Autonomous Underwater Vehicles
Laboratory Report

APPLYING AUV LESSONS AND TECHNOLOGIES TO AUTONOMOUS SURFACE CRAFT DEVELOPMENT

J. Manley, J. Curran, B. Lockyer, J. Morash, C. Chryssostomidis

MITSG 02-12

MIT Sea Grant College Program

AUV
Lab at MIT Sea Grant

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

APPLYING AUV LESSONS AND TECHNOLOGIES TO AUTONOMOUS SURFACE CRAFT DEVELOPMENT

J. Manley, J. Curran, B. Lockyer, J. Morash, C. Chryssostomidis

MITSG 02-12

Sea Grant College Program
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

NOAA Grant No.: NA86RG0074

Applying AUV Lessons and Technologies to Autonomous Surface Craft Development

J. Manley, J. Curran, B. Lockyer, J. Morash, C. Chryssostomidis

Massachusetts Institute of Technology
AUV Lab, Sea Grant College Program
292 Main St. Cambridge, MA 02139
auvlab@mit.edu, http://auvlab.mit.edu

Abstract - **Recent restructuring at the MIT AUV Lab has led to a convergence of autonomous vehicle technologies. Previously, the development of AUVs and Autonomous Surface Craft (ASCs) was pursued independently. In 1999 and 2000 new AUV software and electronic systems were developed and the lab's primary ASC underwent a significant mechanical redesign. The timing of these developments was fortuitous; it allowed the results of both efforts to be brought together during late 2000 and early 2001.**

This work to combine developments in two different vehicle programs streamlined the autonomous vehicle fleet at the AUV Lab. With identical user interfaces and programming requirements any engineer familiar with the AUV can now operate the ASC as well. Similarity in AUV and ASC control systems improves the economics of vehicle maintenance and deployment. Now joint field expeditions can be carried out with fewer spare parts and reduced personnel requirements. It is anticipated that the close similarity of control software in the two vehicles will ease the transition to multi-vehicle behaviors developed for two AUVs through the use of an AUV/ASC pair.

This paper describes the effort to converge separate AUV and ASC research developments into a streamlined lab-wide standard. The final ASC and AUV configurations incorporating AUV based technologies are described and the results of field tests are presented. The paper concludes with an assessment of the benefits and limitations of this approach to autonomous vehicle development and operation.

I – Autonomous Vehicle Development at MIT Sea Grant

A. Autonomous Surface Craft

At the MIT Sea Grant College Program, Autonomous Surface Craft (ASCs) have been under development since 1993. These systems have been designed for various missions and have demonstrated success in three separate iterations. The first ASC produced at MIT Sea Grant was named ARTEMIS. This vessel is a 1/17 scale replica of a fishing trawler (with a total length of 137 cm) that was used as a platform capable of testing the navigation and control systems required by an ASC. This ASC was then used to collect simple bathymetry data in the Charles River in Boston, MA [1].

One of the primary shortcomings of the ASC ARTEMIS was its small size. This limited its endurance and seakeeping. The field operations of ARTEMIS were limited to the Charles River, a region of limited scientific interest. To produce an ASC with more useful capabilities a kayak platform was examined and converted into an ASC. This new vehicle underwent a series of trials on the Charles River. It was then fitted with acoustic tracking systems and used to follow a tagged fish [2].

To continue the automated bathymetry experiments begun with ARTEMIS, a new ASC was developed. The specifications of the next ASC were based on a desire to create a system as versatile and useful as a small manned vessel while maintaining a small size to allow for easy deployment and survey operations. The new ASC ACES (for Autonomous Coastal Exploration System) was developed during 1996 and 1997 [3]. The completed ASC underwent field tests off Gloucester, MA during the summer of 1997. Upon completion of these trials it was outfitted with sensors suitable for hydrographic survey and successfully completed such a survey in Boston Harbor in December 1997 [4]. Beginning in January 1998 the ASC ACES was returned to the lab for a significant upgrade of its mechanical systems. Modifications and design iterations were tested through the summer of 2000 when the new ASC platform was stabilized and renamed *AutoCat* [5]. Subsequently the electronic and control systems of *AutoCat* have been modified to incorporate significant elements of MIT's AUV technology.

