantage for marine archaeology is the ability to identify small objects at ranges greater than would be possible with conventional sonar systems. The current drawbacks of SAS systems, however, are their overall cost, the peripheral need for precise platform navigation, and the significantly increased data-processing demands that require more power on the vehicle and operator expertise for post-processing. As a midpoint, many vendors now sell focused and multi-ping chirp sonars for AUVs that are able to increase along-track resolution. These systems enable more flexibility in mission planning by allowing higher speeds for a given resolution and better image fidelity at longer ranges.

3 TARGET IDENTIFICATION

The identification phase requires confirming that targets detected in the large-area search are indeed of archaeological interest. The difficulty in doing this stems from the quality of the data obtained during the large-area search and the costs associated with additional survey efforts to obtain unambiguous information about a site. This can, in general, be framed as a multi-scalar problem where the larger-area search maximizes coverage and the identification survey maximizes fidelity. Successful strategies in this context can exploit the dual high- and low-frequency capabilities of side-scan sonar systems together with visual images provided from camera systems and magnetometers to identify ferrous materials. Using towed sonar and optical imaging systems the true cost of target identification can quickly become a limiting factor. Repeated site-specific deployments with either ROV systems or by making additional sonar passes with higher frequencies at lower altitudes is time consuming and resource intensive. In this context, AUVs have a distinct advantage to transit quickly between potential targets and to perform small-scale detailed surveys at lower altitudes with higher-resolution sensors. The flexibility in AUV mission planning allows these surveys to account easily for positioning errors in the large-scale search and efficient travel between individual sites.

3.1 Multi-scalar mapping

To attempt to merge the large-scale search and target identification phases, joint operation of towed systems and autonomous systems offers significant potential. In 2008, a joint survey transect stretching from Cape Race to the edge of the Grand Banks south of Newfoundland, Canada, a distance of approximately 240 km, was completed. This survey was designed to experiment with new ideas about underwater archaeological survey. The survey represented the first phase of an anticipated multi-year investigation of the Grand Banks cultural landscape, an area too large to hope to obtain complete coverage without prohibitive expense. The initial survey strategy was based on a series of radial transects, aligned with the cardinal and intermediate points of the compass, originating at Cape Race, Newfoundland. History records more than 3250 known shipwrecks in Newfoundland waters, which represent multiple human uses and impacts on one of the most historically and archaeologically important areas in the North Atlantic.

The transect consisted of two parallel survey lines, 300 m apart (Fig. 3). Along the first line, the *R/V Endeavor* towed a conventional dual-frequency side-scan sonar (100–400 kHz) and ran its 3.5 kHz sub-bottom profiler. Along the second line, the Atalanta AUV (Fig. 3) collected high-frequency (300–900 kHz) side-scan data and 675 kHz multi-beam data. The combined suite of systems and sensors provided high-resolution narrow coverage (120 m swaths) and low-resolution broad coverage (300 m swaths) of the bottom surface together with some subsurface data. The data were used for archaeological site survey, broad cultural landscape survey, and geological survey.

To start the survey, the AUV was deployed and set to loiter in an area offset from the intended ship track. After the towed sonar was launched, the AUV and ship started their respective parallel track lines. This separation kept the AUV safely away from the ship while allowing an area of overlapping data for comparative evaluation of the two different sonar frequencies and incidence directions. Additional periodic loitering points were programmed into the AUV mission to allow coordination to be maintained. Between these points the nominal ship speed of 2.5 kn was adjusted slightly either to give or to take ground from the AUV moving at a nominal 3.5 kn. Small changes in the ship speed do not require significant tow cable management or cause degradation of the data. At a loitering loop the ship and AUV were able to establish acoustic modem contact and to resynchronize their progress. In the event of a communications failure, the looping behaviour maintained the AUV in a known area away from the ship's intended path. For this relatively shallow survey, less

