ADAPTING A SURVEY-CLASS AUV FOR HIGH RESOLUTION SEAFLOOR IMAGING

James Morash, Robert Damus, Samuel Desset, Victor Polidoro, and Professor Chryssostomos Chryssostomidis

MIT Sea Grant Program
AUV Laboratory

E38-374, 292 Main St.
Cambridge, MA 02139
617-253-9310
jmorash@alum.mit.edu
http://auvlab.mit.edu

Abstract

Over the past four years, development work at the MIT AUV Lab focused on a vehicle that is now almost a decade old. "Xanthos," one of the last surviving examples of the venerable Odyssey II series of AUVs (developed at MIT in the early 1990s), is a small, deep-rated, low-drag vehicle originally intended for oceanographic survey work. In this project, the AUV Lab pushed the limits of the Odyssey II platform to bring this aging vehicle up to the state of the art in underwater imaging. Originally designed to carry a CTD and ADCP, Xanthos was refit with DVL and AHRS for navigation, and sidescan sonar, high resolution digital still camera, and high-powered strobe for seafloor imaging. No part of the original vehicle was left untouched; several subsystems were re-designed and rebuilt from scratch to accommodate the new sensors. The ultimate goal: to turn a simple CTD profiler into a tool for deep-water marine archaeology.

Xanthos' rebirth culminated in a visit to Greece, aboard the Hellenic Center for Marine Research's R/V "Aegaeo." This attempt at AUV-based archaeology demonstrated the strengths and weaknesses of the re-design, as Xanthos contended with strong currents, navigation failures, sensor limitations, and mechanical damage.

Lessons learned from the development of Xanthos as an imaging platform form the foundation of the MIT AUV Lab's latest project. The "Odyssey IV," capable of hovering and holonomic maneuvers at depths of up to 3000m, will carry a stereo camera and sonar as its primary sensor payloads.

Introduction

Autonomous underwater vehicle (AUV) development at MIT Sea Grant began in the early 1990s with the *Odyssey* platform, a small, low-cost, deep-diving autonomous vehicle with a free-flooding streamlined fairing, single thruster, and actuated tail fins. *Odyssey* and its descendants are two to three meters in length and weigh between 200 and 500 kg. The core vehicle components are spherical glass pressure housings and oil-filled, pressure compensated electric brushless actuators, rated to a depth of

6000m. Conductivity, temperature, and depth loggers (CTDs) and current profilers (ADCPs) were typical payload sensors in the early days, intended for mapping the large-scale structure of ocean currents and ocean chemistry.

Over the past twelve years of *Odyssey* development, the original deepwater oceanographic survey platform has been adapted for many new missions. Research programs in the mid-'90s produced the second generation *Odyssey II* and its variants (*IIb*, *IIc*, *IId*), while a 1998 commercial spinoff aimed at the defense market resulted in the third generation Bluefin Robotics 21" vehicle, and its smaller 12.75" and 9" diameter siblings. The *Dorado* AUVs at the Monterey Bay Aquarium Research Institute (MBARI) grew out of the same program.

Back in 1995, funding from the Office of Naval Research (ONR) brought MIT Sea Grant's fleet count up to five *Odyssey II*s. As of 2001, these vehicles were either on permanent loan to colleagues at other institutions, or had been stripped for parts. The original team of engineers moved on from the AUV Lab (to Bluefin Robotics and beyond), and infrastructure decayed accordingly.

In the spring of 2001, the *Odyssey II* class AUV *Xanthos* was the last of its kind. This vehicle, built from scavenged parts, had its final deployment on a trip to Greece in June, 2001. *Xanthos* was showing its age and after the cruise, a decision had to be made. Was there any life left in the *Odyssey II*? Could this old design be adapted to the state of the art?

The MIT Sea Grant team decided that the answer was yes, and began an ambitious effort to turn *Xanthos* into a high-resolution imaging platform. The streamlined, field-proven mechanical structure was re-used, while nearly everything else was replaced: control electronics, batteries, actuators, sensors, and software. Since July of 2001, many Xanthos subsystems have been completely redesigned and rebuilt two or three times.

