PAPER

Autonomous Underwater Vehicles: Trends and Transformations

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ABSTRACT

Three examples of inter-agency cooperation utilizing current generation, individual Autonomous Underwater Vehicles (AUVs) are described consistent with recent recommendations of the U.S. Commission on Ocean Policy. The first steps in transforming individual AUVs into adaptive, networked systems are underway. To realize an affordable and deployable system, a network-class AUV must be designed with cost–size constraints not necessarily applied in developing solo AUVs. Vehicle types are suggested based on function and ocean operating regime: surface layer, interior and bottom layer. Implications for platform, navigation and control subsystems are explored and practical formulations for autonomy and intelligence are postulated for comparing performance and judging behavior. Laws and conventions governing intelligent maritime navigation are reviewed and an autonomous controller with conventional collision avoidance behavior is described. Network-class cost constraints can be achieved through economies of scale. Productivity and efficiency in AUV manufacturing will increase if constructive competition is maintained. Constructive strategies include interface and operating standards. Professional societies and industry trade groups have a leadership role to play in establishing public, open standards.

TRENDS

To move forward wisely with ocean science and technology, the United States needs a unified strategy that engages national and international collaboration. Part VII of the Report by the U.S. Commission on Ocean Policy, "Science-Based Decisions: Understanding of the Oceans," not only affirms this assertion, but also identifies a framework for federal agencies to proactively develop and implement policies that embrace the spirit of inter-agency cooperation and cost-effective shared technology. The Commission states that a larger, coordinated investment in infrastructure and technology development is necessary to conduct and support ocean science (Commissioners, 2004; Crimmins, 2004a).

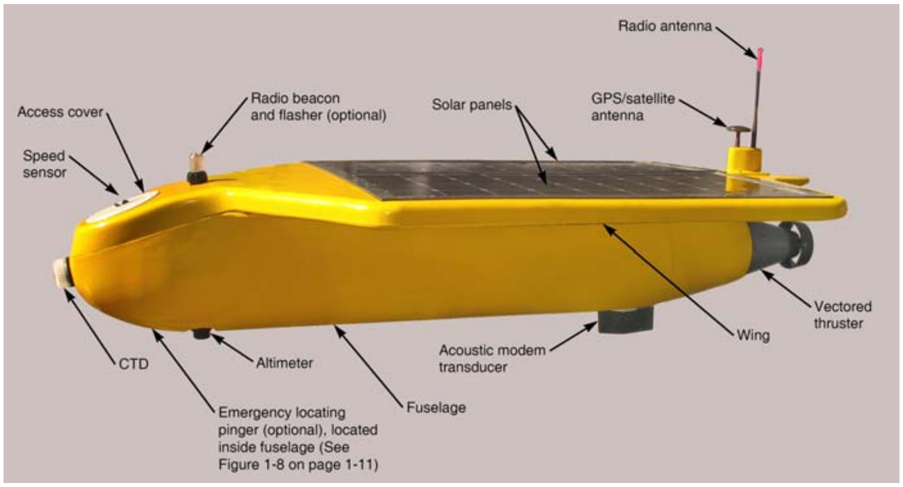
Future ocean sampling and surveillance systems should be capable of global deployment, sustained presence, three dimensional adaptive aperture, real time control and robust performance. These requirements can be met affordably by a network of Autonomous Underwater Vehicles (AUVs). The first generation of AUVs has transitioned from dream to reality (Griffiths, 2003). Engineering progress is now regularly reported and applications are described at many conferences and in an expanding literature of journal publications. Griffiths (2003) provides recent developments in AUV design, construction and operation. A number of commercial manufacturers have emerged to supply the growing market. Clearly, individual AUVs are evolving into useful tools that extend current measurement methods. Three examples involving current generation, individual AUVs will serve to illustrate trends in inter-agency cooperation utilizing this technology. Following these examples, we examine factors that will transform current measurement methods. Network externalities associated with inter-agency cooperation will play a role in driving this transformation.

Recently the Navy joined with the U. S. Environmental Protection Agency, the Narragansett Bay Estuary Program, and the Autonomous Undersea Systems Institute to demonstrate the effectiveness of using a Solar Powered Autonomous Underwater Vehicle (SAUV II) to measure dissolved oxgyen concentrations in Greenwich Bay, Rhode Island. Utilization of an AUV to rapidly move continuously-recording dissolved oxygen sensors over large spatial areas to map the frequency and extent of hypoxia demonstrates cost-effective water quality monitoring (Crimmins, 2005). Real-time monitoring of dissolved oxygen over large spatial scales is important for predicting the onset of hypoxia and mapping its extent (RI Dept Env Mgmt, 2004).