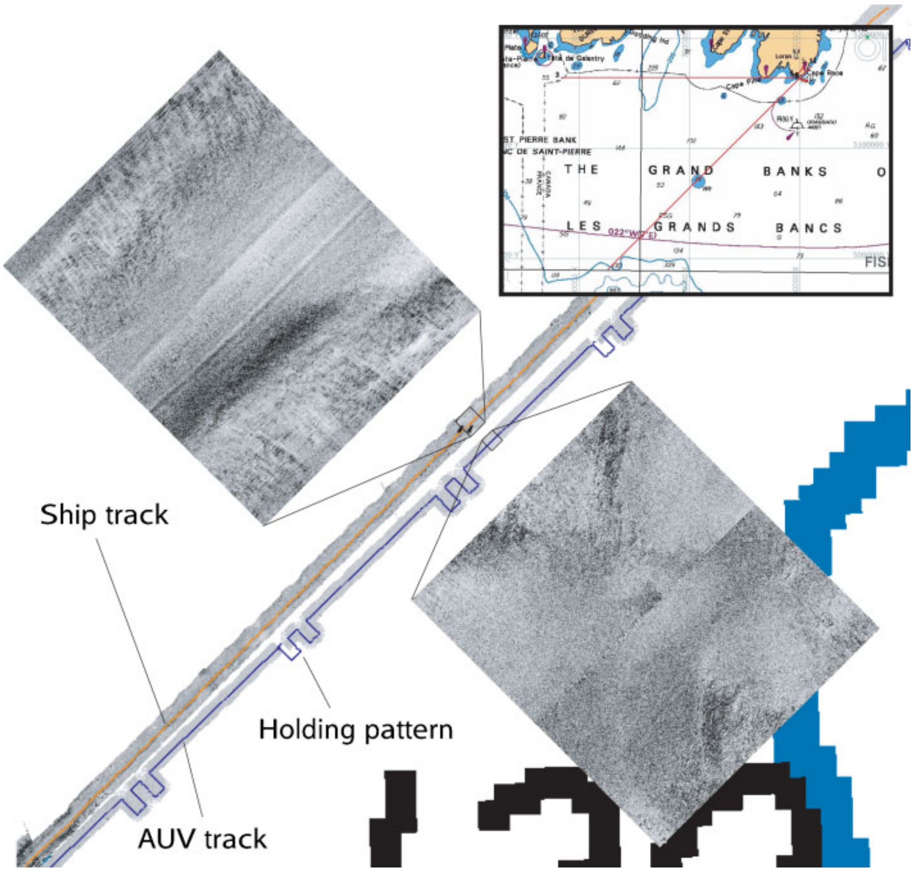


Fig. 3 Section of the joint ship-based side-scan and AUV operation. The AUV performed a high-resolution 300 kHz side scan 40 km long which was line offset from the ship towing a lower-frequency swath system 100 kHz wide. Periodic holding patterns were used to keep the ship and AUV coordinated. A 300 m lateral separation was maintained between the ship and the AUV

than 200 m deep, the AUV was also commanded to surface at a loitering point every 12 km along the line. This helped to bound the accumulated navigation drift by providing a Global Positioning System fix and also provided a safety measure to establish Iridium contact with the AUV in the event of any prolonged acoustic communications blackout. These systematic survey blocks are also comparable with evenly spaced archaeological test units used in conventional archaeological survey.

The benefits of such a survey are increased coverage and multiple resolutions, each obtained at their optimal survey altitude. Further development of this concept will entail acoustically commanding the AUV to investigate targets quickly as they appear on the towed side-scan system. Managing the speed of the ship, the speed of the AUV, and the size of the identification surveys would allow the AUV time to make high-resolution passes over ‘interesting’ targets and then to rejoin the ship. Such a system has several significant benefits. The real-time human in the loop will provide a check and initial classification of the sonar targets before sending the AUV off for further investigations [**35**]. This reduces the need for real-time side-scan target classification algorithms looking for wrecks which may present with various signatures. By accomplishing the investigation at the moment of discovery, there will be little subsequent need to backtrack the ship and towed system for additional looks at targets.

Significant longer-term development of this concept could use the towed side-scan system as a dock for the AUV. The AUV could be released from the dock when a target is found or could periodically reconnect to the dock for power and data transfer. AUV docking has been accomplished for static systems [**36**, **37**] and is likely for moving vessels and tow bodies [**38**]. Access to periodic data download, either from docking or from compressed images telemetered via acoustic communications [**35**], can be used in the event of a significant discovery to stop the entire search operation without having to wait for a complete AUV mission to finish.

