Deepwater Archaeology With Autonomous Underwater Vehicle Technology
Daniel J. Warren, Robert A. Church, and Kimberly L. Eslinger, C&C Technologies

Abstract
Autonomous Underwater Vehicles (AUVs) have had a significant impact on underwater archaeology in the Gulf of Mexico. Increased use of AUV technology for natural resource surveys has increased deepwater shipwreck discoveries. With AUV data, archaeologists can document and interpret deepwater shipwreck sites with a higher degree of detail than possible with deep-tow systems. Using examples from the Gulf of Mexico, this paper discusses the use of AUVs for deepwater archaeology, including survey methodologies, and data analysis techniques.

Introduction
The introduction of commercial AUVs to the Gulf of Mexico began a new era of deepwater natural resources exploration. The use of AUVs also provided archaeologists with a cost-effective tool for documenting deepwater shipwrecks. This paper will show how archaeologists are using AUVs by examining the history of AUVs and archaeology in the Gulf of Mexico, the advantages of AUVs in deepwater archaeology, AUV archaeological survey methods, and site analysis and planning from AUV data.

History of AUVs and Archaeology in the Gulf of Mexico
The history of using AUVs for archaeology in the Gulf of Mexico and the expansion of deepwater natural resources exploration are connected. Traditionally, deep-tow side scan sonars were the mainstay of deepwater engineering and geophysical surveys.1 When exploration moved into deeper waters, deep-tow systems began to reach their limits of practical operation. Oil and gas companies exploring these areas required a more cost-effective, accurate, and faster means of surveying at extreme depths. New AUV technology provided the answer to the industry’s survey needs.2 The AUV’s attributes make it ideal for both oil and gas exploration and deepwater archaeology. The AUV is so ideal for deepwater archaeology that archaeologists have used AUVs in the Gulf of Mexico since their introduction.

Introduction of AUVs to the Gulf of Mexico
C & C Technologies (C & C) brought the first commercial deepwater AUV in the Gulf of Mexico online in 2001 in response to industry needs for a more accurate deepwater survey system (Figure 1). One of the first projects the AUV was used for was the Mardi Gras Transportation route, a 480-kilometer pipeline route with water depths ranging from 120 to 2,200 meters.3 Since 2001, C & C AUVs have investigated over 75,000 line kilometers of deepwater seafloor areas in the Gulf of Mexico, Mediterranean Sea, Florida Straits, Brazil, and West Africa.4 Along the way, AUV data has helped archaeologists discover several historic shipwrecks including a World War II U-boat and aircraft carrier.

This first commercial deepwater AUV in the Gulf of Mexico was a multi-instrument survey platform, meaning it collected data from several systems simultaneously. Its primary sensor package consisted of a 200-kHz Swath Bathymetry System, dual frequency 120- and 410-kHz side scan sonar, and a Chirp Subbottom Profiler. An inertial guidance system controlled this AUV’s positioning and navigation. Command and control of the AUV was accomplished with a High Precisions Acoustic Positioning system (HiPAP), an acoustic command link (ACL), and an acoustic data link (ADL) back to the support ship.4

In the C & C AUV, two titanium spheres housed the control and payload processing units. These computers used artificial intelligence algorithms to analyzed data from 75 on board sensors to continually monitor and adjust system performance. The “AUVS navigation, mechanical motion, health, and power” systems are contained within the control sphere. The payload sphere held the proprietary software for mission and sensor control, guidance, and data recording.4

The AUV used a 200-kHz system with a depth sensor accurate to 35 centimeters for its swath bathymetry. At the AUV’s standard survey altitude of 40 meters above bottom, the system could record a 220-meter wide data swath. The system’s relative accuracy was equal to a hull mounted system in 40 meters water depth.3
This AUV’s side scan sonar was a dual frequency 120 and 410 kHz system. During typical survey operations the 120-kHz sonar pinged three times per second as the AUV flew approximately 40 meters above the seafloor. At this ping rate and altitude, the sonar imaged approximately 225 meters of seafloor per channel. When high-resolution seafloor imagery was needed, the 410-kHz high frequency side scan sonar system was used. To optimize the performance of the high frequency system, the sonar pinged at rate of 10 to 20 times per second as the AUV cruised 10 to 20 meters above the seafloor. This allowed acquisition of high-resolution data coverage out to approximately 50 meters per channel.4

