Deep Water, Archaeology and Technology Development

PAPER

David A. Mindell and
Katherine L. Croff
DeepArch, *Deep Water Archaeology Research Group*
Massachusetts Institute of Technology
Cambridge, Massachusetts

ABSTRACT

Over the past decade and a half, archaeology in deep water has been driven by technology available to only a handful of archaeologists. The field has now grown to a point where new tools are needed to address new questions and requirements. This paper addresses the problems inherent in conducting archaeological work in deep water and the new directions in which technology can go in response to these challenges. We describe technological developments over the past thirteen years that have been a result of archaeological expeditions, and their implications for more widespread use. We then pose a series of challenges and potential solutions to the four primary phases of an archaeological project: large area search, target identification, localized survey, and excavation.

INTRODUCTION

It has become apparent in recent years that archaeology is possible in the deepest parts of the ocean. Previously, maritime archaeologists were not able to take advantage of underwater vehicles and sensors available to the oceanographic community. Increasingly, however, a small number of archaeologists have employed an array of tools that have helped significantly in furthering of the field. By and large, they have been using technology that was designed for other purposes such as geology, oil exploration, and marine biology. Yet as the field advances, specialized tools are required; new technologies are constantly under development, and archaeology in deep water presents problems that can help define the next generation of undersea robotics.

Robert Ballard and his team's discovery of the *Titanic* in the 1980s, and the subsequent exploration of a number of high profile wrecks in deep water, made it clear to the public that the deep ocean holds both mysteries and answers about the human past. A series of discoveries and explorations beginning in the 1990s demonstrated to the scholarly community that archaeology in deep water could add useful knowledge to our understanding of the human past, and that it was at least theoretically possible (if not yet technically achievable in all respects) to perform rigorous, scientific-quality archaeology with remote and autonomous vehicles in the deepest parts of the ocean. Now, an increasing number of research groups are conducting archaeological projects in deep water and refereed journal publications are beginning to appear, both from the technology side and from archaeologists. A conference on "Technology, Archaeology, and the Deep Sea" at MIT in 1999 helped establish the conceptual foundations of the field, and a second similar symposium at MIT in 2002 demonstrated that it has indeed begun to flower (Mindell, ed., forthcoming).

As archaeology moves beyond diver depths and into the provinces of underwater vehicles, it becomes dependent on technology as never before. (Our definition of "deep water," for these purposes, is not a specific depth but rather where no direct human presence is possible.) Indeed, it is a notable feature of the discourse surrounding archaeology in deep water to say that technological change "enables" archaeology to take place in deep water. This is indeed partially true, as the proliferation of ROVs in science, industry, and the military has certainly provided access to deep water for a broad community, and hopes are that AUVs will further reduce the cost of working in deep water, and hence enlarge the community.

The thesis of this paper, however, is that the influence goes two ways: new technology enables the advancement of underwater archaeology, but archaeology in deep water also raises engineering questions that can help define the future of underwater technology. Technology does not move forward in a frenzy of autonomous progress, but rather is the product of engineers, research groups, and companies responding to particular problems and opportunities. Archaeological investigation in deep water is such an opportunity, and poses a set of engineering problems that, when taken up and solved by engineers, will generate new technologies with applications scientific, military, and industrial arenas as well. Our goal in this paper is to present some background, and then to suggest some areas where engineers might respond to the requirements of archaeology.