The project goal was to demonstrate the utility of a small, autonomous vehicle in the growing field of deepwater archaeology. Today, archaeological work beyond diver depth relies on remotely operated vehicles (ROVs) in order to make a careful, close inspection of targets of interest. Such examination of wreck sites in deep water requires a large and costly support ship, a long, high-strength tether and bulky management system, and a powerful, heavily instrumented science ROV. Only a handful of these vehicles exist in the world, and they are in great demand. This limitation makes it difficult to perform a wide area search, or to examine a large number of unclassified targets.

A low-cost, easily deployable AUV that can provide seafloor imagery approaching ROV quality would decrease the cost of exploratory archaeological expeditions, and make it possible to examine more potential targets over a wider field than ever before. The role envisioned for such an AUV is that of the advance scout, gathering detailed information about potential dive sites before committing more expensive assets. Such a capability has applications well beyond archaeology; current work at MIT Sea Grant includes experiments in imaging of deep, cold-water coral reefs, for example.

Similar work is proceeding in parallel elsewhere, notably at Woods Hole Oceanographic Institution (WHOI), where the SeaBED AUV [1] has proven to be a very successful camera platform. MIT Sea Grant chose to develop this capability in-house, in an effort to continue a track record of contributions to the state of the art in underwater robotics, and to give a young engineering team a challenging opportunity for hands-on learning.

Figure 1
AUV *Xanthos*, on the R/V *Shana Rae*

The version of *Xanthos* developed for this project represents a slightly different approach to the particular problem of archaeological search. The vehicle includes a 1.3 megapixel digital camera as well as a sidescan sonar (600 kHz) intended for medium-resolution wide-swath acoustic imaging. In a previously unexplored area, *Xanthos* can scan up to one square kilometer per dive, turning up potential wreck sites that are only tens of meters wide. Tightly spaced follow-up camera surveys *with the same vehicle* can then be used to positively identify the target. New ground can be covered with a minimum of infrastructure. Ultimately, on-line detection algorithms might enable the vehicle to switch from sidescan survey to camera inspection on the fly.

Packing two sophisticated sensors into a small vehicle proved to be no small engineering challenge. The following sections explain changes made to *Xanthos* since mid-2001, describe some of the successes and failures of the development process, and discuss vehicle performance on a return trip to Greece in June, 2004.

Updating core components

The modern *Odyssey IIx* AUV has a substantial list of standard components. First, there's the control sphere, containing the main vehicle computer (MVC), magnetic compass and inertial sensors, power control & conversion modules, radio devices, and motor controllers. The acoustic modem, emergency drop weight, depth sensor, altimeter, battery, and doppler velocimeter are mounted forward of the main sphere, while the thruster and fin actuators are packaged in a "tailcone" assembly at the stern. Payloads must fit in the remaining unoccupied space, typically in the mid-forward section (occupied by a second glass sphere in earlier *Odyssey* vehicles). Consolidation to one sphere was made possible by the substitution of new, smaller commercial off-the-shelf (COTS) components for many of the control sphere subsystems, and by Bluefin Robotics' pressure tolerant lithium ion polymer battery design, which is intended to operate without a pressure housing at depths up to 3000m (see **Improving reliability**).

Early *Odysseys* ran OS9, a commercial real-time multi-tasking operating system, on a Motorola 68000 series processor. The main vehicle computer was built from military-standard Versa Module Europa (VME) cards. In 1998, the bulky VME card cage was replaced with an Intel 486-based PC/104 card stack, a well known standard for rugged embedded computing. In the last several years, many other control sphere components have been integrated into the MVC stack, creating a compact robot control package that is readily transferrable to other vehicle designs.

The main processor, still well behind the curve of desktop computing for thermal reasons, is a fanless Pentium MMX clocked at 166MHz. The vehicle runs GNU/Linux, the well known open source operating system, and MOOS, the Mission Oriented Operating Suite, a cross-platform robot control package developed at MIT Sea Grant by Dr. Paul Newman and Robert Damus [2]. The MVC stack also carries a 40GByte 2.5" hard drive, 12 opto-isolated serial ports, a 10/100 Mbit Ethernet switch, 5V, 12V and 24V wide-input DC to DC converters, GPS receiver, FreeWave spread-spectrum radio modem, wireless networking adapter, and the power switch board that controls all vehicle power circuits. Eleven of the fifteen bulkhead connectors on the control sphere connect directly to a detachable wiring panel on the main PC/104 stack, linking external sensors to data ports and switched power circuits. The remaining four bulkheads connect the tailcone actuators to their controllers, carrying motor phase lines and Hall effect rotor and encoder feedback signals.