B. Autonomous Underwater Vehicles

During 1991 and 1992 a revolutionary new autonomous underwater vehicle (AUV) was developed at the MIT Sea Grant College Program AUV Laboratory. This vehicle, called *Odyssey*, was designed to provide marine scientists with economical access to the ocean [6]. This first *Odyssey* AUV underwent field trials off of New England in 1992 and (deployed from the National Science Foundation (NSF) icebreaker the Nathaniel B. Palmer) off of Antarctica in early

1993. The results of these deployments led to the creation of a second-generation vehicle, *Odyssey II* [7]. In the spring of 1994, *Odyssey II* was deployed from an ice-camp in the Beaufort Sea in support of a program to understand Arctic sea-ice mechanics. Under Sea Grant support, *Odyssey II* was operated as part of the 1994 and 1995 VENTS programs (in a collaboration with the NOAA Pacific Marine Environmental Laboratory).

In 1995, four new vehicles were built under Office of Naval Research (ONR) sponsorship. As some elements of the design were improved, these vehicles are denoted as the Odyssey IIb class. The original *Odyssey II* was upgraded to match the Odyssey IIb vehicles. These vehicles proved to be relatively simple to use and robust. For example, in June of 1996, two of the Odyssey IIb AUVs were used in a month-long experiment that studied the dynamics of frontal mixing in the Haro Strait, off of Vancouver Island. Over a 21-day period, the two vehicles performed 67 dives with no failures of the base vehicles and only one day lost to weather.

During 1997 through 2000 the AUV Lab focused its efforts on developing and demonstrating an Autonomous Ocean Sampling Network (AOSN) [8]. This effort was funded by ONR and involved numerous collaborators, notably the Woods Hole Oceanographic Institution (WHOI). While the MIT AUV Lab continued its vehicle development work, WHOI developed a mooring system that allowed the AUVs to dock for data downloading and battery recharging. Additional moorings and communications systems were developed that provided seamless interface, albeit with low bandwidth, between the AUVs and ship or shore controllers. The components and eventually the entire system were tested and demonstrated in several field experiments ranging from the Labrador Sea to Monterey Bay. This effort was officially concluded with a final field experiment in August 2000.

In parallel to the AOSN work, efforts were conducted to commercialize the MIT AUV technology and make it available to an audience beyond ocean science and research. In 1997 Bluefin Robotics was incorporated. Market studies and business analysis led to the opening of Bluefin's design and manufacturing facility in 1999. Over the same time period, Dr. James Bellingham, the AUV Lab Manager transitioned to a new position as Director of Engineering at the Monterey Bay Aquarium Research Institute (MBARI).

Also during this time a significant new AUV development effort was begun as part of the Atlantic Layer Tracking Experiment (ALTEX). This joint development effort involved, among others, MIT, MBARI and Bluefin Robotics. The final AUV design was licensed to Bluefin for commercial use as the Odyssey III class. At MIT many of the significant design changes were applied to the remaining Odyssey IIb vehicles. The new versions were dubbed the Odyssey IIc class and supported the continuing field program of the AUV Lab [9]. MIT now maintains one Odyssey IIc with a second full vehicle for spare parts.

II – Convergence of Vehicle Technologies

A. Sensors and Core Electronic Systems

To capitalize on the advances in electronics and sensors since the original *Odyssey II* design, many improvements were made to the ALTEX/Odyssey IIc systems. A core suite of systems was stabilized and includes a new main vehicle computer (described below) and the Crossbow Technologies™ DMU-AHRS attitude heading reference system. The DMU-AHRS replaced both a KVH® Fluxgate compass and a KVH® inclinometer. However, software was developed to facilitate use of the legacy KVH® systems if needed.

Additional systems that the ALTEX/Odyssey IIc specifications made standard are NMEA compatible GPS receivers and Freewave Technologies® radio modems. Currently the Odyssey IIc vehicles use a GARMIN GPS-25 OEM module but the rapid evolution of GPS receivers necessitated the NMEA interface to the AUV. The radio modems have become the standard remote access tool for AUV programming and operation when the vehicles are deployed. Field experience has indicated that these modems allow for reliable serial communications between the ship and the AUV at ranges well over one mile if necessary.