TECHNOLOGY AND ARCHAEOLOGY IN DEEP WATER

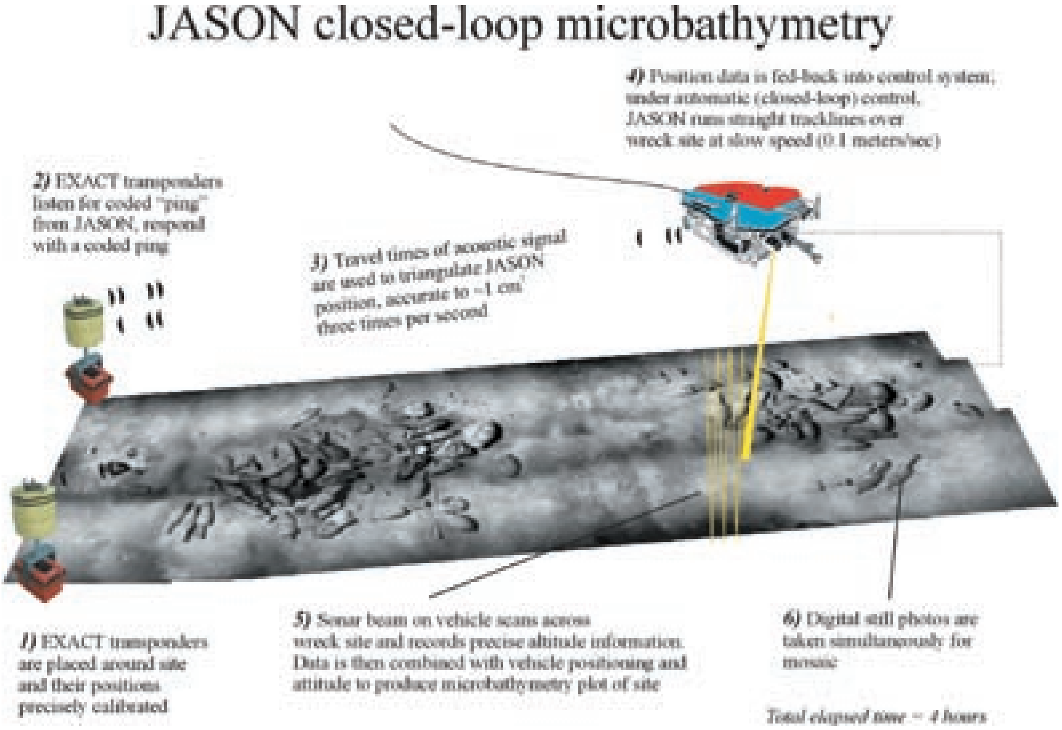
The ability to examine human-made artifacts on the seafloor of course has a great military interest, stemming from the Cold War. Many of the techniques described below were either built on military technologies or were themselves funded by research bodies like the Office of Naval Research (Weir, 2001). While the public and the press have focused on the "enabling" nature of technology in archaeology in deep water, it has also served as an impetus and a test bed for technology developments. Consider a number of projects in recent decades, conducted by the Deep Submergence Laboratory at the Woods Hole Oceanographic Institution. The team was led by Dr. Robert Ballard, and author Mindell participated in all of the projects (except the first).

In 1989, in one of its first operational deployments, *Jason* imaged and explored a Roman shipwreck known as "Isis" near Skerki Bank in the Tyrrhenian Sea (McCann, 1994; Ballard et. al., 2000). Demonstrating ability for precision manipulation, *Jason* used custom-designed end-effectors to recover a number of amphorae and small artifacts for later analysis, all with essentially no damage. This expedition also initiated live satellite broadcasts from sea to science students all over the United States, a practice that has now become common as federal science agencies support live web-casts from oceanographic expeditions. The following year, *Jason* investigated two sunken warships from the War of 1812, the *Hamilton* and the *Scourge* in Lake Ontario. In this case, the permit from the Canadian government forbade touching the site, so a variety of non-contact techniques were developed. These included instrumenting the site with precision navigation transducers (the Sonic High Accuracy Range and Positioning System, or SHARPS) so the vehicle would be precisely tracked at all times, and using that data along with new techniques in computer graphics to create "photomosaics" and three dimensional sonar images of the wrecks. These precision techniques also had applications in the ocean sciences, and the following year were further developed to map hydrothermal vent sites in the pacific, this time with a wireless version of SHARPS called EXACT (Yoerger and Mindell, 1992; 1999). Figure 1 illustrates the process by which ROV *Jason* uses EXACT, a scanning sonar, and electronic still camera to collect microbathymetric data and photographs to create high-resolution maps and mosaics.