3.2 Multi-sensor investigations

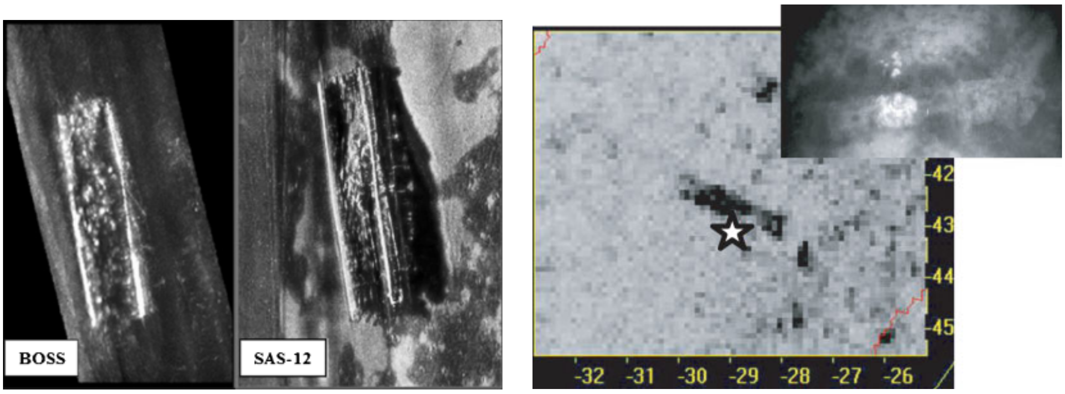
The archaeological community will also benefit from the military-funded efforts related to subsurface target classification and identification techniques. The mine countermeasures problem has sponsored a significant amount of research for object classification using bottom penetration acoustics and surface imaging with simultaneous magnetic sensing. The AUVfest 2008 demonstrations featured the bottom-object-scanning sonar (BOSS) system [**39**] with a real-time tracking magnetic gradiometer (RTG) [**40**]. The BOSS system is a low-frequency broadband 3–20 kHz bottom-penetrating sonar which uses synthetic aperture processing to create subsurface images of buried objects in the upper bottom layers. The combined RTG provides coregistered identification of magnetic targets [**41**], and from an archaeological perspective is a power tool for disambiguating potential artefacts in complex terrain. Figure 4 shows example data for the BOSS system, which was able to register acoustic and magnetic field signatures of buried cannons and numerous other smaller objects.

Beyond confirming sites of interest, such multi-scalar and multi-modal capabilities will enable simultaneous studies of specific wreck sites to be made, together with the larger environmental context in which they lie. Many physical factors such as the dissolved oxygen concentration for sites in the Black Sea [**42**] and the local currents which cause scour around a wreck [**43**] are indicators of the overall preservation state of a wreck.

4 SITE SURVEY

Detailed investigations of archaeological sites underwater have been carried out by human divers for the past several decades [**44–46**]. Frequently these are efforts of enormous undertaking requiring thousands of man-hours to complete over multi-year field seasons. The move past the depth limitations of human divers with the technological capabilities of controlled robotic vehicles was first seen using ROVs to explore ancient wrecks in the Mediterranean Sea starting in 1989 [**47**, **48**]. Since then the practice of deep-submergence archaeology has strived to provide site documentation and mapping at a standard set by the archaeological communities' practices for shallow marine sites and land excavations. This requires detailed photographic mapping and preservation of the spatial relationships between objects at the site [**49–51**]. Achieving this goal spawned the innovation and adoption of high-precision local acoustic positioning, the use of high-resolution cameras for multi-image photomosaicking [**52**], and sonar systems for microbathymetric mapping [**10**]. Examples of a recent and typical wreck survey using these techniques are shown in Figs 5 and 6. Although this and the majority of similar work [**53–55**] have been completed using ROVs the survey potential using an AUV has been demonstrated [**9**] and is clearly viable.

The execution of successful AUV surveys over such sites lies at the intersection of a vehicle's surveying capabilities, the sensor suite that it is able to carry, and the subsequent data-processing techniques that will be used to create the final data products. The vehicle capabilities for small-area surveys are defined by low-speed handling for precise track-line



(a) BOSS / SAS12 comparison (b) BOSS / RTG

Fig. 4 Data from the BOSS system: (a) comparison of the low-frequency BOSS system with the higher-frequency SAS12 sonar over a 12 m sunken barge; (b) localization of a cannon 2.5 m long shown over BOSS data. The localized magnetic location is indicated by the star. The inset shows an optical image of the cannon taken in turbid conditions