B. Main Vehicle Computer and Control Software

The software used on the Odyssey IIc AUVs is primarily the core ALTEX vehicle software written in collaboration by MBARI, MIT, and Bluefin Robotics. Inspired and influenced by the *Odyssey II* software, the ALTEX software has been completely re-written from the ground up in POSIX-compliant C++. The software is currently compiled for the QNX operating system and run on the PC104-based Main Vehicle Computer (MVC) within the Odyssey IIc control sphere. The control software of the vehicle is based upon the Layered Control scheme developed for the *Odyssey* II by Jim Bellingham and the MIT AUV Lab [10].

Layered Control involves the interaction of several concurrent "behaviors". Each concurrent behavior of a Layered Control architecture is responsible for meeting a certain goal (maintaining a depth envelope, following a survey line or homing in on a waypoint, for instance) and each is independently capable of issuing commands to the vehicle's dynamic control system. When the commands of two behaviors conflict, for instance when the target of a waypoint behavior is deeper than what the depth envelope behavior is trying to maintain, the dynamic control command of the higher-priority behavior (in this case, depth envelope), overrides all conflicting commands. This interaction of simple behaviors can lead to the relatively complex actions needed by an intelligent AUV.

This same simplicity allows the core code to be applied to both the Odyssey IIc vehicles and the Odyssey III class. In the case of the Odyssey IIc AUVs the only significant change is the different propulsion and control systems. The Odyssey III uses an articulated and ducted propeller while the Odyssey IIc uses a fixed prop and more traditional rudder and elevator fins. The only code change required is the implementation of a different set of drivers. The layered control architecture is never altered.

This is also the case for *AutoCat*. Eventually, the core Odyssey III code will be carefully tailored to the needs of the ASC. However, for preliminary trials it is possible to, once again, simply modify drivers for the "tailcone." In the case of the ASC the tailcone consists of twin electric trolling motors. As there is no need to control pitch or depth the layered control of the ASC is simply set to zero depth and the same core code can be applied.

C. Interface and Operation

Over time the AUV Lab has deployed many vehicles in a great variety of field experiments. This experience has led to the development of new interface tools to simply AUV operations. These tools are designed to interface to the basic code and can be modified to meet the specific needs of the AUVs or *AutoCat.*

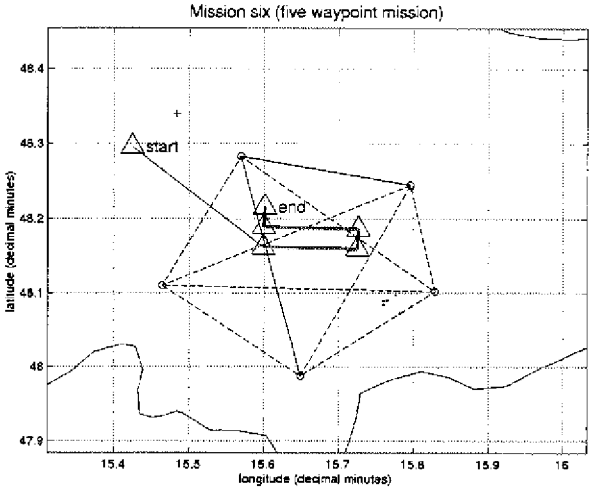

Fig. 1. The MATLAB® Mission Planner

During the last major AUV deployment, mission planning was dramatically improved by an impromptu (but well-conceived) MATLAB®-based navigation tool. This allowed multiple setpoint and multi-waypoint missions to be planned by clicking on appropriate regions of the map. The map was created from a digital file depicting the local coastline. Moreover, the software was capable of generating syntactically correct mission files that could then be downloaded directly onto the vehicle and used immediately. This feature became particularly useful for some of the longer waypoint missions. Because of the positive experience with this tool, and the lack of an analogous existing tool for the ALTEX/Odyssey III software, an effort is currently underway to create an "official" graphical mission planner. For the short term the prototype version is significantly enhancing AUV deployments.

The other new development for the Odyssey family is a simple joystick controller for use on the surface. This device was conceived as a student project at MBARI and the results have been applied at both MIT and MBARI. This basic controller provides two joysticks so the "pilot" can command the AUV speed, heading, and elevator pitch. The joysticks are interfaced to the AUV through a simple basic stamp programmed to translate stick movement into the proper AUV commands. These commands are passed through a radio modem connected to the controller. Currently there are two distinct chips for the command box, one for the AUVs and another for the ASC. It is anticipated that these will be replaced by one chip and a "toggle" switch to select which vehicle is to be controlled.