On these projects, the numerous interactions and discussions between archaeologists and engineers made it clear that archaeological practice required mapping the sites, and recording the location and orientation of any artifacts as precisely as possible before any mechanical intervention like recovery or excavation. Spatial relationships are the cornerstone of archaeological investigation and interpretation (Muckelroy, 1978; Bass, 1966; Delgado, 1997). The position of each artifact must therefore be carefully documented previous to disturbance of the site, as well as throughout an excavation.

Some naysayers at the time asserted that such recording was impossible. Such cri-

Figure 1. ROV *Jason* uses EXACT, a scanning sonar, and electronic still camera to collect microbathymetric data and photographs to create high-resolution maps and mosaics of the Skerki D, or "Isis," wreck.



tiques ironically came from opposite camps—both from archaeologists who did not believe scientific quality work could be undertaken in deep water, and from treasure hunters who argued that since proper archaeology was impossible at great depths, the sites should be open to anyone with a steel cable and a clam bucket. Subsequent projects and the technologies they produced proved both wrong in dramatic, quantitative fashion. The development of these techniques, then, has served not only to legitimize the science, but also to protect cultural resources in deep water, as treasure hunters can no longer use difficulty as an excuse.

In 1997, the Roman and Carthaginian sites at Skerki Bank were revisited with an improved and updated *Jason*; this project again spurred development of technology. A breakthrough was achieved with precision mapping techniques, and detailed quantitative maps were made of the sites, producing dramatic images with spatial resolutions on the order of a few cubic centimeters (Figure 2). Precise, closed-loop control of the ROV allowed not only precise sonar surveys, but also detailed, stable and comprehensive photographic coverage with a digital camera (Whitcomb et. al., 1998). Advances in image processing generated large, integrated digital photomosaics of the site, using both automated techniques (for single strips) and manual point-and-click feature identification (for digitally stitching strips together). These representations of the archaeological site were unlike anything that had been seen before. They not only delimited the precise outline, dimensions, and extents of the sites, but also revealed a variety of features that had been invisible through the video camera of the ROV, or even looking out the window of the NR-1 submarine. A number of the amphorae, for example, were embedded in small craters that seemed to derive from sediment scour patterns on the site. Similarly, the outline of the ship's buried hull may be present in the subtle change in the topography as it curves around the site. These images were so novel, in fact, that it required some education on the part of the archaeological team for them to understand their importance as part of the scientific data set (Singh et. al., 2000). The engineers also learned to modify the images to present them in a way more useful to archaeologists, for example by adding specific artifact identifications to the photomosaic. These images have been important elements in the archaeological analysis and publication (Ballard et. al., 2000; McCann, et. al, forthcoming).

These techniques were again employed and further refined for the investigation of two wrecks off of Ahskelon, Israel. In 1997, the submarine NR-1 identified two ancient shipwrecks, and collected video footage that suggested they might be interesting and important. A group returned to the site with the ROV *Jason* in 1999, and the wrecks were confirmed to be Phoenician, from the 8th century BC. Each wreck had hundreds of amphorae, which when recovered were proved to be nearly exactly the same size (+/− about 3% in volume) (Ballard et. al., 2001). As at Skerki Bank, *Jason* was put into closed-loop control, and precision photomosaics and microbathymetry were collected (Singh, et. al. 2000). Again, they revealed an overall picture of the site and precise dimensions and topography not available with the ROV alone—in this case showing a large, circular crater surrounding the entire wreck, analogous to the smaller craters on the Skerki bank wreck.

The 1999 Ashkelon survey also tested a technology that had been inspired by prior work—a high-frequency, narrow-beam sub-bottom profiler (Figure 3). Using a 2-3 degree beam and a 150kHz frequency with a 30cm circular array, this device has the potential to acoustically peer inside buried shipwrecks without touching them (Mindell and Bingham, 2001a). When combined with precision navigation and control, such narrow-beam profilers could potentially map the buried site in three dimensions. Such data could enhance the accuracy of, and reduce the need for, physical intervention. Archaeologists sometimes dig trenches through sites just to see what is there—this technology, while still at an early stage of development, could allow them to replace those trenches with sound waves.