The AUV’s subbottom profiler was a chirp system modulated between 2 and 8 kHz. It used a single transducer to generate the pulses for imaging near seafloor sediments. The system could resolve reflectors in clay filled basins to approximately 75 meters below the mudline.4

The AUV’s positioning and navigation was controlled by the vehicles inertial navigation system. The system used a Doppler velocity log with a Kalman filter, precision gyros, and accelerometers to keep the AUV on course as it flew preprogrammed missions. DGPS updates from the support ship ensure the AUV’s relative positioning system’s accuracy of ±5 to 10 meters real time and ± 3 to 5 meters post processing.4

C & C’s AUV used Aluminum Oxygen fuel cells for power. This power sources allowed the AUV to operate submerged an average of 45-kilowatt hours or approximately 48 hours per mission. With this fuel system, the AUV attained speeds up to four knots submerged during normal survey operations.

**AUV Archaeology Projects**

In the six years since the AUV’s introduction, archaeologists using AUVs in the Gulf of Mexico have identified, discovered, and investigated almost a dozen shipwrecks. The early projects provided a knowledge base for archaeologists to build upon. Lessons learned on these early projects helped develop the methodologies being used today to accurately assess deepwater shipwrecks. Several notable examples are discussed briefly below to illustrate how AUVs are used for deepwater archaeology.

**Early deepwater Projects**

AUVs were essential to several early deepwater archaeology projects including the shipwreck investigations of German U-boat, _U-166_, the passenger-freighter _Robert E. Lee_, and the steam yacht _Anona_. Ironically, these early projects surveyed shipwrecks originally found and misidentified, except in _Robert E. Lee’s_ case, with deepwater systems. Later, archaeologists correctly identified the wrecks using AUV high-resolution geophysical data.

The first AUV archaeology project investigated the wrecks of _U-166_ and S.S. _Robert E. Lee_. Both wrecks were located during a 1986 oil and gas survey, but _U-166_ was incorrectly identified as the freighter S.S. _Alcoa Puritan_. In 2001, an industry survey using the AUV imaged both wreck sites with low frequency sonar. Data review raised suspicions that the alleged _Alcoa Puritan_ was actually the German U-boat, _U-166_. To test the hypothesis that this might be the lost German submarine, the AUV surveyed both wrecks using high-frequency side scan sonar, subbottom profiler, and swath multibeam. At an altitude of just 15 meters above bottom, the AUV flew 33 lines spaced 20 meters apart over the suspected U-boat in approximately 2 hours, something impossible to do with a deep-tow.5

Detailed side scan and multibeam data left little doubt that the freighter was the _Robert E. Lee_ and that the second wreck was a submarine, but was it _U-166_ (Figure 2)? These images were the impetus for a Remotely Operated Vehicle (ROV) inspection in May 2001. This inspection used coordinates and sites maps from the site specific AUV survey. The ROV dropped 1,524 meters below the surface of the Gulf of Mexico and positively identified _U-166_, the only World War II U-boat lost in the Gulf of Mexico.5

In July 2002, an oil and gas firm requested an AUV survey of another wreck found during a 1995 deep-tow survey and interpreted as a modern workboat. The AUV collected data on the wreck as part of a larger survey supporting proposed lease development activities. This survey used the AUV’s entire systems suite of side scan sonar, swath multibeam, and subbottom profiler to document the wreck site. The AUV flew 18 lines spaced 25 to 50 meters apart over the area that included the wreck and a debris trail extending north from the wreck.

When archaeologists assessed the AUV side scan data they noted an intact, partially buried shipwreck, 41 meters long, 5 meters wide, and up to 2 meters high. The acoustic void in the subbottom data over the wreck was a result of the sound waves failing to penetrate the hull suggesting it was metal. This evidence was consistent with attributes of a modern workboat. The detailed images of the hull and deck areas, however, were inconsistent with a modern workboat’s hull. The original deep-tow showed indistinct reflectivity, but the AUV data provided detailed imagery. The shallow data showed the bow, but it lacked detail. The AUV image of the bow indicated it was relatively sharp with a notch where a bowsprit once rested. Archaeologists then looked at the vessel’s deck, and again the high frequency AUV data provided the details. Side scan imagery indicated possible machinery remains, such as an engine or boiler that were inconsistent with a modern vessel.