III – Current Vehicle Configurations

After several mechanical design iterations the ASC AutoCat has stabilized. Its mechanical systems were thoroughly described in [5] and are shown in Fig. 2. The current electronic configuration is presented in Table 1.

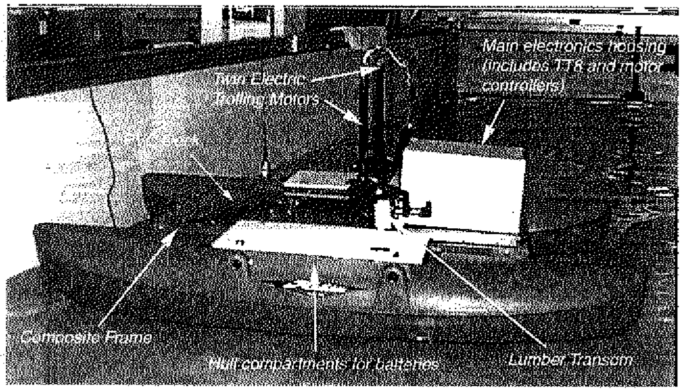

Fig. 2. The ASC *AutoCat*

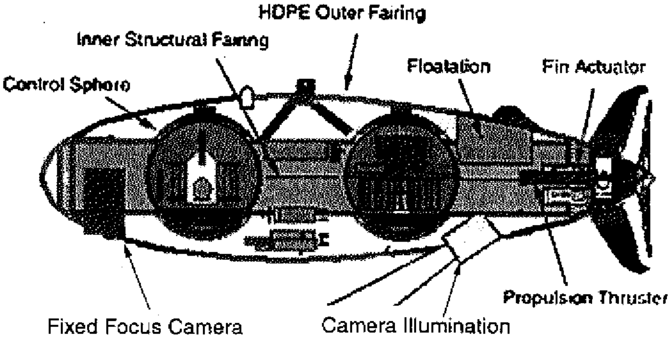

Fig. 3. *Xanthos* in Video Survey Configuration

The remaining Odyssey IIc AUV active at MIT is called *Xanthos*. Its mechanical systems are relatively unchanged from the original *Odyssey II* design [7]. A cross section of the current configuration, including its video camera payload, is shown in Fig. 3.

Despite their different mechanical configurations, *AutoCat* and *Xanthos* share a significant number of common systems. These systems are listed in Table 1. Both vehicles use identical PC104 stacks as their MVC. The software run by each vehicle differs only in the implementation of the different navigation systems and due to the use of specialized "tailcone" drivers for each vehicle.

The different navigation systems are called for by the greater complexities of sub-surface navigation. *AutoCat*, as a surface platform can use a DGPS system. The accuracy of this system allows for a lower quality, and less expensive, heading sensor. In the case of *Xanthos*, a Doppler Velocity Log (DVL) is used in combination with the DMU-AHRS to improve the dead reckoning of the AUV while submerged. On the surface the GPS updates the vehicle position. Both GPS systems interface to the MVC through standard NMEA strings. This makes the DGPS on the ASC a transparent system. The only code difference is the use of a driver for the DVL on *Xanthos*.

Sub-system	AUV *Xanthos*	ASC *AutoCat*
MVC	PC104, 133 MHZ	PC104, 133 MHZ
Heading Sensor	Crossbow™ DMU-AHRS	KVH® Compass
GPS Receiver	GARMIN GPS-25	Starlink® DNAV-212
Navigation Aid	RDI® DVL	Differential GPS
MVC Interface	Freewave® RF modem, Ethernet Tether	Freewave® RF modem, Ethernet Tether
Power Supply	48 V bus, AgZn Cells	24 V bus, Gel Cells

Table 1. AUV and ASC Sub-systems

The last distinction between the vehicles is in their power systems. With a significant payload capacity *AutoCat* can use less expensive Gel Cell batteries. This leads to the use of a 24-volt main power supply. This is a difference from the 48-volt Silver Zinc power system on the AUV. However, the ASC power conditioning circuits are actually just a sub-set of those on the AUV. If the need arose to use the silver zinc cells it would be simple to add one more DC/DC converter to the ASC (making a system identical to the AUVs) and immediately run at 48 volts. Even in this simple system commonality between AUV and ASC was maintained.