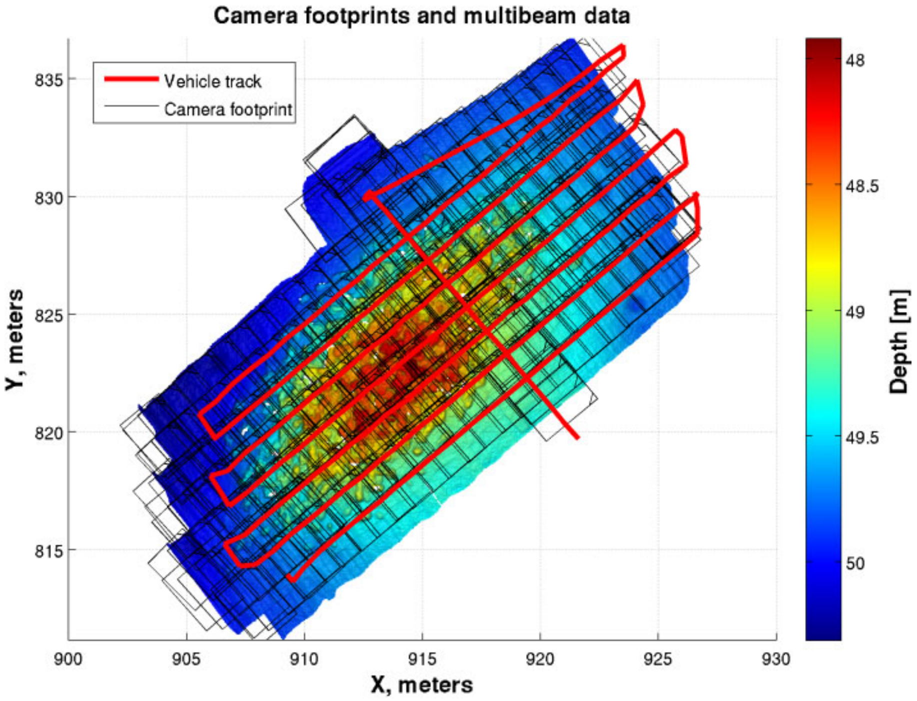
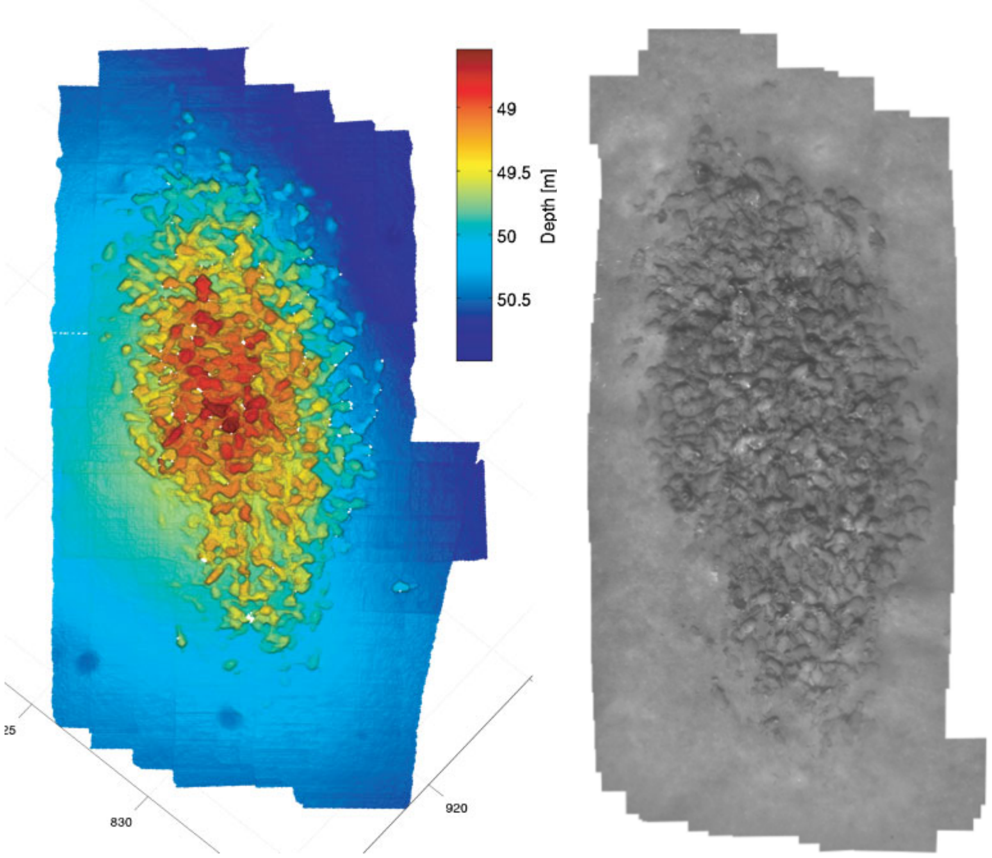