Based on the AUV data, archaeologists hypothesized that the wreck was likely an historic iron hulled sail or steam vessel. A later ROV inspection of the wreck confirmed it was a steam powered iron hulled vessel. Additional research identified the wreck as the steam yacht _Anona_. _Anona_ was a steam yacht built in 1904 by George Lawley and Sons of Boston for Theodore DeLong Buhl. Originally a Great Lakes ship, _Anona_ survived forty years before its hull gave way in 1944
while carrying potatoes to the British West Indies for the Panamanian Banana Producers Association.

Recent deepwater Projects

Recent deepwater projects have relied on AUVs to document shipwreck sites. Among these are the Mardi Gras Wreck and the Ewing Banks Wreck. The methods employed for these recent deepwater projects are based on experiences from early AUV projects such as those discussed above.

A 2003 ROV survey in the Mississippi Canyon Area located the remains of an unknown wooden shipwreck in nearly 1,200 meters of water. Archaeologists ground truthed the site, referred to as the Mardi Gras Wreck, with an ROV in 2004 while conducting a shipwreck study in the area. The ROV provided substantial data on the site’s material remains, but archaeologists did not have an overall understanding of the site's layout and dimensions. Two items which were necessary for planning future site investigation and possibly excavation. To obtain this information, officials sanctioned a high frequency, or high-resolution AUV survey. Drawing on skills learned in four years of AUV shipwreck projects, the survey team and archaeologists planned a survey which incorporated all of the AUV’s data collection systems. In May 2005, the AUV flew 24 lines spaced 5 to 20 meters apart at an altitude of just 10 meters. The resultant map was one of the most complete acoustic maps of a shipwreck ever collected in the Gulf of Mexico.6

The data once processed, reviewed, and integrated provided archaeologists with a three dimensional cross-section of the wreck site. From the data, archaeologists determined that the site measured approximately 21 x 8.5 meters in size. Most of the material is concentrated in an oval depression that may represent remains of the vessel’s hull (Figure 3). Amazingly, the AUV’s subbottom profiler also imaged subsurface remnants of the wreck, indicating that it extends approximately 2 meters below the seafloor (Figure 4). This data helped plan additional ROV investigations over the wreck site in 2006.6

During a 2006 block hazard survey near the Ewing Banks and Green Canyon Areas, a shipwreck was imaged on a single line of AUV side scan sonar (120-kHz) and multibeam data. Archaeologists reviewing the data recognized the shipwreck could be historically significant. The Ewing Banks Wreck is approximately 45 meters long, 15 meters wide, and extends roughly 3 meters above the ambient seafloor. The side scan data imaged an oval shape structure with an outer area of moderate reflectivity surrounding an inner zone of high reflectivity (Figure 5). The processed multibeam imagery over the wreck showed an oval ship-like feature surrounding a central depression (Figure 6). The elevated area surrounding the central depression corresponds to the moderate reflective area noted on the side scan sonar. The central depression, a result of sidelobe detection, corresponds to an area of high reflectivity visible on the side scan data.

Based on the low frequency side scan sonar and multibeam data archaeologists suspect the wreck is a historic wooden vessel. They considered the moderate reflectivity area to represent hull remains, while the high reflectivity area in the center is likely cargo or ballast. A follow up high-frequency site-specific survey was carried out over the site using the AUV. Preliminary data review supported the initial assessment that the wreck is a wooden historic vessel. The high frequency data provided the wrecks construction features and what may be the vessel’s keelson. Final assessment and interpretation of this data set is in progress. When completed it will provide a three dimensional image of the wreck similar to that of the Mardi Gras Wreck and will assist archaeologists planning future site investigations.

Advantages of Using AUVs in Deepwater Archaeology

Many of the advantages AUVs have over towed systems that make them ideal for engineering and geohazard work also apply to deepwater archaeology. These advantages and the cost-effectiveness of AUV surveys are allowing more deepwater archaeological investigations than previously possible with deep tow systems. Advantages include better data quality, navigational and positioning accuracy, survey time, survey flexibility, and digital data delivery.