IV - Field Results

A. Odyssey IIc AUVs

The Odyssey IIc configuration was first tested in January 2000. With positive results of early trials, two more Odyssey IIb vehicles were upgraded to the new standard. These vehicles were equipped to support the Generic Oceanographic Array Technology Sonar (GOATS) 2000 field experiment. While there were some failures due to the pure age of the platforms (e.g. a worn actuator gear) the new sub-systems of the Odyssey IIc class performed quite well [9].

After GOATS 2000 the two Odyssey IIc vehicles returned to MIT. One was sacrificed for spare parts to support the lead vehicle, *Xanthos*. The electrical wiring on *Xanthos* (a noted trouble spot at GOATS 2000) was fully refurbished. The DVL was added and a camera system was installed. In this configuration *Xanthos* was deployed to Nisiros, Greece to perform video surveys of a shipwreck. Other than a depth sensor failure the only significant problems encountered on this cruise were the challenging bottom conditions.

The wreck site was just off a volcanic island and there was a steep drop off of the bottom. This forced missions to be run along the depth contour of the wreck. Early traditional survey patterns failed as the AUV either aborted its dives to avoid the bottom or became stuck on ridges if the safety settings were reduced. The only mission profile which was possible in the demanding terrain was a "dive bomb" approach straight down to the suspected wreck and then a quick return to safer depths. While this technique did not yield an extensive video survey of the wreck it did confirm the wreck's location, a fundamental objective of the cruise.

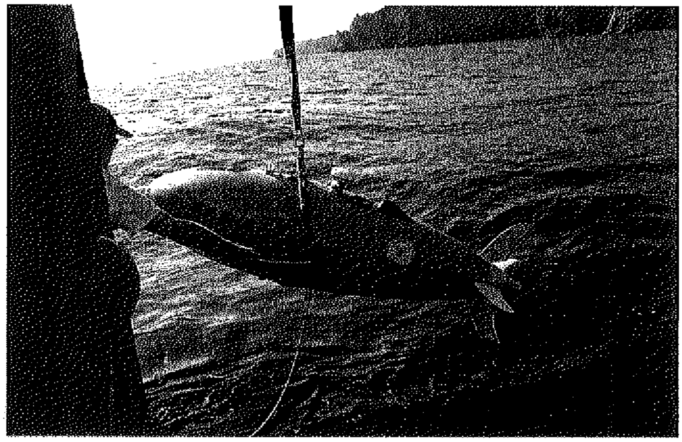

Fig. 4. *Xanthos* being deployed in Greece

B. ASC AutoCat

AutoCat has been less intensively tested than the Odyssey IIc AUVs. Due to the demands of the AUV field operations only simple checkout operations have been completed with the ASC. These operations have been conducted in the Charles River near MIT. The basic shared ASC/AUV architecture has been validated on *AutoCat* and the use of the joystick controller has been demonstrated. The remainder of 2001 will be dedicated to experiments with modifying the AUV layered control for the ASC.

