New Archaeological Uses of Autonomous Underwater Vehicles

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Abstract – This paper explores the intersection of two fields of research: autonomous underwater vehicles (AUVs), and archaeology in the deep sea. Archaeology in the deep sea poses a range of difficult, interesting problems for autonomous underwater vehicles. These include broad area sonar searches, target identification, and precision survey. Broad area sonar searches for archaeology have requirements similar to those in other AUV applications – collecting sonar data to locate targets for further inspection. We briefly discuss what existing vehicles can contribute to archaeological searches. We then describe the challenges for AUVs in identifying archaeological sites. Then, we discuss the importance of precision survey of archaeological sites and its implications for vehicle design and control. By "mowing the lawn" with computer-controlled tracklines over an archaeological site, an AUV could collect imagery and sonar data for precise maps of a particular site. We propose an archaeology-specific AUV to conduct such surveys and describe the requirements for such a vehicle to work in precision, instrumented environments.

I. INTRODUCTION

In the past decade, autonomous underwater vehicles have matured and become operational assets, useful for a variety of oceanographic and military applications. Small, high-performance vehicles have proven adept at a variety of undersea survey, mapping, and measurement tasks. The ability to operate free from tethers, from expensive dynamically-positioned vessels, and without human intervention during the dive sequence has great potential for replacing traditional towed-systems and remotely operated vehicles. More important, it has also become clear that AUVs have unique capabilities such as close-in terrain following, multiple vehicle operations, and extremely long endurance [1][2].

During the same period that AUVs have been developing, archaeology has been moving into deep water. Archaeologists have been using SCUBA and related techniques to work in relatively shallow depths since at least the 1960s [3][4]. Yet they have recently been using deep submergence vehicles, originally developed for military and oceanographic applications, to investigate shipwrecks in much deeper water. The discovery of the *Titanic*, in 1985 in approximately 4,000 meters of water, put deep wrecks into the public consciousness. Recent projects at Skerki Bank in the Tyrrenhian Sea, off of Ashkelon (Israel), and in the Black Sea have demonstrated that archaeology can be accomplished with remote and human-occupied submersibles [5][6][7]. We argue for the convergence of these two lines of development, namely the application of autonomous underwater vehicles to the emerging field archaeology in deep water. We first review applications of existing vehicles to broad area archaeological surveys in deep water, and lay out new challenges for AUVs for identifying archaeological sites. Then, we discuss the importance of precision survey of archaeological sites, and propose an archaeology-specific AUV to conduct such surveys. Throughout, we emphasize the synergistic relationship between archaeology and engineering in the deep sea: each poses questions and problems for the other, which lead to new developments in both [8].

II. ARCHAEOLOGY IN DEEP WATER

Archaeology in the deep sea poses a new range of difficult, interesting problems. These include (but are not limited to):

A. Sonar Search / Broad area Survey
B. Target Identification
C. Precision Survey
D. Excavation

Below, we discuss each of A-C in turn, and their relationship to AUV design and operations. Remote excavation, even from ROVs, is in its infancy and remain outside the range of current AUV technology, so we will not address it here [9].

III. SONAR SEARCH / BROAD AREA SURVEY

The first step in conducting archaeology in deep water requires finding human cultural remains of interest (primarily shipwrecks, but also including submerged settlements and dwellings). The search is directed by a "research design" that specifies questions about the human past to be investigated and explored, and makes use of existing data (historical, archaeological, geological, meteorological, etc.) to specify a search area. Archaeological remains are sparsely distributed across the seafloor, and so broad areas must be covered. Existing AUVs prove useful for this task.

Today's successful AUVs have been conceived as survey vehicles, originally as replacements for tethered, towed systems [11]. The common element in these designs is their optimization for long-range survey, emphasizing high energy capacity and navigation in unstructured ocean environments. These vehicles present several benefits for archaeological searches. As platforms for side-scan sonars, for example, they do not require cables and winch systems and can operate from smaller vessels than towed systems. This advantage becomes greater as depth increases, and is particularly important for archaeological projects operating in locales that are difficult and expensive for oceanographic vessels to reach.

As with most technologies, however, the true importance of AUVs stems from their unique capabilities, rather than simply as improved versions of older machines. In the case of autonomous vehicles, these include terrain following and platform stability. With towed systems, altitude is adjusted by varying the speed of the ship and the length of the tow-cable. Hence, they work best where the depth of the terrain is relatively constant, or in variable terrain are towed on isobaths. AUVs, by contrast, can navigate through difficult and variable terrain, and thus improve the probability of locating targets in variety of environments. Figure 1 shows an example. The vehicle is programmed to survey down slope maintaining a constant altitude, turn off the sonar, return to the surface for a GPS fix, and begin another survey line.