The original *Odyssey II* tailcone electronics relied on an obsolete standard for transformer-isolated serial communications, known as the Serial ASCII Instrumentation Loop (SAIL) [3]. The *Xanthos* upgrade replaced the homebrew SAIL bus with COTS brushless motor controllers on a multidrop RS-485 serial network. The motor controllers are powered directly from the main battery bus, and like most other sensors on board, they are connected to an opto-isolated serial port on the MVC. The use of three-wire opto-isolated serial connections ensures data quality, keeps transformer-isolated DC power buses separate, and prevents ground loops, a common source of electrical noise.

Adding a Pentium processor and a number of new sensors to *Xanthos* led to increased demands on the power system. The first update to the control sphere substituted high-output Vicor DC-DC converters for the low-power Lambda converters of the old design, thus saving space and increasing power conversion efficiency. The Vicor converters were also expected to radiate less high-frequency switching noise, but that proved not to be the case (see **Integrating the sidescan sonar**).

Another subsystem to benefit from COTS miniaturization was the dynamic control feedback: compass, gyroscopes, and accelerometers. Separate flux-gate compass, tilt sensors, and three-axis gyro were all replaced by a Crossbow Technologies Attitude/Heading Reference System (AHRS), a solid state device that runs an internal Kalman filter and outputs smoothed values for roll, pitch and yaw at up to 10 Hz.

The control sphere's new power switch board (PSB) was added to ease debugging of noise-sensitive payloads suffering from unknown sources of electrical interference. The *Xanthos* PSB features twelve solid-state switched circuits off the main battery bus; the on-board microcontroller can shut down or restart the motor drives, toggle the state of any of the various sensors or the regulated DC power converters, or reboot the main computer in the event of a crash. Devices can be turned off to save power on long missions and re-activated on demand. The power switch board is also responsible for firing the emergency drop weight, either on software command, watchdog timeout, or external trigger (see **Improving reliability**).

The addition of the FreeWave long-range spread-spectrum radio modem in the mid-'90s *Odyssey II* proved enormously helpful in field operations and debugging. Earlier vehicles required a cabled link for re-programming and could only respond to a gentle shove downward, starting a mission when the depth sensor read at least two meters deep. Since then two more COTS radio devices have been added to the vehicle. First, a 12-channel Global Positioning System (GPS) receiver used for navigating to surface waypoints, initializing the Kalman filter pre-dive, uniform clock synchronization, and automatic georeferencing of survey data. *Xanthos* has been through three GPS receivers and two different antenna manufacturers before finding a reliable solution.

The second new radio device is an 802.11b network adapter ("wireless Ethernet" or "Wi-Fi"). Though they are designed for indoor, medium-range use, Wi-Fi radios are popular in mobile robotics and other outdoor applications due to their low cost, high bandwidth, and easy integration. Wi-Fi in *Xanthos* has proven useful in engineering trials but unreliable at sea. The high bandwidth makes it possible to retrieve an entire mission's worth of sidescan data or a random sampling of photos in a matter of minutes, without recovering the AUV. Standoff distance is critical, however, as are the gains and vertical beam-widths of the antennas on either end of the link. It is not uncommon for the link to break unexpectedly, and refuse to reconnect until the intervening distance is reduced by half or more.

Xanthos also carries an acoustic link to the support vessel. The WHOI Micromodem provides an 80bps data connection, allowing the operator to receive estimated position updates even without surface-based tracking, and to remotely terminate missions or redirect the current mission task.

Improving navigation and tracking

Prior to this project, *Xanthos* and other *Odyssey* vehicles were largely used for midwater cruising and low-resolution surveys. *Odyssey* navigation relied on open-loop thrust-to-velocity based magnetic-compass dead reckoning, augmented by careful modeling of vehicle dynamics. On some missions, long baseline (LBL) beacons were used as an absolute position reference. *Xanthos* has been deployed with LBL arrays on previous expeditions, but when searching a wide area, the overhead associated with deploying, calibrating, and subsequently moving seafloor LBL beacons is prohibitive. Simple dead reckoning, while adequate for large-scale oceanographic mapping and modeling, is insufficient for generating high resolution mosaics of the seafloor.