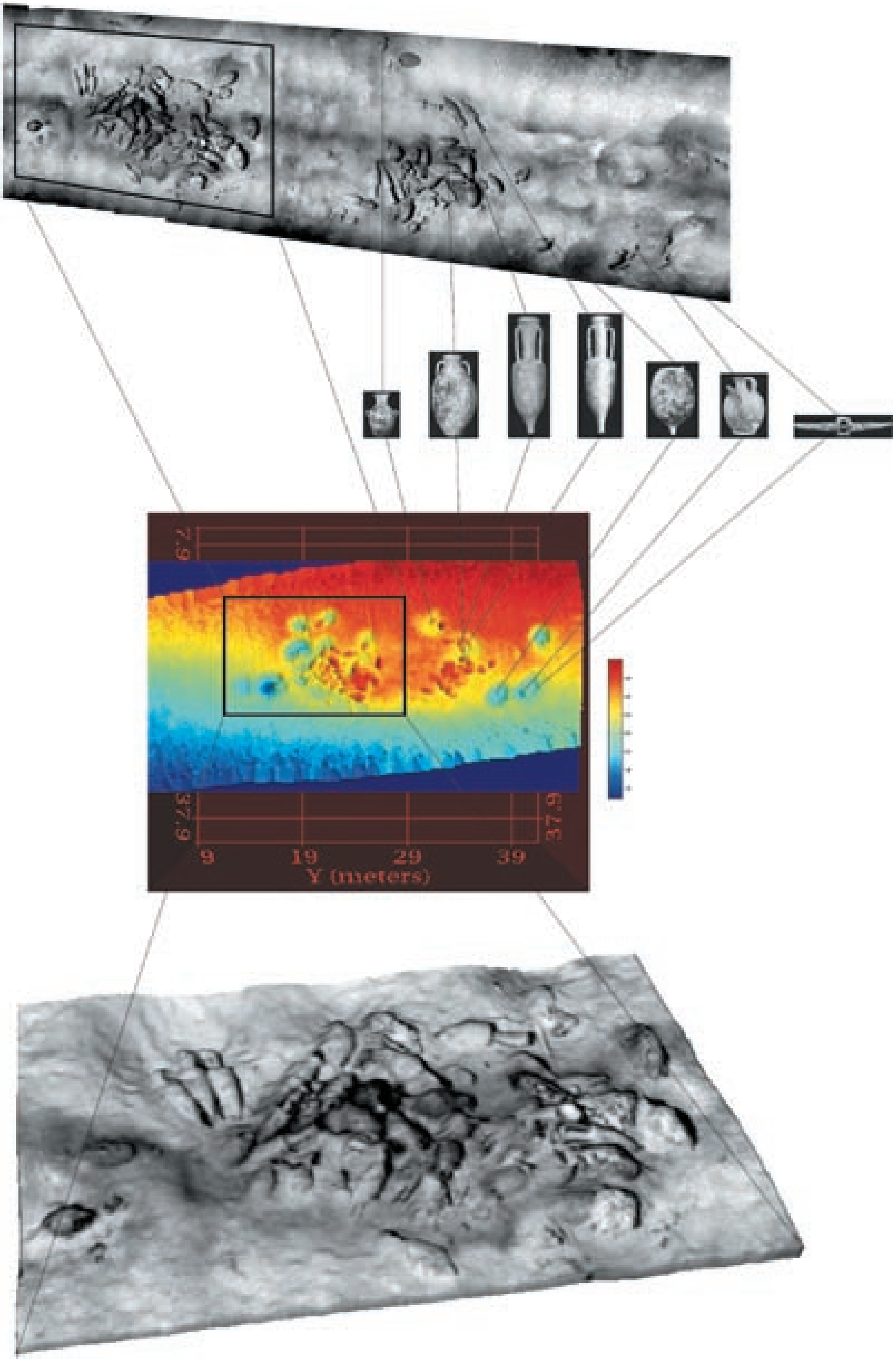
This brief survey of deep water archaeology and technology development in the past decade and a half covers but a few of the developments, in a variety of groups and projects, that have been accomplished when archaeologists work together with engineers. Technology benefits, as does our understanding of the human past. As we have said earlier, archaeology in deep water poses some of the most challenging problems in ocean robotics today. These projects have also revealed that there are still a great many out there: interesting, useful problems with applications well beyond archaeology. What are some of those problems? And how might they be solved?