The SAUV II (Figure 1) is a solar powered AUV designed for long endurance missions such as monitoring, surveillance, or station keeping where real time bi-directional communications to shore are critical. The SAUV II operates continuously for several months using solar energy to recharge its lithium ion batteries during daylight hours. The SAUV II was fitted with a fast-response galvanic oxygen micro-sensor (AMT Analysenmesstechnik GmbH). This sensor provides rapid *in situ* profiling of dissolved oxygen at depths of up to 100 m with a response time of a few hundred milliseconds. The SAUV II was also fitted with a NXIC conductivity-temperature-depth (CTD) sensor (Falmouth Scientific Inc.). CTD data are essential for detecting water column stratification, which affects the development and breakdown of hypoxia (Crimmins, 2005).

Figure 1

Solar powered Autonomous Underwater Vehicle (SAUV II) used in the survey.



Three temporally contiguous transects were sampled in Greenwich Bay, representing areas of different depth and degree of exposure to wind waves and Narragansett Bay (Figure. 2). Upon completion of each transect, the vehicle surfaced, maintained station at a defined waypoint, and transmitted data to shore via an RF link. The survey ran continuously for 7.5 hr, covering 15 km of trackline undulating between depths of 0 and 9 m. Over 12.7 MB of dissolved oxygen and engineering data were collected and transmitted to shore in 4MB segments in near real-time. The SAUV II utilized approximately 25% of its battery capacity of 2000 whrs during the 7.5 hrs of operation. This demonstrated connectivity and endurance offers promise for future data gathering operations in shallow coastal waters, where AUVs may be one of the few practical options for routine monitoring.

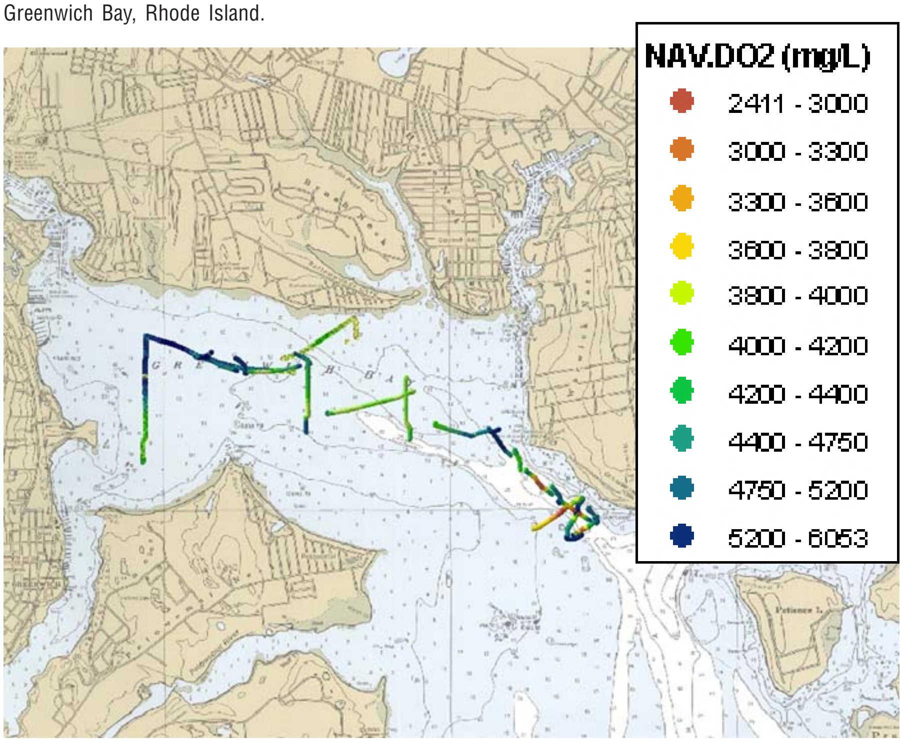
The SAUV II, initially a joint U.S.– Russian design, was developed by the Autonomous Undersea Systems Institute (AUSI), Technology Systems Incorporated, and Falmouth Scientific Incorporated with funding by the Office of Naval Research. The Naval Undersea Warfare Center Division Newport originated the collaborative demonstration project in Greenwich Bay, coordinated the effort, and produced many of the final products. The U.S. Environmental Protection Agency's Atlantic Ecology Division contributed ecological expertise and logistical support, and the Narragansett Bay Estuary Program contributed knowledge of the local dissolved oxygen dynamics. AUSI provided the SAUV II and supported its operation.