Following industry practice, *Xanthos* was outfitted with an RD Instruments "Navigator" Doppler Velocity Log (DVL) in 2002. This accurate, reliable sensor measures body velocity along both horizontal axes, as well as altitude above the seafloor. The long-range 300 kHz version was chosen to maximize the water depth at which DVL dead reckoning could begin from the surface. Xanthos depends on DVL velocimetry to hit waypoints and follow survey patterns, with trackline spacing anywhere from 6 meters (accomodating the minimum turning radius) to 100 meters or more.

Due to mechanical constraints of the Odyssey platform, it is quite difficult to repeatably align the separate DVL housing with the Crossbow AHRS mounted inside the glass sphere. This compass/velocimeter alignment inaccuracy results in a fairly high error accumulation rate for Xanthos' DVL-aided dead reckoning, on the order of 3% of distance traveled. For small searches (less than a square kilometer at typical survey spacing) the navigation is of acceptable quality.

The last core hardware component to get a COTS update was the external tracking system. While under way, *Odyssey* vehicles are typically tracked using a surface ultra-short baseline (USBL) array and an on-board ORE Multibeacon. *Xanthos* still carries a USBL beacon as backup, but the pinger for everyday use is part of a larger tracking system known as GPS Intelligent Buoys (GIB).

A GIB network uses four buoys, each with a GPS receiver, to form a self-calibrating inverted LBL array for high-fidelity tracking. The vehicle's pinger carries a high precision clock that is synchronized to GPS time and pings once every two seconds. GIB tracking data has proven accurate to roughly five meters and the four buoys cover up to a one-kilometer square, moored or drifting at the corners [4]. GIB tracking data is used for supervision during missions, and in post-processing to produce a more accurate representation of the vehicle path.

Improving reliability

As part of the upgrade process, two *Xanthos* subsystems with a history of causing downtime at sea were replaced: the battery and the fin actuators. As of 2001, *Odyssey II* vehicles were using silver-zinc (AgZn) batteries in a simple 48V pack. AgZn cells contain toxic electrolyte, must be shipped in fireproof vermiculite packing, work best when kept refrigerated, and suffer irreversible damage when overcharged or overdischarged by as little as 10mV. Frequent cell failures were costly and time-consuming to address. Any battery maintenance, including charging, required that the battery sphere be unsealed and resealed. In addition, the AgZn pack's 5A current limit prohibited the use of high-power payloads such as a photographic strobe.

Fortunately, a massive development effort was underway at Bluefin Robotics, with the goal of creating an easy to use, mass producible battery for underwater vehicles. The resulting 28V battery pack is built up from 3.6V sealed Lithium-ion-polymer cells in series-parallel combination, with a peak output of 25A. The complete, waterproof pack used in Xanthos weighs 25kg and stores almost 2.5kWh of energy. It does not require a pressure vessel and can be swapped out for charging in a matter of minutes.

A few minor integration issues were encountered during inital tests, when bugs in the new battery management electronics caused the AUV to shut down unexpectedly while under way. Overall, however, the new lithium battery has made a major contribution to vehicle reliability. *Xanthos* is able to run for six to eight hours on a battery charge, day after day, with zero cell failures in the field.

The next task was to improve the tail fins. The main problem with the existing *Xanthos* tailcone was the lack of position feedback on the rudder and elevator shafts, leading to intermittent loss of dynamic control. To improve fin performance, 2000 line magnetic encoder wheels were added to the fin shafts. The encoder Hall effect sensors were solid potted and mounted in the aft end of the free-flooding tailcone gearbox, under the corresponding shafts.

It was also necessary to address the voltage mismatch between the new 28V battery, and the existing 48V brushless motors used to drive the tail fins; this became an opportunity to refit the rudder and elevator actuators with faster, higher-torque brushless motors wound for the lower battery voltage. After these upgrades were complete, fin positioning accuracy and reliability showed immediate improvements, with a corresponding bandwidth boost to dynamic control, but the tailcone remains somewhat fragile (see **Performance in the field**).