DEEP WATER METHODOLOGY

From the point of view of technology, archaeological work can be generally divided into four phases, each of which has its own set of technical requirements and problems (Mindell & Bingham, 2001b). These are:

- Large area search
- Target identification
- Localized survey
- Excavation

Figure 2. This image of Skerki D maps the texture of the microbathymetry (middle) onto the photomosaic (top) for a portion of the wreck, showing the relief of individual amphorae, which cannot be discerned by still image alone. Also indicated are the locations of individual amphorae that were recovered and conserved. Photomosaics courtesy Hanumant Singh © WHOI, IFE.



We will examine each of these in turn, discussing some of the problems they raise, and posing a few of the questions that would be fruitfully addressed by engineering research. Our goal is not to be comprehensive, but rather to support our thesis that archaeology in deep water raises problems of engineering interest that, if pursued, could generate new technology and lead to a broad array of applications.

Large Area Search

The first step in an archaeological survey is to find a shipwreck or other submerged cultural site, according to some clearly-defined research design. Because of the wide disbursement of cultural remains on the sea floor, something we understand only imperfectly for deep water, a relatively large area must be surveyed in order to locate a site. The survey area is defined in the research design, which is developed to identify the objectives of the project and the questions about the human past that are to be answered by the area to be explored. How does one search the seafloor for submerged cultural remains? The answer to this question depends on whether one is looking for a particular wreck (e.g. the *Titanic*) or for a type of wreck in a particular area (e.g. an ancient wreck along a particular trade route). What is the most efficient way to cover these (and other) types of survey areas? Sonar images are well known for their ambiguities, leading interpreters to conflate a pile of rocks with a pile of amphorae. What other types of data might be collected simultaneously to resolve these ambiguities? What are the signatures (acoustic, optical, chemical, etc.) of shipwrecks of varying types and how can they be detected from long ranges?

Currently we have no means of searching for buried shipwrecks, yet we suspect these will be the best preserved of all. How does one search for a shipwreck buried in 10, 50, or 100 meters of sediment? Research into the military side of this question clearly has implications for archaeology, and the reverse may be true as well.

Once a survey area is defined, some suite of tools must be employed to collect data. This task is perhaps the most similar to other non-archaeological types of activities. A side scan sonar towfish is currently the most commonly used device for this purpose.

In addition, autonomous underwater vehicles (AUVs) have been developed over the past decade to replace the towed array, and are rapidly proving their worth for this task (Bellingham, 1997; Singh, et. al., 1997). Survey-class AUVs are optimized for energy efficiency and do not require long turns between tracklines. Because they are not tethered to the surface, the AUVs are far more stable than towed systems, and are more capable of terrain following, giving them a clear advantage over a towed system in a steep or otherwise uncertain terrain (Yoerger, et. al., 1998). As shown in Figure 4, the Odyssey-class AUV is able to follow the terrain of a steep slope (approximately 27 deg.), return to the surface to take a GPS fix, and begin another trackline. A towed sonar system would not be able to perform such a task. How can AUVs best be employed in these operational scenarios? What combination of cost/size/payload/endurance is optimal for an archaeological search mission? (Mindell & Bingham, 2001b)

Figure 3. *Jason* performing a subbottom survey of the Ashkelon wreck. The narrow-beam, high-resolution subbottom profiler has the potential to allow archaeologists to "virtually" excavate a buried shipwreck.