In another successful partnership demonstration, the Navy and NOAA used a small AUV to image an historical shipwreck in Massachusetts Bay. A multi-disciplinary, interagency team of scientists and engineers gathered in October 2004 to collect images of the *Paul Palmer*, a five-mast coal schooner that sank on June 13, 1913 sailing south after discharging a cargo of coal in Maine. The *Paul Palmer* caught fire and burned to the waterline north of Cape Cod before sinking in 80 feet of water in what is now known as Stellwagen Bank National Marine Sanctuary. Strategic partners on this project included NOAA's Office of Ocean Exploration, NOAA's National Undersea Research Program, NOAA's National Marine Sanctuary Program, the University of Connecticut, NUWC Division Newport and Fort Key Ltd.

The team used a commercially available Remote Underwater Environmental Monitoring Unit (REMUS) vehicle provided by NUWC. The REMUS, which was modified by NUWC for an earlier port security project, was specially equipped with a PC 104 computer and four commercially available Atlantis Model AUC-5600 color cameras positioned around the nose section in port, starboard, downward, and upward positions. During the shipwreck survey three cameras recorded data (port, starboard and downward cameras) to an AMP VCODER digital recorder that captured and compressed the real-time video. Divers attached transponders to the bow and stern of the wreck to aid in navigation and the

Figure 2

The run profile of the SAUV II dissolved oxygen survey that was conducted on 8 September 2005 in Greenwich Bay, Rhode Island.



REMUS was programmed to home between transponders with a slight offset during each leg of the survey. The survey ran for approximately 60 minutes recording a total of 324,000 frames using all three cameras. Three separate survey missions were completed. The resulting video was post-processed to geo-reference the video image with the vehicle's trajectory. Scientists at Fort Key generated a mosaic using custom algorithms that capture the first frame of the video and stitch together the differences from each subsequent frame until a complete image of the run is captured (Figure 3). Fort Key LTD processed the information into a single video mosaic of the starboard track of the survey. The *Paul Palmer* project demonstrated an *in situ* inspection capability with wide application.

Figure 3

Sample small video mosaic of the Paul Palmer wreck produced by Fort Key LTD. The video images were collected on 6 October 2004 using the NUWC Division Newport REMUS vehicle integrated with a specialized video system. This mosaic represents two complete passes over the wreck as viewed from the downward camera.

A third example of cooperation utilizing AUVs is a study of the ecological effects from dredging activities (Crimmins, 2004b). Local scientists and those at the U.S. Army Corps of Engineers Research and Development Center were interested in understanding how the suspended sediments from residual dredge material resettle in the environment, both near field and far field from the dredge activity. The 2003 Providence River and Harbor Maintenance and Dredging Project provided a consortium of federal and state scientists and environmental regulators with an opportunity to monitor dredging activities using innovative sensing methods. A REMUS vehicle, provided by NUWC, outfitted with a YSI-6000 multi-probe sensor system provided by the University of Rhode Island Graduate School of Oceanography, enabled researchers to sample the affected environment using an AUV equipped with an advanced chemical sensing payload.

The REMUS ran several survey tracks through an area in Providence Harbor collecting environmental data during a portion of the dredging project. Geographic information systems software was used to analyze and visualize the turbidity data in two and three dimensions (Figure 4). Preliminary analysis of the data indicates that turbidity and dissolved oxygen levels were beyond the acceptable limits identified by the Rhode Island Department of Environmental Management. Data collected in this experiment were useful in providing researchers and regulators with information on which to base additional monitoring exercises (adaptive sampling).