In case of emergency, *Xanthos* now carries a drop weight in the bow; when released, the bow gains up to 5 kg of buoyancy (configuration dependent) and the vehicle makes rapid headway toward the surface. Drop weights are typically constructed using a burn-wire, but this can be very slow to actuate and somewhat unpredictable. In *Xanthos*, it was important to guarantee an immediate weight release, in the event of a sudden collision avoidance maneuver (due to limited obstacle detection abilities). A solenoid-triggered drop weight mechanism was developed at MIT Sea Grant and tested in the 40 ft. deep salt water tank at MBARI. The solenoid is fired by a switched circuit inside the control sphere. Once the weight is released, the vehicle heads for the surface very quickly.

The drop weight can be triggered by the AUV control software if it detects a problem, or remotely via the acoustic modem. The WHOI Micromodem features two remotely operable output lines, one of which is tied to a trigger input on the power switch board. In the event of a battery failure leading to a total vehicle shutdown, the drop weight will fall within 12 hours by the dissolution of a a galvanically timed release (a.k.a. 'corroding link').

Integrating the digital still camera

After two attempts at using analog video cameras for autonomous imaging, the decision was made in late 2003 to use all digital components, and to rely on still photos rather than video. A color camera was chosen, in an effort to gather as much visual information as possible, with a sensor resolution comparable to medium-quality consumer cameras at the time (1.3 Mpx).

To illuminate the seafloor brightly enough for color imaging, a 200 Joule strobe was specified. The strobe, as delivered from Ocean Imaging Systems, produces a peak illumination intensity of nearly 200,000 Watts, decaying to zero in about three milliseconds. The high peak output is necessary because, unlike many other camera platforms, *Xanthos* is unable to hold still over a target while taking a photo. Trimmed for 1-2 kg of positive buoyancy in case of a thruster failure, the AUV must keep swimming nonstop to maintain altitude control. Images must be taken with as brief an exposure as possible to avoid motion blur.

The lens angle (12mm focal length with 2/3" CCD) was chosen to provide a seafloor image footprint of 4m (along-track) by 3m (cross-track), at an altitude of 4m. This was intended to provide a small (~10%) image-to-image overlap along track, at an average survey speed of 1.2 meters per second and a strobe recycle time of three seconds. In practice, captured image quality was considerably better at 3 to 3.5m altitude, resulting in minimal image overlap on most actual surveys (see **Performance in the field**).

The camera, connected to a FireWire (IEEE 1394) port on a dedicated PC/104 stack, was housed in a 3000m-rated cylinder from Deep Sea Systems, Inc. with a flat acrylic viewport. The FireWire interface, conforming to the standard DVCam spec, proved easy to interface to MIT's MOOS software, and the camera's built-in synchronized, isolated trigger line was used to fire the strobe on each exposure. A rough guess of 200 Joules for the strobe pulse proved to be plenty of light, making it easy to adjust the camera iris for a deep depth of field and provide an overall focused image. The CCD sensor shows mild "rainbow static" noise due to high gain settings, but it does little to obscure the captured images. Initial worries about excessive motion blur proved unfounded.

Integrating the sidescan sonar

Sidescan sonar is the technology of choice for searching the seafloor. Low frequency sidescans can cover swaths a kilometer wide, while ultra-high frequency models can image features on a sub-centimeter scale. A moderately high frequency (600kHz) was chosen for *Xanthos*, to aid detection of objects of archaeological significance (e.g., amphorae) while still covering a sizable swath.

One of the very few commercial sidescan sonars that fits in the *Odyssey II* payload envelope is the "Sea Scan PC" from Marine Sonic Technology, Ltd. (MSTL). It is a small, low cost system, sold by the dozens in towfish form, and has been successfully deployed in a number of Hydroid, Inc.'s REMUS vehicles [5]. The low cost of the system is reflected in the design: the Sea Scan PC is provided as a kit of parts, consisting of a PC/104 computer with custom analog to digital interface, an amplifier ("fish board") and a pair of transducers. The user is left to address questions of power regulation and filtering, susceptibility to interference, cabling, and other details that are easily answered in a towfish, but only with some difficulty in a complex AUV.