In addition, side-scan sonar is gradually achieving higher and higher frequencies. Whereas systems of 75-150 kHz once predominated, side-scans of 500 and even 1000 kHz are increasingly common [11]. These are capable of collecting data with near-photographic resolution, and in the ideal case can even produce site-plans of a wreck with archaeological quality. Yet sonars using these high frequencies become heavily dependent on their platforms because any pitching, heaving, or misalignment can seriously compromise the quality of the image. The “sweet spot” for a high frequency system is so small that it can be exceedingly difficult to capture an ideal picture with a towed system, due to factors like weather, motion of the surface ship, and cable dynamics. AUVs, then, present the advantage of stable, programmable trajectories, and can make ideally situated passes on sites of interest.

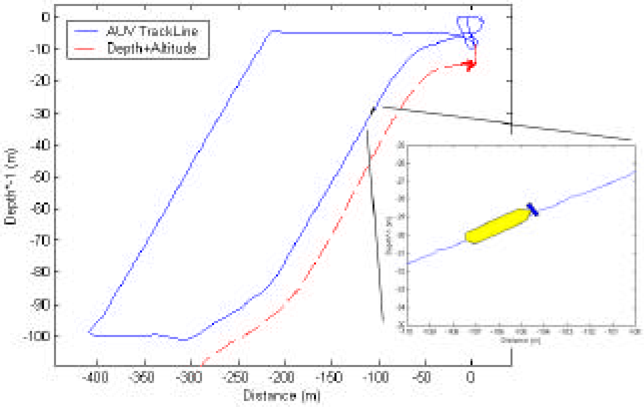

Fig. 1. Terrain following during a broad area AUV survey. Terrain is shown as the depth-plus-altitude data. The vehicle follows the terrain down, and then at 100 m depth returns to the surface for a GPS navigation fix and transits to another line. The inset shows the AUV to scale, the recorded vehicle pitch, and the actual slope of the trackline. (Courtesy MIT Sea Grant AUV Lab/Bluefin Robotics.)

IV. TARGET IDENTIFICATION

Sonar search is just the beginning for archaeology. When an AUV returns to the surface, as in other types of searches, engineers and archaeologists interpret the sonar record, and locate “targets,” which then require further inspection to be identified. Archaeological sites have subtle acoustic signatures, often not dramatically different from geology or other seafloor features. They are often obscured by rocks, grasses, and mud. Because even today’s high-resolution sonars cannot always distinguish between the two, positive target identification requires an optical sensor (i.e. a still or video camera). Our natural inclination to trust optical over sonar imagery also makes visual confirmation a necessary follow-up to sonar searches.

Several options are available for collecting this imagery. Traditionally, sonar surveys have been followed up with ROV operations for target identification. In the rare case, as with the US Navy’s NR-1 nuclear research submersible, sonar search and optical identification can be accomplished during the same dive. In AUV operations, an imaging vehicle equipped with cameras can identify targets. 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 identification? This raises the question of what kind of information is required to identify an archaeological site. It must answer several questions. First, is the feature natural or anthropogenic (“man-made”)? Second, 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? Third, what is the approximate date of the site? For modern wrecks, this can often be estimated by observing hull shapes and materials. For ancient wrecks, the hull is often buried and/or decayed, and dating is accomplished by observing the cargo, often ceramic jars or “amphoras.” The shape and size of the amphoras roughly indicates the date and origins of a ship. From this information, an archaeological team can determine if, according to the research design, the site is worthy of further study (usually in a subsequent field season). If not, the data is archived and presented to the local governing authorities for reference and cultural resource management.

How to answer these subtle questions with an AUV survey presents a challenge for AUV mission planning and design. Simply flying over a set of coordinates at a fixed altitude will usually be insufficient to accomplish target identification. Navigation uncertainty in the sonar survey, combined with that of the optical survey, may be larger than the field of view of a camera, so multiple tracklines will be required. Furthermore, sites often have three-dimensional features; experience with ROVs suggests that target identification requires close-in inspection, and horizontal (or at least downward angled) optical sensors. What is the optimal strategy for an AUV to approach and identify a sonar target in the minimum time with the minimum energy? How might this problem influence the design of an imaging AUV?

We pose this as a valuable research problem for the AUV community – one where adaptive behaviors based on sensor inputs may prove useful. Again, it supports our central point: the difficult requirements of archaeological research poses new research problems for deep-ocean robotics.