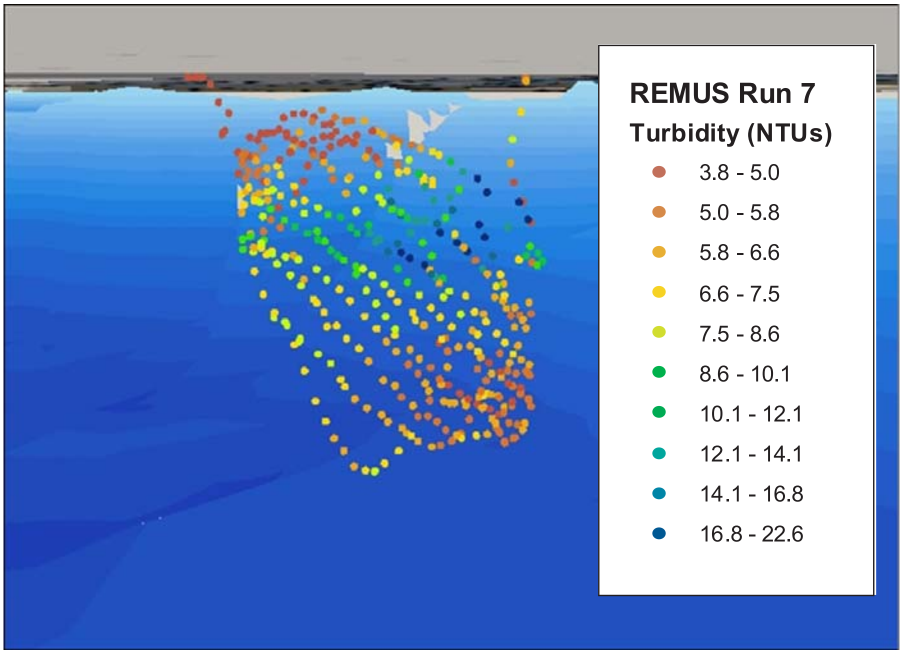
The three examples above illustrate achieving mutual goals with one vehicle. In the future, mutual goals will be addressed using multiple vehicles from different agencies working in a coordinated effort. Optimization and control of such multiple objective, multiple constraint missions are being explored in a number of current research experiments.

Transformations

The deployment of multiple, cooperating vehicles controlled in a network will transform current measurement methods (Curtin, 1993, 2001). A network of interactive AUVs is a distribution of mobile, controllable sensors with feedback time and spatial resolution adaptable to the mission, providing variable sensing aperture to track spatial gradients in the environment and targets moving through the environment. It also enables synoptic cov-

Figure 4

Three-dimensional GIS representation of REMUS Run 7 turbidity levels. Data collected during the Providence River and Harbor Maintenance Dredge Project in the summer of 2003.



erage of a region to minimize aliasing of temporal-spatial variability, maximize probability of target detection and minimize false alarm rate. Finally and importantly, it provides flexible options for managing system limitations in energy, communication and navigation.

To realize an affordable and deployable network, a network-class AUV (AUV$_{NC}$) and its associated subsystems must be designed with concepts and constraints not necessarily applied in developing solo AUVs. The principal subsystems within an AUV are platform, navigation, control, energy, communication, and sensors. This paper focuses on platform, navigation and control issues. A subsequent paper will fully address associated energy, communication and sensor issues.

Platform

There are many ways to categorize AUVs including size, cost, method of propulsion, and operating depth. In size-cost space, an AUV$_{NC}$ must be designed and produced within a defined envelope (Figure 5). The bounds of this envelope are not exact and may be application-specific, but clearly for any reasonably populated network (10-100 nodes), average vehicle cost exceeding $300K and size exceeding 200 kg are outside the envelope. Logistics (deployment, retrieval), payload (sensor type) and packaging (custom) costs can drive a unit out of the envelope. Energy storage keeps the envelope away from the origin. Production costs (economies of scale) can keep a unit within the envelope.

Designing within this envelope, also provides the critical benefit of affordable, repeatable testing cycles and manageable risks. Limited size opens up many opportunities for testing from a variety of manned platforms. Cost constraints allow true autonomy to be exercised without the risk of catastrophic loss (of a very expensive vehicle). AUVs, typical of all complex machines, require thousands of hours of *in situ* testing at the prototype stage to achieve robust performance. Vehicle developments outside the AUV$_{NC}$ design envelope rarely accumulate enough *in situ* testing hours to achieve operational maturity.

Within the design envelope, cost-effectiveness may be further achieved through specialization. The trade-off between optimized specialization and modular generality is challenging to assess and often dynamic in nature as technologies and demands evolve.