Extensive bench testing, aided by MSTL engineers, was required before *Xanthos*' self-noise levels were low enough for acoustic imaging. In several rounds of revisions to the electrical system, interfering DC-DC converters were replaced, while the Sea Scan components were carefully shielded, and provided with a filtered and isolated power supply. The "fish board" amplifier was moved from inside the control sphere to an independent cylindrical pressure housing, allowing a transition to coaxial transmission lines and shorter transducer cable runs.

Before the sonar was purchased, the intent was to retain some fraction of the original *Odyssey*'s deep-diving capability; the MIT and Marine Sonic engineering teams eventually compromised on a design depth of 1500m. Prior to this project, Marine Sonic had limited experience with deep-water transducer design. One such system had been built for a US Navy program, but all the sonar data had been classified, so customer feedback was limited. [6]

The new deep-rated transducers proved to be unusually susceptible to conducted electrical noise, perhaps due to a change in housing material from compressible PVC to conductive titanium. All of the AUV's motorized actuators had to be re-designed to electrically isolate them from seawater. This refit reduced (but did not eliminate) the interference, making the sonar usable for the first time.

Unfortunately, the deep-rated transducers proved inferior to the originals in other ways. In the projected beam, sidelobes overwhelm the main lobe, producing severe vertical banding on the sidescan trace. Since the end of this project, standard plastic transducers have been installed on *Xanthos* in place of the originals, and image quality has improved (at the expense of depth rating). [7]

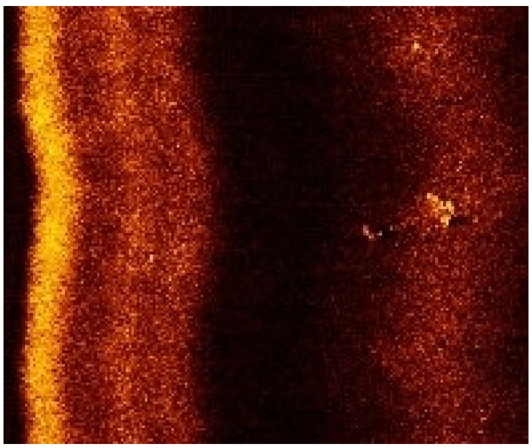
Performance in the field

Weather conditions generally limit field work in New England to May through October. *Xanthos* was not ready for post-upgrade field testing until January of 2004, so the AUV and a generous supply of spare parts and tools were packed up and shipped to Monterey, California for engineering trials at MBARI. Tank tests at the Institute and field deployments off the R/V *Shana Rae* showed that most of the new components were working as designed.

After another round of revisions to the electrical system, a second warm-weather field trip was made in March; this time to Dania Beach, FL, where Florida Atlantic University hosted further testing of *Xanthos* and the sidescan sonar. Field trials continued throughout the spring, when weather permitted, at Mystic Lake in Medford, MA.

A return trip to Greece was scheduled for June, 2004. Shortly before two tons of AUV and support equipment were due to be shipped across the Atlantic, field tests were brought to a halt and sidescan performance was declared "good enough". In practice, noise sensitivity and the distorted transducer beam pattern combined to produce relatively low-quality images. Highly reflective targets were still visible on the sonar record, however, and Xanthos was able to make its first archaeological find: an anchor, roughly four meters in length, of unknown origin.

Figure 2
Anchor detected by sidescan sonar on starboard channel (enlarged)

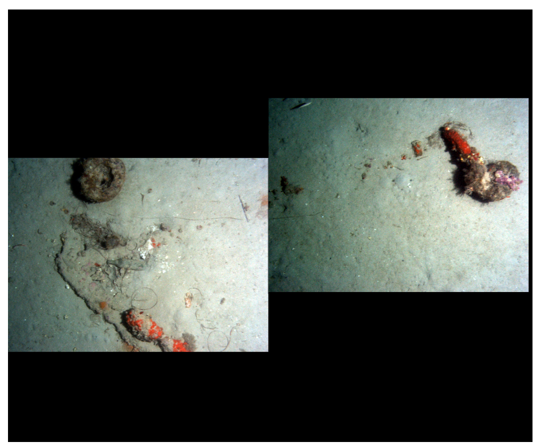


The camera system was largely untested until its first deployment in Greece. The two dependable AUV test sites in greater Boston (the Charles River and Mystic Lake) are muddy enough to cut visibility down to centimeters at all times. Due to late delivery of the digital imaging sensor, there had been no opportunity for a decisive field trial elsewhere.