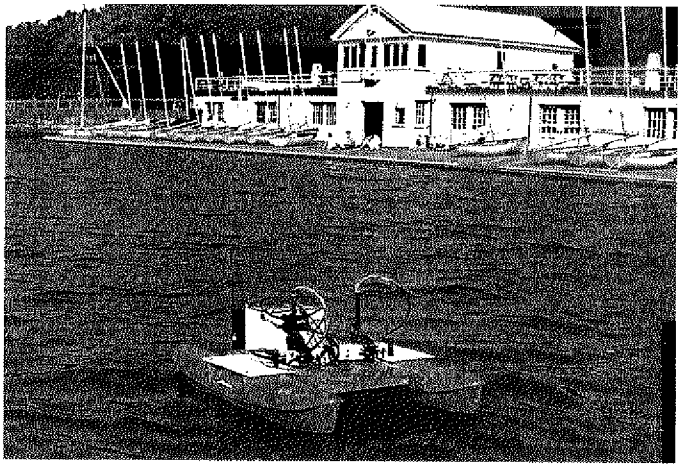

Fig. 5. *AutoCat* on the Charles River

V – Conclusions and Future Work

The MIT AUV Lab has successfully converged the technology of its primary autonomous vehicles. The combination of existing compatible AUV/ASC systems with identical user interfaces and programming requirements has notably streamlined the autonomous vehicle fleet at the AUV Lab. Now any engineer familiar with the Odyssey IIc can operate the ASC as well. The new Odyssey III vehicle slated for delivery to the lab in late 2001 will also use the same architecture and interface making all three MIT vehicles compatible. Similarity in AUV and ASC interface and subsystems improves the economics of vehicle maintenance and deployment. Joint field expeditions can be carried out with fewer spare parts and reduced personnel requirements.

These improvements in field performance will allow the AUV Lab to continue an aggressive field schedule with its autonomous vehicles. Planned operations include fish habitat surveys in the Gulf of Maine (Fall 2001), additional GOATS experiments (Spring 2002) and further marine archaeology efforts (Summer 2002).

In addition to improved field capabilities, the results of this effort toward technology convergence will support further autonomous vehicle research. The AUV Lab aims to develop behaviors and protocols for networked autonomous vehicles. Now that *AutoCat* uses the same fundamental technologies as the Odyssey IIc and III AUVs, it will be able to serve as a simulator for such protocol development. Initially it will be used to test adaptive layered control behaviors in response to external communication (acoustic and RF). Following that, it will provide for two-vehicle tests with reduced logistical demands. Eventually, all three vehicles will serve as a testbed network and *AutoCat* will serve as gateway node via its RF communications.

Acknowledgments

The authors would like to acknowledge the support of their colleagues at the MIT Sea Grant College Program. The participation of MIT students was made possible by the MIT Undergraduate Research Opportunities Program and is greatly appreciated. The MIT Sea Grant College Program, under grant number NA86RG0074, supported the work described here.

References

[1] T. Vaneck, J. Manley, C. Rodriguez, and M. Schmidt, "Automated Bathymetry using an Autonomous Surface Craft," *NAVIGATION, Journal of the Institute of Navigation*, Vol. 43 No 4, Winter 1996-1997.

[2] C. Goudey, T. Consi, J. Manley, M. Graham, B. Donovan, and L Kiley, "A Robotic Boat for Autonomous Fish Tracking," *Marine Technology Society Journal* Vol. 32 No. 1, Spring 1998.

[3] J. Manley, "Development of the Autonomous Surface Craft ACES," *Proceedings of Oceans '97,* MTS/IEEE, Halifax, Nova Scotia, October, 1997.

[4] J. Manley and T. Vaneck "High Fidelity Hydrographic Surveys Using an Autonomous Surface Craft," *Proceedings of Oceans Community Conference '98,* MTS, Baltimore, MD, September, 1998.

[5] J. Manley, A. Marsh, W. Cornforth, and C. Wiseman, "Evolution of the Autonomous Surface Craft *AutoCat*," *Proceedings of Oceans 2000,* MTS/IEEE Providence, RI, October, 1997.

[6] J. Bellingham, C. Goudey, T. Consi, and C. Chryssostomidis, "A Small, Long-Range Vehicle for Deep Ocean Exploration," *Proceedings Second International Offshore and Polar Engineering Conference*, San Francisco, Volume 2, pp 461-467, 1992.

[7] J. Bellingham, C. Goudey, T. Consi, J. Bales, D. Atwood, J. Leonard, and C. Chryssostomidis, "A Second Generation Survey AUV," *Proceedings AUV '94*, Boston MA, pp 148-155, 1994.

[8] T. Curtin, J. Bellingham, J. Catipovic, and D. Webb, "Autonomous Ocean Sampling Networks," *Oceanography*, Vol. 6, No. 3, pp 86-94, 1993.

[9] J. Manley, "Developments in Odyssey II Class AUVs for the GOATS 2000 Joint Research Program," *Proceedings of Underwater Vehicle Networks for Acoustic Oceanographic Measurements in the Littoral Ocean (GOATS 2000 JRP Conference),* NATO SACLANTCEN, La Spezia, Italy, in press

[10] J. Bellingham, and J. Leonard, "Task Configuration with Layered Control," *Mobile Robots for SubSea Environments, International Advanced Robotics Programme*, Monterey CA, pp 193-202, 1994.