One approach is to develop a standard delivery platform with mission specific payload and sensor modules. User groups could lease, borrow, or jointly develop the specific sensor modules a discipline requires. The AUV might be owned by the user group, an academic or government institute or an equipment lease company. The key to making this concept work is having the AUV community develop specific electrical, mechanical and communication standards that industry will embrace. There are currently over 15 commercial builders of AUV systems producing products with little or no compatibility. Standards may be the tide that raises all boats, but achieving consensus on standards is known to be difficult. A top-down approach, in which a dominant user establishes de facto standards, can be effective but tends to stifle innovation. Critical mass network externalities can also tip the market to a standard by providing multiplicative value to the customer. Manufacturers who understand this and develop a strategy to profit from public, open standards will contribute most to the advancement of ocean sampling.

The AUV$_{NC}$ can be segmented into three broad types based on operating regime: surface layer (AUV$_{NC-S}$), interior (AUV$_{NC-I}$) and bottom layer (AUV$_{NC-B}$). The AUV$_{NC-S}$ will primarily serve as a data fusion node, communication link and absolute navigation reference. These vehicles will have a variety of acoustic and radio communication capabilities, and computers with large memory capacity. They will be designed for stability and survivability in the energetic ocean surface layer. In some forms, these vehicles may be powered by air breathing engines or harvest available solar and

Figure 5

Design envelope for a network-class Autonomous Underwater Vehicle.

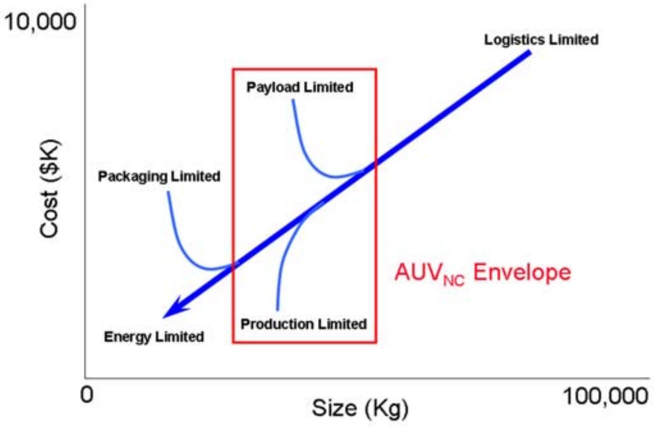
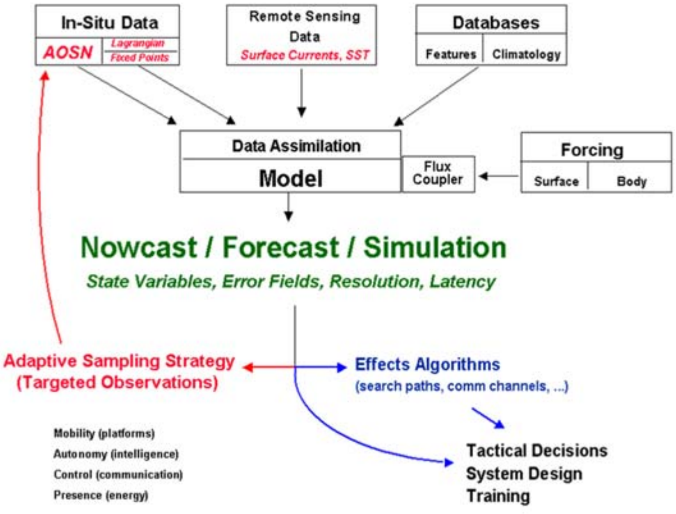


Figure 6

The Autonomous Ocean Sampling Network (AOSN) provides initialization of models which in turn provide feedback to guide AUV re-positioning (targeted observations) to minimize error fields used for effects algorithms, tactical decisions, system design and training.



wave energy. As controlling nodes, they will function as network servers providing store-and-forward communication links between subsurface acoustically transmitted information and above surface radio transmissions and providing geo-coordinates and time reference from the global positioning system.