Fig. 5 Track lines from an ROV survey over a wreck site. The lines were flown at a constant altitude of 2.5 m using closed-loop control. The overlapping image footprints are shown over the simultaneously collected multi-beam bathymetry. The full bathymetry map and photomosaic are shown in Fig. 6

following, constant altitude control, and general platform stability. The two general classes of AUVs which have been developed, namely torpedo shaped and hovering, have different characteristics in this regard. Hovering vehicles such as the Woods Hole Oceanographic Institution SeaBED vehicle [**56**] shown in Fig. 7 are specifically designed for low-speed stability and manoeuvrability. With down-looking cameras and sonar the vehicle is able to survey at slow speeds (10–25 cm/s) and to complete tight, nearly zero-radius turns. This allows efficient surveys over small sites and tight altitude control with minimal pitch motion. Torpedo vehicles on the other hand require a minimum forward speed, typically between 1.5 kn and 2.5 kn, to maintain control. These vehicles will also see more roll and pitch coupling during manoeuvres and have a harder time adjusting to maintain a constant altitude over length scales of tens of metres. Some of these vehicles, however, have been fitted with forward fins and ducted lateral thrusters to improve their stability for SAS applications [**57**] and use in complex harbour environments. The forward fins and thrusters aid in track-line following by allowing the vehicle to fly lines without crabbing in a cross-current and also to reduce the minimum steerage speed, resulting in denser sampling with fixed-rate sensors. The potential advantage of designing a torpedo-style vehicle in this manner is its dual applicability for the large-area search problem. Hovering vehicles have a significant drag and power disadvantage for working over larger areas at speed upwards of 3 kn typical for side-scan sonar work. Hybrid concepts, however, such as the Woods Hole Oceanographic Institution Sentry vehicle, which preserves the high stability of a hovering design in a low-drag shell, offer potential for operations on both scales.

The sensor suites appropriate for AUV and ROV survey operations have become identical because of the shrinking size of high-frequency multi-beam sonars and high-resolution and dynamic-range cameras. The results shown in Figs 6, 8, and 9 were produced using 12-bit Prosilica cameras, a 2250 kHz Blueview multi-beam sonar, and a single 532 nm laser line for structured light imaging.

The full potential for AUV mapping comes from addressing the navigation and data collection requirements in the context of the intended data products and processing techniques. Precise underwater navigation is a persistent problem. There are numerous options to obtain metre-level ground-referenced positions with either long-baseline systems or, depending on range, some ultra-short-baseline systems. The options are fewer, however, for obtaining ground-referenced centimetre-level or better direct-positioning measurements over an archaeological site [**50**, **58**] consistent