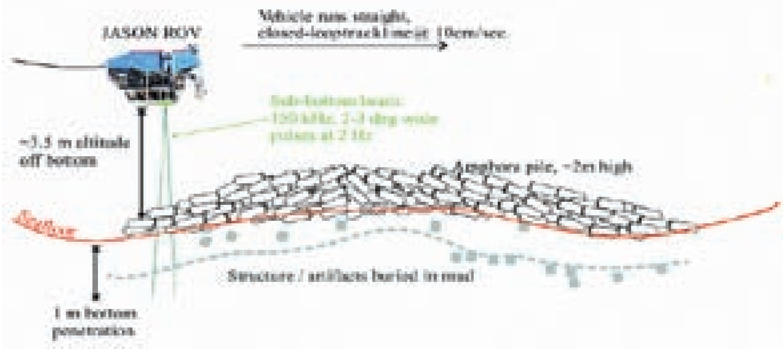
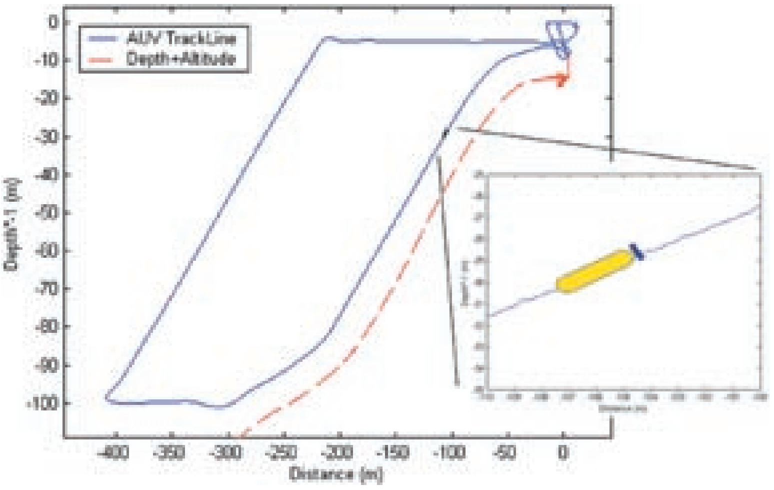


Figure 4. The terrain-following capabilities of the Odyssey-class AUV are far superior to the abilities of towed systems. The vehicle follows the terrain down the slope. At 100 m depth, it returns to the surface for a GPS navigation fix and transits to another line. The inset shows the AUV to scale, the recorded vehicle pitch, and the actual slope of the trackline. Data courtesy MIT Sea Grant AUV Lab/Bluefin Robotics. (Mindell & Bingham 2001b)



Target Identification

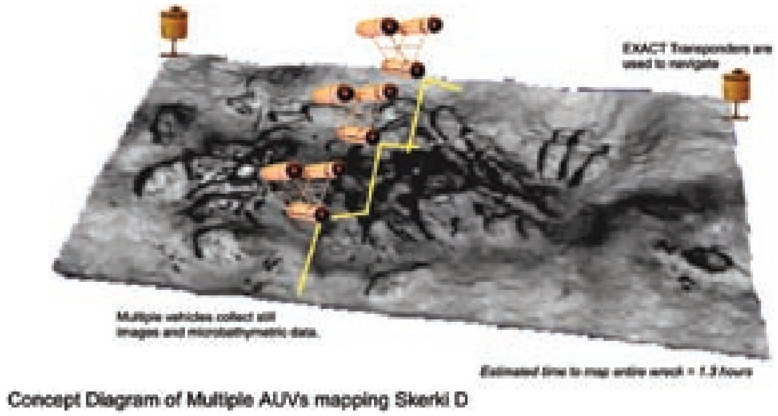
Anyone who has used side-scan sonar is likely familiar with the puzzled remark: "What is it? Well, it's definitely something." After a side scan sonar data set has been collected, one must select sites of interest and return to them to identify whether or not they are of archaeological value (or, more precisely, of interest for the current project), or even whether they are human made, "anthropogenic," at all. First, a series of sites of interest, "targets," must be selected from the raw sonar data. What are the criteria for this selection? Can automated tools aid the process?

The targets of interest are then revisited, usually to collect some kind of optical data for visual confirmation. Today, this task is typically accomplished by a remotely operated vehicle (ROV), which provides real-time video of the sites. This allows a team of archaeologists, geologists, and other scientists to view the targets collectively, providing a forum of discussion that cannot be achieved when utilizing manned or autonomous vehicles. What are the options for an AUV to perform target ID? How does one design an AUV dive series to survey, inspect and collect data to identify targets, while maximizing both dive efficiency and likelihood of success?