Data Quality

Good quality data is essential to deepwater archaeology investigations. Archaeologists typically rely on acoustic data to assess deepwater archaeological sites. In the past, deep tow data because of tow heights and system limitations rarely provided the resolution necessary to identify specific wreck features. These limitations have resulted in the misidentification of several historic Gulf of Mexico deepwater shipwrecks. The data systems on AUVs and the ability to survey close to the bottom are giving archaeologists highly detailed imagery of shipwreck sites. Using this data, archaeologists are able to accurately determine site boundaries, debris fields, hull composition, and construction details. They are also using high resolution AUV data to develop realistic avoidance zones that protect deepwater archaeological sites from destruction by bottom founded industry activities.1

Navigational and positioning accuracy

Positioning is by far the most important aspect of any deepwater archaeological project. Precision navigation and positioning is essential to accurately survey deepwater shipwrecks, relocate the sites, and analyze the spatial relationships between site features. Accurate positioning with deep tows has always been problematic and expensive, often requiring acoustic beacons on the towfish or the seafloor, and a second chase boat to track the towfish. Even with these measures, deep tow positioning can be off by tens of meters because of the effects of sound velocity variations, currents, cable lengths, and tow speed changes.1

1
The AUV’s positioning and navigation accuracy is higher than positioning from a towed array. The AUV’s inertial navigation technology integrates data from onboard accelerometers, precision fiber-optic gyros, and a Doppler velocity system to precisely navigate and position the vehicle. Positional drift resulting from the Coriolis effect is offset by DGPS corrections that are acoustically transmitted from the AUV’s surface support vessel. This technology allows the AUV to fly at a constant altitude above the seafloor and collect georeferenced data accurate to at least 3 to 5 meters.

**Survey Time**

Deepwater archaeology projects are typically limited in time and funding so survey speed is an important facet of these projects. Deep tow survey speeds, 1 to 1.5 knots depending on cable out lengths, and line turns that can take up to 8 hours make these systems impractical and cost prohibitive for deepwater archaeology. Since AUVs are untethered, they have high maneuverability allowing them to cruise over the seafloor and locate potential sites for further investigation. As a result, archaeologists are more inclined to allow shipwreck investigations on their projects using the AUV than they would using a deep-tow system. This aspect of the AUV has given archaeologists a cost-effective and expedient means of investigating deepwater shipwreck sites that does not cost their clients large amounts of time or additional money. As a result, archaeologists are performing more deepwater shipwreck investigations in the Gulf of Mexico than ever before.

**Survey Flexibility**

Deepwater shipwreck investigations require low survey sensor altitudes and tightly spaced survey lines. These types of surveys are impractical for deep-tow systems and if attempted would take a long time and likely result in a large seafloor impact crater. The AUV’s terrain avoidance systems and tight maneuvering capabilities make them ideal for this work. Its maneuverability and the surface crew’s ability to modify survey plans on the fly make it a valuable archaeological tool. The ability of AUVs to cruise low to the seafloor and survey lines just meters apart allows the collection of detailed data sets from multiple survey systems. Archaeologists integrating this multisystem data now have the ability to develop three-dimensional perspectives to aid in site assessments.

**Digital data**

The AUV’s digital collection format is more efficient for reviewing, sharing, publishing, and manipulating data collected on deepwater archaeology projects. Deepwater archaeology projects tend to be multidisciplinary endeavors. Project scientists can be scattered around the globe. The digital data format makes distribution of large project datasets easier and faster. The digital format also allows easier multisystem data integration. Using this format, side scan, multibeam, and subbottom data can be uploaded into a visualization software package for 3-D modeling.

**AUV Archaeological Survey Methods**

AUVs are deployed to locate and document shipwreck sites using two basic methods, the broad area survey and the site-specific survey. The first use of these methods in the Gulf of Mexico was on the U-166. In the six years since that first investigation, scientists have successfully employed these two methods for investigating numerous deepwater shipwrecks with AUVs in the Gulf of Mexico. Today, the broad area and site-specific surveys remain the best means for locating and documenting deepwater shipwrecks sites.

**Broad Area Survey**

The broad area survey’s purpose is to image large sections of the seafloor and locate potential sites for further investigation. During broad area surveys, AUVs cruise at higher altitudes, usually 40 meters above bottom, collecting data using low frequency systems at long ranges to maximize seafloor coverage. Typically, archaeologists use oil and gas, or cable route surveys as proxies for broad area surveys. They review the data from these projects and note any potential sites. Scientists conduct site-specific surveys over the targets as time and opportunity permit.

**Site-specific Survey**

Site-specific AUV surveys collect data for detailed site analysis and planning. They are flown at lower altitudes using all of the AUV’s survey systems or specific sensors to identify particular characteristics of the wreck site. On a typical site specific survey, the AUV flies only 10 to 20 meters off bottom collecting with the 410-kHz side scan sonar, 200-kHz multibeam, and 2- to 8-kHz subbottom profiler. Survey line spacing varies depending on the site, but can be 5 meters or less.