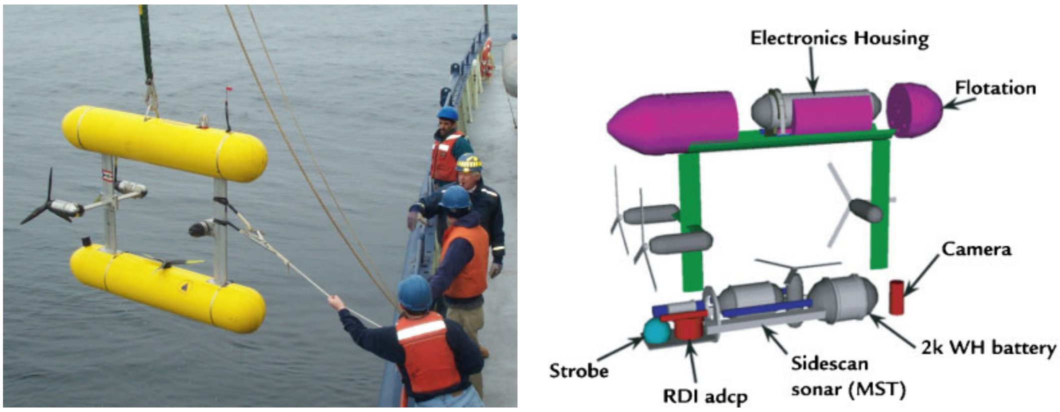


(a) Bathymetric map, two meter vertical scale

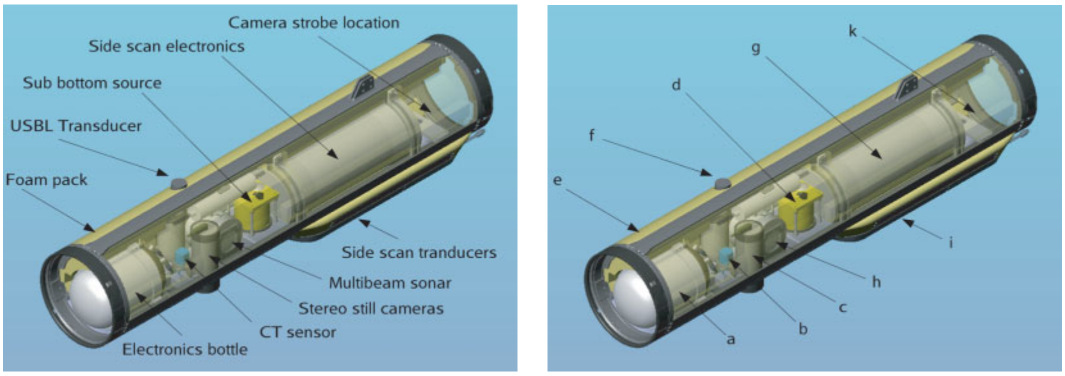
(b) Photomosaic

Fig. 6 (a) Bathymetric multi-beam map of an ancient wreck, showing 2 m of relief, produced using a 2250 kHz sonar; (b) photomosaic of the same wreck site assembled from 192 still images taken with a down-looking fixed-focus camera and strobe lighting

with using scuba divers and direct measurements [**59**, **60**]. Dead-reckoning solutions utilizing high-performance fibre-optic gyroscopes and Doppler velocity log speed over the ground measurements are able to achieve this level of performance over the short term but cannot fundamentally bound the time-dependent error growth from continual integration [**61–63**]. To combat these limitations in a way applicable to both hovering and torpedo-shaped vehicles, data-processing techniques have leveraged the simultaneous localization and mapping (SLAM) framework that has become a well-developed topic within the robotics community as a whole. The main benefit of the SLAM framework is the use of mapping sensor data, either visual or acoustic, to minimize the negative effects of poorly constrained direct navigation measurements. The use of SLAM techniques, however, places some conditions on the survey execution and data coverage. Such visual [**64–69**] and acoustic mapping techniques [**70**, **71**] require dense data coverage and high image or swath sonar overlap to ensure that sufficient constraining information is available to reduce navigation errors uniformly. These constraints directly dictate the required track-line spacing, speed, and altitude of the vehicle during a survey. Camera images over such sites are typically collected at altitudes between 2.5 m and 5 m, depending on the water clarity. High-frequency multi-beam or scanning sonars are typically able to maximize the resolution using range scales of 5 m or 10 m. Visual data processing in general benefits from image overlaps of at least 50 per cent in both along-track and cross-track directions, which practically implies track-line spacings between 1 m and 2 m. SLAM techniques also benefit from ‘tie’ lines which cross back over previous track lines to ensure complete back projection of accrued errors. These constraints are easily handled by hovering vehicles but can pose a significant challenge to torpedo vehicles. The use of forward fins to reduce steerage speeds in conjunction with high-rate imaging is a potential solution for this. The development of light-emitting diode strobes as fast lower-power alternatives to traditional flash bulbs



(a) Seabed (b) Components



(c) Atalanta (d) Components

Fig. 7 (a) Twin-hulled SeaBED AUV being recovered (photograph provided by H. Singh, Woods Hole Oceanographic Institution); (b) component layout of SeaBED, with sensors and heavy items on the bottom, and flotation in the top hull for high passive stability (RDI adcp, Teledyne RD Instruments acoustic Doppler current-profiling instrument; MST, Marine Sonic Technology, Ltd); (c) Atalanta AUV designed as a combination of a commercially available Hydroid REMUS 600 and a custom-designed payload section for mapping and searching; (d) sensor layout of the Atalanta payload section (USBL, ultra-short-baseline; CT, conductivity–temperature)

[**72**] will probably provide the necessary frame rates to keep the required survey speeds above the 1.5 kn steerage threshold while maintaining image overlap.

Even with these dense data constraints, ROVs and AUVs have been able to photograph and map wreck sites in a manner of hours that would have otherwise taken years with human divers. There are, however, some limitations which need to be overcome to ensure complete and accurate mapping. A significant issue is the persistent occlusions created by using only down-looking cameras from above a site. The stereo pair reconstruction in Fig. 8 shows how this manifests itself as areas of nondescript information around objects with vertical surfaces. Although the coverage shown in the photomosaic in Fig. 6 looks complete, there is a significant amount of undocumented space in regions with significant three-dimensional shape. As data-processing techniques improve and the inclusion of images taken from more diverse vantage points is possible, archaeological surveys will benefit from vehicles carrying oblique-looking cameras at lower altitudes over wreck sites. The potential difficulty in doing so, beyond obstacle avoidance, will primarily be creating appropriate lighting. Lighting is difficult for vehicles which carry their own lights, and the placement of lights relative to the cameras is the dominant factor in obtaining clear underwater images not contrast-limited by backscatter [**73**]. The solution will probably require multiple light sources on a vehicle which project sufficient light and minimize shadowing problems within single images and between images taken at different locations. For example, a single strobe creates oppositely cast shadows on adjacent survey lines flown with reciprocal headings. This can make subsequent image processing difficult, as the