The $\text{AUV}_{\text{NC-I}}$ will primarily serve as a mobile sensor. These vehicles may have a variety of sensors, and will be capable of navigating and communicating throughout the water column. They will be designed for cooperative behavior, able to cluster into variable aperture antennas to detect and measure ocean processes and signals of interest. These vehicles will be powered by rechargeable batteries or advanced fuel cells. Sensor payloads will be modular, and sensing diversity can be distributed on or among vehicles. Payloads can be passive or active enabling remote sensing, multi-static sensing and target interaction and intervention. The best distribution of sensors for a specific mission is a function of time and will be determined by an adaptive sampling and optimization algorithm resident on the network. Critical in this adjustment is data feedback and assimilation into relevant models (Figure 6). Feedback latency and practical convergence times are important research issues.

The $\text{AUV}_{\text{NC-B}}$ will primarily serve as a transport, tanker and relative navigation reference. These vehicles will be optimized for energy storage capacity with a docking fixture for energy transfer to and piggy-back transport of other vehicles in the network, and have a long baseline acoustic transponder. They will be designed to operate as AUV_{NC} carriers for long haul transits and as mostly stationary, bottom dwelling energy caches and location references. They will move vertically when necessary to re-fuel from an $\text{AUV}_{\text{NC-S}}$ or from a ship of opportunity such as a network-participating submarine. They may move horizontally on occasion if the network repositions to another area or reconfigures to improve performance. $\text{AUV}_{\text{NC-B}}$ and $\text{AUV}_{\text{NC-S}}$ types may be combined into an integrated unit serving as a building block infrastructure node.

Prototype AUVs of each type exist today. Most advanced are the $\text{AUV}_{\text{NC-I}}$. For example, the evolution of the first generation undersea glider (Figure 7) from concept to reliable tool is depicted in Figure 8. The 10-15 year maturation time is typical for ocean instrumentation. The SAUV II, discussed above, is primarily an $\text{AUV}_{\text{NC-S}}$ type. Potential $\text{AUV}_{\text{NC-S}}$ types are being investigated in three current DARPA contracts to develop Persistent Ocean Surveillance buoys utilizing energy harvesting (Latt, 2005). Least developed is the $\text{AUV}_{\text{NC-B}}$. Progress toward a transformational sampling capability is now limited in many ways by the availability of an integrated, multi-functional infrastructure node as described above.

Figure 7

First generation undersea gliders.

	Slocum Glider Electric	Slocum Glider Thermal	Seaglider	Spray Glider
Weight	123 lb	132 lb	110 lb	114 lb
Diameter	21 cm	21 cm	30 cm	20 cm
Length	1.5 m	1.5 m	2.8 m	2.15 m
Horiz. Speed	0.6 knots	0.6 knots	0.6 knots	0.6 knots
Max Depth	200 m	2000 m	1000 m	1500 m
Endurance	15-30 days	5 years	6 months	6 months
Range	600-1500 km	40,000 km	4000 km	4500 km
Energy	Battery	Environment	Battery	Battery
Comms	Iridium	Iridium	Iridium	Iridium

Navigation

Navigation is the maneuvering of a vessel in the water from one location to another. Navigating has two important considerations: knowledge of the vehicle's geo-referenced or locally-referenced position and collision avoidance.

Estimates of AUV position are obtained from a number of navigation subsystems that continue to improve in accuracy and precision. Today's Inertial Navigation System/Doppler Velocity Log (INS/DVL) subsystems can achieve 0.05% of distance traveled gauged by Circular Error of Position (CEP) (e.g., Kearfott "SeaDevil") or 5 m/hour (e.g., iXSEA-Oceano "PHINS"). Long Baseline (LBL) subsystems are accurate to within a few meters (e.g., Sonardyne "AvTrak", EdgeTech "PS8000", Benthos, Simrad). Ultra Short Baseline (USBL) subsystems perform to < 1% of slant range accuracy and 0.2% of slant range repeatability (e.g., Sonardyne "Big head", Simrad "HiPAP", Nautronix, ORE). The accuracy of Global Positioning System (GPS) buoy repeaters depends on the satellite receiver employed (e.g., ACSA "GIB", Hydroid "Paradigm").

The performance of integrated systems reflects the advances in subsystems. For example, Hugin 3000 (IMU, gyrocompass, DVL, GPS, HiPAP USBL) reports 12 m real time at 2000 m depth and 3.5 m post-processed. BPAUV (Compass, 300 kHz DVL, GPS) has documented position accuracy as < 1% of distance traveled. REMUS (LBL navigation) positions are conservatively accurate to < 10 m, but often more precise depending on the dimensions of the LBL layout. MARIDAN 600 (Kearfott INS, 1200 kHz DVL, GPS) specifies accuracy of 0.03% of distance traveled RMS.