AUV operations might involve two vehicles: a sonar vehicle to perform the initial large-area search and an imaging vehicle equipped with cameras could identify targets. What is the simplest possible navigation system that would provide enough repeatability to allow a second vehicle to find and revisit a site? Ideally, then, the sonar vehicle continues on to further searching. If two vehicles are not available, a single AUV equipped with both cameras and sonar could examine a series of targets and then continue the sonar search.

How can an AUV autonomously collect enough data for a sufficient target ID? The AUV must return with enough data that a human can answer the following questions: 1) Is the feature natural or anthropogenic? 2) If anthropogenic, what is the size of the site, and its three-dimensional character? Is it a scattering of pottery on the seafloor? Or an aircraft carrier thirty meters high? 3) What is the approximate date of the site? These and similar questions allow an archaeological team to determine if, according to the research design, the site is worthy of further study. For an AUV to collect this data, it would require behaviors that could locate the site, identify its extents, and cover the area with imagery. This raises further questions. What is the optimal strategy for an AUV to approach and identify a sonar target in the minimum time using minimum energy? How might this problem influence the development of an AUV specially designed for archaeological imaging? (Mindell & Bingham, 2001b) These and similar questions pose research problems for AUV designers. Adaptive behaviors and sensor-based surveys would prove useful here. Again, the difficult requirements of archaeological research pose challenging research problems for deep-ocean robotics.

Figure 5. Concept design of multiple vehicles mapping a portion of the Skerki D shipwreck. Using more than one vehicle can reduce mapping time and provide a platform for bi- or multi-static acoustic arrays.



Localized Survey

As an example of archaeology's potential influence on technology, let us examine the problem of precision survey of local sites, and the directions it is suggesting for new types of vehicles. In a previous section we describedthe precision navigation, closed-loop control, and imaging technologies developed for mapping an archaeological site to scientific standards. The examples given were all generated by the ROV *Jason*, a vehicle specialized for science; few other vehicles possess the navigation and control precise enough to create a quantitative microbathymetric map and/or photomosaic of a site. In deep water, tethered vehicles tend to be expensive to operate, due to their cables, handling systems, and the vessels required to support them—hence confining the techniques to well-funded projects. Making precision site survey techniques simpler and less expensive would open deep-water archaeology to a broad array of researchers.

AUVs have a largely untapped potential to contribute to precision mapping of archaeological sites. As AUVs are further developed, they are increasingly diversified from original purposes, such as replacements for towed systems; new systems will be tailored to perform tasks required by new problems. No single AUV design, or even AUV paradigm, will be appropriate for all applications.

Current AUVs were not designed for the slow, methodical survey work necessary on archaeological sites. Rather, most were designed for covering as much area as possible (e.g. 80

sq. km), and hence are constrained by onboard energy capacity, sensors, and navigation. By contrast, a precision survey of an archaeological site in a 100m box involves orders of magnitude less site area, with a corresponding (or greater) increase in accuracy. Furthermore, a precision survey AUV does not have to find its way through a large, complex, and uncertain ocean, and hence could employ a limited set of sensors and behaviors.

Creating precision maps on small, instrumented sites presents a distinct set of mission requirements for vehicle design that may translate into a new class of AUVs. By focusing on a single application environment, precision AUVs will differ from conventional systems in their simplified instrumentation, ease of deployment, reduced costs (for both construction and operation) and new capabilities.

The ability to make centimeter-scale photomosaics and microbathymetric maps quickly, easily, and cheaply itself opens up a new arena of possibilities—not necessarily confined to deep water. For example, archaeologists might choose to model their site not simply once, at the beginning of a project (as was done on the sites discussed), but once per day as the site is excavated, creating a precise, 4-D record (spatial change through time) of the site and all interventions to it. A cultural resource manager might wish to make such a site map once per season, on dozens of sites—the deltas between these maps could then be used to document environmental changes (such as scour), human intervention (such as looting), or site formation (such as the decay of a shipwreck's structure). Furthermore, magnetic or chemical sensors might be added to the vehicle's suite—enabling the creation of specialized maps to identify iron, for example, or to map chemical signatures of particular materials. Similarly, building on the work mentioned above in narrow-beam sub bottom profiling, multiple small vehicles could be employed to form acoustic arrays, enabling the kind of sub-surface imaging in the undersea world that we now see only in medical applications like pre-natal ultrasound.