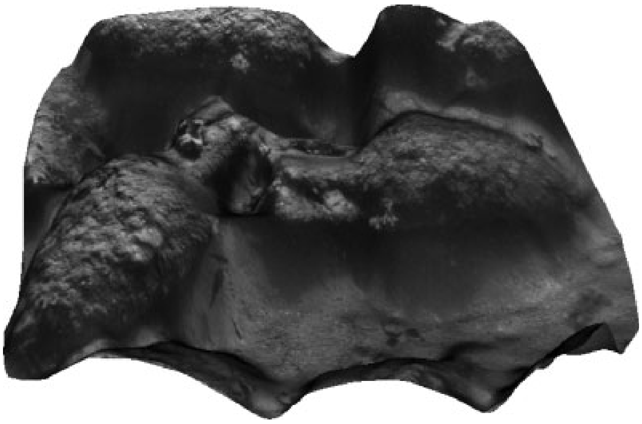
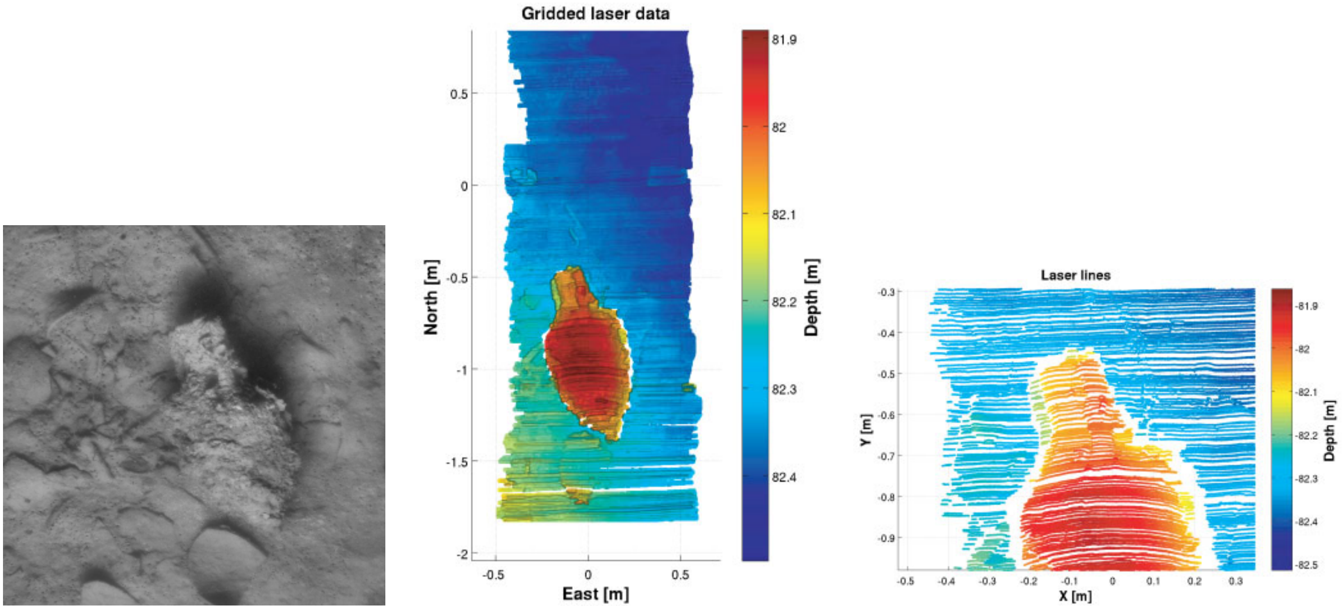


Fig. 8 Three-dimensional stereo reconstruction of a 1.5 m × 1.5 m section from the survey in Fig. 6 showing several ancient amphora. Note the nondescript edges and overhung occlusions that are a persistent problem for obtaining truly complete data coverage. The stereo cameras were 2 m above the scene and had a baseline separation of 30 cm

shadow edges are typically distinct but varying features in a scene [**66**]. Unfortunately, maintaining several light sources and cameras sufficiently separated is practically difficult. The potential advantage of using multiple vehicles for optimally placing cameras and light source has been proposed [**74**], but the inherent issues of relative positioning, coordination, and reliability have not yet been implemented in practice. In this regard, ROVs have the advantage of being generally larger, more flexible vehicles without stringent drag constraints. To date, ROVs have primarily been used to create the most detailed maps of these sites, down to subcentimetre resolution (Fig. 9), but the potential for AUVs is enormous and will continue to spur innovation.