Advances in micro navigation, multi-vehicle navigation and feature-based navigation are currently being pursued. Micro navigation capitalizes on high resolution sensing of the bottom roughness. Multi-vehicle navigation is closely tied to advances in acoustic communication. Feature-based navigation has great potential for bootstrapping a deployed system to greater levels of accuracy over time.

Collision avoidance involves some knowledge of signs, rules of the road, associated maps and the ability to manipulate the controls so as to mobilize the vehicle. The International Regulations for Preventing Collisions at Sea (COLREGS) Navigation Rules (Commandant, 1999) were written to provide guidelines that ensure consistent operating methods intended to avoid collision between vessels.

The Navigation and Navigable Waters section of the Code of Federal Regulations, address the rules dictating navigation. From CFR 33 section 97.27-10 "Reckless or negligent operation is prohibited by law." Subsection 13(a) of the act of April 25 1940 (46 USC 526l) reads as follows; "No person shall operate any motorboat or any vessel in a reckless manner so as to endanger the life, limb, or property of any person."

So that all mariners may operate safely when in proximity to one another, a hierarchy of "respect" has been established. Through this order, a vessel can immediately recognize their responsibility to "give way" to another vessel or not. In order from most privileged to least, the list goes: not under command (NUC), restricted in ability to maneuver (RESTRICTED), constrained by draft (CONSTRAINED), engaged in fishing (FISHING), sailing and underway (SAILING), power-driven and underway (POWER), and seaplane underway (SEAPLANE).

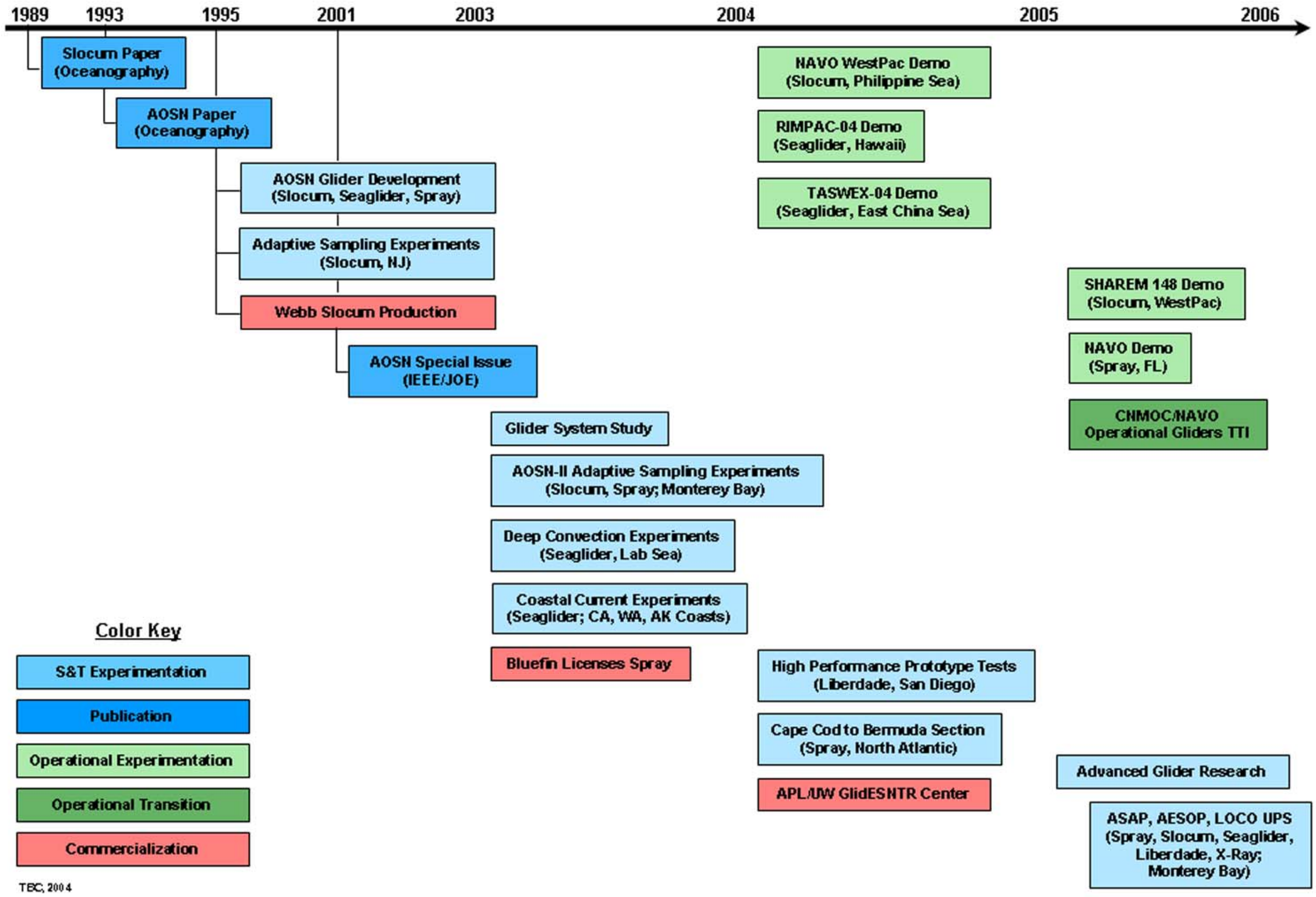
To avoid confusion in discussing legal issues, we include the Autonomous Surface Vehicle (ASV) (sometimes called an Unmanned Surface Vehicle, USV) and the Autonomous Underwater Vehicle (AUV) (sometimes called an Unmanned Underwater Vehicle, UUV) as members of a broader class called Autonomous Marine Vehicle (AMV). An AMV could be classified as a "vessel not under command" at all times. In some sense this seems appropriate, because there is no human operator maintaining a lookout and navigating in the traditional sense. This is not a practical approach, however, as this classification is generally thought to describe a vessel that is only temporarily without command, either because of machinery malfunction, broken mooring line, or other unforeseen event. It is more appropriate that the AMV be considered a vessel restricted in her ability to maneuver.