V. PRECISION SURVEY

Archaeological survey is the careful, complete documenting of a site. In shallow water, this usually involves divers and tape measures, using specially constructed grids and manually recording of large numbers of points for subsequent computer aided triangulation [4]. For deep water sites, the JASON ROV (a 6,000 meter rated vehicle system requiring a dynamically-positioned surface vessel) has proven the ability to record this data automatically, under-closed loop control, to high precision. By "mowing the lawn" with computer-controlled tracklines over an archaeological site, the ROV can collect imagery and sonar data [12]. The former can be incorporated into large photomosaics (~200 images) of a site, and the latter can be integrated into fine-scale "micro-bathymetric" models. These techniques have proven useful for documentation of archaeological sites, but at the moment remain exclusive to the JASON ROV [13][14][16]. Yet small, inexpensive AUVs could potentially perform closed-loop control, microbathymetry, and digital photomosaicing in both shallow and deep water. Such vehicles would make these precision maps available to a broad community of scientists, and help open up deep water for archaeological research. The idea raises the question of how to design an autonomous vehicle to operate in precision, instrumented environments.

Precision archaeological survey occurs in a pre-defined, well known area, essentially within a 100m square site. Hence the area can be instrumented for precision navigation. By this we mean laying out precision acoustic transponders, such as those used by the EXACT system, or (in shallow water) a cabled navigation net such as SHARPS (both 300kHz) [15]. Such systems provide centimeter-scale absolute-referenced navigation fixes to the vehicle several times per second. They allow the vehicle to conduct surveys that are not only precise, but also repeatable. For example, a photomosaic and microbathymetric map could be made once per day of an archaeological site as it is excavated, creating a precise, 4-D record (spatial change through time) of the project.

Such an instrumented environment differs from the unstructured ocean for which current survey-class AUVs were designed. These systems' performance is constrained by onboard energy capacity, sensors, and navigation. For example, a typical AUV might survey for 12-15 hours at 3 kt, traveling approximately 80 km of linear distance. Instrumented with a typical side-scan sonar the vehicle might cover 150m across track with a 7m height (and 7m nadar). With the appropriate overlap this all translates into approximately 3 km^2 of seafloor coverage. By contrast, a precision survey of an archaeological site in a 100m box involves two 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.

VI. TOWARD PRECISION SURVEY AUVS

Creating precision maps on small, instrumented sites presents a distinct set of mission requirements for vehicle design that 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. An instrumented environment reduces the number and size of navigation sensors required, and building precision maps and mosaics requires only a sonar (mechanically-scanned or multibeam) and a digital still camera with appropriate strobes (video cameras and their associated lighting may be unnecessary given that the target of interest is not moving). The finite survey area reduces the energy needs for the vehicle, enabling a combination of smaller vehicle size, higher power payloads, and longer duration. Hovering and precision control require a vehicle shape and actuator configuration optimized for slow-speed precise operations. Ideally, such a vehicle would be small enough to be deployed from a small ship (i.e. a fishing boat) with a small crew.

TABLE I
Functional requirements of a vehicle for the express purpose of precise optical and bathymetric mapping of discrete areas of the seafloor.

Functional Requirements	Design Parameters
Work in moderate current environment.	1.5 kt
Ability to hover and move at very low speeds	Omni-directional, 3-D controllability, down to ~10cm/sec.
Precision navigation	~1 cm precision (x,y,z) @ 1Hz update w/i 100m cube Measure pitch/roll < 0.1° Hold heading < 0.5°
Endurance sufficient to thoroughly survey a archaeological site	~10km linear survey
Operate in deep water	>diver depth (100m) < full ocean depth goal ~1000m

These capabilities differ from those of prior AUVs and demand a similarly distinct physical form and configuration. Embodying the requirements of Table I in a vehicle will require a fresh approach to AUV design, and requires further analysis of available sensors, actuators, and energy sources. With the navigation and sensor data integrated into a single product, for example, there are opportunities for new interpretations. Consider, as examples, the combination of navigation and side-scan sonar data from Odyssey class vehicles, and the use of ABE navigation data to infer vent current measurements on sea vents [17]. The authors are currently in the process of exploring the elements of vehicle design in the light of these requirements for a mission specific vehicle.

VII. CONCLUSION

No single type of AUV will solve all problems in the ocean. Complex, multi-dive science missions like archaeology are likely to require a mix of different types of assets – including ROVs, manned submersibles, and several types of AUVs. Some aspects of archaeology in deep water, such as broad area sonar surveys, can be accomplished with existing vehicles. Other tasks, such as target identification, will require new applications and algorithms. Precision survey presents a sufficient challenge that entirely new types of vehicles will be required. A precisely navigated, tightly controlled survey AUV can deliver a higher-resolution dataset than an ROV or towfish, within a limited area. Archaeological requirements pose exciting new problems for engineering, and in solving those problems engineers are likely to raise fundamental issues in undersea robotics, including interrelationship of navigation, sensor data, and vehicle design.

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