Excavation

Robotic excavation of an archaeological site in deep water presents extremely difficult questions. After a site is located, identified, and deemed worthy of excavation, it is time to begin digging. There are four primary questions that are raised in regard to the issue of excavation: 1) Which areas of the ship are most interesting? 2) Which artifacts should be recovered? 3) How does one go about recovering the necessary objects? And 4) How is does one monitor the site throughout excavation? (Soreide and Jasinski, 1998)

Excavation can be an extremely time-consuming endeavor—many projects have taken at least a decade to complete (Pulak, 1998). In contrast, working in deep water requires different tools, ships, and expertise than shallow water, and a decade-long time frame is not desirable, nor necessary. How, then, does one narrow down the search for buried artifacts? How can the archaeologically interesting areas of a ship be determined? Sub-surface imaging with a high-resolution subbottom profiler can shed some light on this problem. As described previously, archaeologists would be able to use a 3D rendering of a shipwreck to prioritize the areas of the excavation (Mindell and Bingham, 2001a). This, and other remote sensing tools, such as magnetometers, can be utilized to determine the most interesting areas of a shipwreck and can narrow the focus of an excavation.

Which artifacts should be recovered? Conservation is costly and time consuming; it would therefore be to the archaeologist's advantage to determine which artifacts are truly worthy of further study and which are not. How does one go about learning the size, chemical composition, and other characteristics of an object on the seafloor? What current techniques can be employed for archaeology (i.e. magnetometry, chemical sensors, laser spectroscopy, etc.), and what other sensors can be developed?

We are finally posed with the problem of recovery. A shipwreck can contain anything from a pollen seed to a 30-ton steam engine. How does one design a vehicle that can handle such a diverse array of artifacts? Or, should more than one vehicle or tool be employed for varying tasks? And if so, what would the design requirements be for such platforms? The oil exploration or naval salvage communities can likely shed some light on large-scale operations, but would their tools be delicate enough to recover a piece of fine china?

As has been stated previously, spatial relationships are the cornerstones of archaeology. How, then, does one monitor the movement of artifacts throughout an excavation? Once disturbed, a site can never be returned to its original state; a record of site movement must therefore be made. One solution could be the creation of a daily map of the excavation site throughout the duration of a project. As previously described, a new class of robotic vehicles, perhaps AUVs, could be developed to document the spatial change through time.

No one tool or vehicle currently exists to address all of the questions posed here for localized survey and excavation. In fact, no one tool may ever exist, as it would likely be more beneficial for an archaeologist to be able to choose from among a suite of available instruments to investigate the questions that are being asked about a particular site. Engineers and archaeologists must therefore pose problems and challenges to each other, and work together to develop the next generation of deep-water survey tools.

CONCLUSION

We should always be wary of general statements like "new technologies are driving archaeologists to explore the deep ocean," for the opposite is also true—the great interest and potential of archaeology in the deep ocean is driving our technology forward as well. Engineers, particularly those who work in the ocean, are always interested in investigating difficult problems, especially if the problems challenge them to think in new directions and create new technologies. From a long history of technology, both underwater and elsewhere, we know that fundamental problems often generate technologies that have benefits well beyond their original scope, and beyond even what their designers had imagined (in fact, that is partly the meaning of "fundamental" research).

Archaeology in the deep ocean raises such questions—with applications well beyond the study of shipwrecks. What scientist studying a hydrothermal vent would not like to precisely model an area of the seafloor in 3-dimensions, and then to repeat that survey again and again over a period of years? What naval officer would not like to autonomously identify seafloor anomalies, or to know what is buried in the mud? What security officer at a port would not like to know what has recently changed on the seabed? What oil company would not like repeatable, centimeter-scale surveys of their submerged structures?

Despite these applications, the most exciting aspect of the new technologies developed for archaeological research in deep water is that their most important impacts are likely to be in areas we do not currently foresee.

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