In the past year, a variant on the site-specific survey has come into use on shipwreck investigations in the Gulf of Mexico. This method requires the AUV to fly the survey pattern over the wreck multiple times, each time with a separate system collecting data. Using this method reduces cross-talk noise between systems and improves data quality. This method in conjunction with tight line spacing on shipwreck surveys has provided archaeologists with extremely high-resolution multisystem data.

**Site Analysis and Planning Visual Investigations from AUV Data**

Archaeologists are using multisystem AUV data to produce detailed shipwreck site analyses and plan visual investigations. In the past analysis and planning for ROV investigations were limited to using side scan data. Today, the AUV’s multisystem datasets gives archaeologists the ability to analyze sites and plan projects using side scan sonar, multibeam, and subbottom data.
Analyzing multisystem AUV site data

The use of AUVs for deepwater shipwreck site investigations is allowing archaeologists to analyze sites using data from multiple geophysical systems rather than just one system as in the past. Integrating multisystem geophysical data gives archaeologists the ability to develop three-dimensional acoustic site plans (Figure 9). Viewed in a 3-D perspective the geophysical data set provides a better understanding of a shipwreck’s vertical and horizontal boundaries. Cross-sectioning the 3-D data set can also illuminate spatial relationships between site components, an important aspect of archaeological site assessments. In the future, the use of integrated datasets in conjunction with visual data from ROVs has the potential to allow even better correlations between material remains on the seafloor and subseafloor deposits. These types of correlations will be invaluable to scientists planning deepwater shipwreck excavations.

Visual investigation planning from AUV data

Deepwater shipwreck visual investigations are time consuming, logistically challenging, expensive, and require extensive planning. Highly accurate and quality geophysical data is essential for planning these investigations to acceptable archaeological standards. The multisystem geophysical data from AUVs have been key to planning several visual shipwreck inspections and large shipwreck studies. The integration of the AUVs side scan sonar, subbottom, and multibeam data has provided archaeologists with accurately georeferenced views of shipwreck sites. Working with these acoustic maps, scientists have been able to plan ROV surveys in detail, insuring there are no gaps in visual coverage. Cross-sectional views have assisted in planning excavation areas by highlighting subsurface debris concentrations. Finally, the 3-D data set can allow personnel to take part in practice runs that help them to better understand project objectives and reveal flaws in the investigation plan. As a result, realistic and efficient field plans are being developed that make the best use of project time and make it less likely that the investigation will miss or destroy valuable information.

Conclusions

As energy exploration expands further into the ocean depths, AUVs will play a large part in future expansion and in deepwater archaeology. New technologies may allow more exact and detailed deepwater shipwreck assessments. Dynamically focused side scan sonars with the ability to resolve objects to 70 cm at over 200 meters range are already being integrated with next generation AUVs. Increased use of these new high-resolution systems on AUVs will make them the preferred tool for deepwater archaeology studies. Discoveries made using these new AUV systems will increase awareness about deepwater shipwrecks and greatly add to our understanding of global maritime history.

Acknowledgements

The authors would like to thank C & C Technologies, Inc., Remington Oil and Gas Corporation, The National D-day Museum, BP America, and Shell International Exploration and Production, for the use of the data examples for this paper. Our thanks also go to Tony George for allowing the time and opportunity to produce this paper.

References


Figure 1. The first commercial AUV in the Gulf of Mexico shortly after launch from its support vessel.

Figure 2. High-frequency 410-kHz AUV side scan sonar data: A) S.S. Robert E. Lee, B) U-166.
Figure 3. Swath Bathymetry image of the Mardi Gras Wreck showing a seafloor depression outlining the wreck with portions of a site map overlain.
Figure 4. AUV subbottom profiler data showing subsurface deposits at the Mardi Gras Wreck site with close-up and interpretation in lower corner panel.

Figure 5. Low frequency 120-kHz AUV side scan sonar data showing the Ewing Banks Wreck.
Figure 6. AUV swath bathymetry data looking north over the Ewing Banks Wreck.

Figure 7. Side scan sonar mosaic created from data collected from an AUV broad area survey of Robert E. Lee and U-166 shipwreck sites.
Figure 8. Site specific sonar mosaic image of U-166 wreck site showing AUV trackline survey pattern.
Figure 9. Example of a 3-dimensional perspective site plan from the Mardi Gras Wreck site. The upper panel is an eastward longitudinal cross-section view. The lower panel is a southern perpendicular cross-section view.