Once in the clear waters of the Aegean, precise calibration proved nearly impossible, as the camera lens provided only manual focus and iris control. The vehicle dove with approximate focus and iris settings, and took a series of photos while varying CCD gain and exposure time until an acceptable result was achieved. The resulting calibration was used successfully for the rest of the cruise, but image quality could be improved by more careful tuning. In the end, camera performance far exceeded expectations, and *Xanthos* took thousands of photos during the cruise, mostly of sand, rocks, and some very surprised fish.

The MOOS DVL-aided dead-reckoning estimator navigated so well that, after the sunken anchor was spotted on the sidescan trace and georeferenced, *Xanthos* was able to return to the same location and photograph the artifact in two successive snapshots. The visible sideways drift of the vehicle between frames is thought to be due to external current forcing.

Figure 3
Anchor photographed in two frames



Vehicle performance overall was more than satisfactory. Xanthos was able to perform survey missions consistently and repeatably. Total submerged time during the eight-day deployment in Greece was 19.4 hours, with 11km total sidescan survey length (0.67 km^2 coverage at 60m swath width) and 11,770 photos taken.

Unfortunately, two failure modes led to repeated downtime and misbehavior. Three times, careless handling of the vehicle while on the crane or near the support boat caused a slight bend in a tailcone rudder or elevator shaft. This bending, barely detectable at first glance, was just enough to widen the gap between the magnetic encoder wheel and its corresponding Hall effect sensor to beyond the sensitivity threshold. The resulting loss of fin position feedback made the vehicle unable to perform missions, and repairs required complete disassembly of the tailcone gearbox.

The effect of a damaged rudder actuator was clearly visible on the GIB tracking display, when, shortly after reaching target depth at the beginning of a survey, the vehicle spiraled out of control. The operations team was able to transmit an acoustic abort and recover the vehicle for repair. Several methods of increasing fin feedback robustness are under consideration.

The second failure mode, which occurred twice, was a shutdown of the navigation estimator due to loss of incoming DVL velocimetry. Without DVL updates, the dead reckoner quickly exceeded its internal uncertainty limits and was forced to abandon the mission.

The loss of velocity data was caused by an intermittent sychronization failure between the DVL and the sidescan. The long-range RDI DVL uses a 300kHz pulse, which interferes with the collection of 600kHz sidescan data unless the two pings are simultaneous. Once synchronized, the DVL ping appears in the water column portion of the sidescan record, and can easily be ignored.

Navigation shutdowns occurred when the DVL was waiting for sidescan trigger pulses at the start of a survey pattern. The sidescan control software would accept a command to start pinging, but would then fail to act on the command or to report any problem. The MOOS software responsible for DVL/sidescan synchronization has since been re-written to double check that the sidescan has, in fact, begun to ping when requested, before taking the DVL out of free-running mode.

Conclusion

A successful trip to Greece has shown that *Odyssey II* continues to be a useful sensor platform into the immediate future. However, the AUV is still flawed in several respects. The thruster is too weak to resist more than minimal current forcing, making it unsafe to operate the vehicle too near shore or submerged rocks (where shipwrecks are most likely to be found). Exacerbating this problem is the inadequate obstacle avoidance sonar, currently limited to a forward-looking pencil-beam altimeter. Xanthos did not reach its goal of becoming a truly deep-rated survey vehicle, due to depth limits on the sidescan transducers and battery.

A new vehicle under development at MIT Sea Grant addresses these concerns. *Odyssey IV* is just slightly larger than *Xanthos*, but carries four one-horsepower thrusters (two on an actuated pitch mount), more energy storage, and more sophisticated payloads, including a stereo camera and high quality sonar. It is hover-capable and is expected to achieve a top cruising speed of nearly five knots. *Odyssey IV* is built for a minimum 3000m depth rating on every component. Sea trials are scheduled for spring 2006 [8].

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