5 EXCAVATION

The excavation of an underwater site by human divers or robotic vehicles is a resource- and time-intensive undertaking. Beyond the numerous issues and questions related to the overall methodology, site preservation, object recovery, and treatment of cultural artefacts, there are enormous technical challenges. Successful excavations with scuba divers have taken a decade to complete [**46**]. For such projects, AUVs offer a compelling efficiency in documenting the progress of an excavation carried out by divers or ROVs. A significant fraction of the excavation process involves surveying the site after items are removed or new items are uncovered. The goal should be recording and preserving these steps by compiling a time lapse digital excavation with sufficient fidelity to enable additional work to be carried out from the records after the actual excavation has been com-



(a) Single amphora (b) Gridded laser data (c) Raw laser lines

Fig. 9 Small-scale laser-structured light mapping: (a) photograph of an amphora; (b) bathymetric representation gridded on 2.5 mm mesh; (c) close-up of the laser sample lines showing sufficient resolution to distinguish between the handle features pleted. The repeatable survey capabilities of AUVs could be used to make periodic photographic and topographic maps of wreck sites in far less time than would be possible with human divers and even pilot-intensive ROV surveys. This would significantly reduce many of the true costs for such excavations by shortening the total time requirements and enabling appropriate resources and man-power to be better allocated. The efficiency of collecting data and processing it for mapping and change detection will also result in feedback to create better real-time planning of on-site operations. Subbottom profilers and sonars such as the BOSS system will also be extremely valuable when attempting excavations with purely robotic tools.

6 SUMMARY

Looking forwards, there are many specific aspects of marine archaeology that will substantially benefit from the use of AUV systems. Their large-scale search capabilities provide efficient coverage and operation beyond what is currently possible with towed systems alone. Additionally, the coordinated use of AUVs and towed systems is a promising future direction which offers multi-scalar mapping and mission adaptation to increase overall productivity and target investigations. For site mapping and recording, AUVs are able to perform detailed surveys and to obtain coregistered multi-sensor data. In shallow water they can provide high-fidelity data and complement efforts of human divers to produce significant time savings. The specific requirements for this work translate to several design aspects for hovering and torpedo-style vehicles. The ability to fly dense survey patterns and to achieve high along-track and cross-track sensor overlap is essential to make full use of the many subsequent data-processing techniques able to handle navigation uncertainty robustly. Future developments in these areas for the broader set of AUV applications will also ensure that AUVs play an increasingly beneficial role in marine archaeological work. Directly connecting these technologies, however, with the needs and demands of the archaeology community remains an open question in many aspects. For large-scale searches and target identification, AUVs are unquestionably the most powerful tools available, but a complete cost–benefit analysis including the expenses for ship time, the assets themselves, and the personnel to run them is difficult to generalize and is project specific. Access by the archaeological community to these systems is, however, increasing through collaborations such as AUVfest 2008. Partnerships developed during AUVfest will make AUVs available to the archaeological community for an upcoming project at the Thunder Bay National Marine Sanctuary and Underwater Preserve in Lake Huron sponsored in part by the NOAA Office of Ocean Exploration and Research (OER). The inclusion of submerged cultural resource surveys into the planning processes of agencies such as the US Minerals Management Service, which is responsible for permitting offshore energy projects, will also provide multi-use archaeological and geological data. Projects by companies such as C & C Technologies in the Gulf of Mexico [**11**] and partnerships on Noways's Ormen Lange gas field [**75**] demonstrate the use of these assets for cultural assessment when prospecting in economically important areas. For detailed site surveys there are still numerous questions pertaining to the achievable mapping accuracies that ROV and AUV systems can actually provide. In general, it is difficult to predict and convey many of the errors that are specific to each sensor type and generally vary spatially over a site. The millimetre-level accuracy now afforded to the land archaeology community by common commercial laser scanning systems is becoming more achievable for deep-submergence archaeology. A best practice, however, for translating these vehicle-based optical and acoustic mapping surveys into useful archaeological data and site maps is still being developed [**60**].

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