It is important to note the significance of the approved definitions relating to some of the terms in the COLREGS. "Underway" means not attached to the ground, it does not mean moving through the water. "Making way" means moving through the water (Mellor, 1990). The distinction is significant when considering the responsibility of the vessel in regards to avoidance of collision, and in terms of the necessary day shapes and lights used to identify the vessel's classification.

As a practical matter, it is conceivable that the AMV is really no more than an "obstruction" when operating on the surface, but due to the fact that the vehicle is equipped with propulsive equipment, it appears that these vehicles are obliged to perform according to the COLREGS as discussed above. It would be prudent to make every effort to provide adequate forewarning to other mariners of the intention to operate the AMV in specific wa-

Figure 8

Milestones in the development of the first generation undersea gliders.



ters. This notification would best be carried out through the Coast Guard's 'Notice to Mariners', so that adequate distribution through standard channels may be made. The Coast Guard requests a minimum of one week's lead time, and appreciates a month's notice before broadcasting bulletins from mariners. Clearly, these stipulations would not always be reasonable to fulfill during AMV operations.

While it is difficult to conclusively determine the legal ramifications associated with operating autonomous vehicles on and in navigable waters, certain definitive conclusions can be drawn. First, despite the AMV's unique nature as an "atypical" craft, it very likely qualifies as a "vessel" and is therefore subject to all the laws of Admiralty and its jurisdiction, enforced in the United States by the Coast Guard. This implies the conveyance of risk associated with liability as defined in "tort" law that may arise through normal operations that involve damage to persons or property. Legal liability may be conveyed to the owner, the operator and the underwriter. Conclusive determination may not be established until a case of precedence is set in Court.

Second, the AMV will be responsible for observing the entire standard "rules of the road" as spelled out in the US CFR (COLREGS). Furthermore, as the CFR dictates the necessity for an "able" lookout, the AMV is inherently burdened with a responsibility to avoid collision. In addition, as this is a motorized craft, it is likely to still be seen as the "give way" vessel in many (and perhaps most) circumstances. Additional requirements include the use of lights, day shapes and other methods as spelled out in COLREGS. In any case, the AMV is required to operate responsibly, and more to the point "not in a reckless manner so as to endanger other vessels, people, objects, etc."

Lastly, there may be some possibility of seeking "research vessel" status for certain AMV configurations. This would relax certain lighting and visual aid requirements, but would not relax the requirements for observing the rules of safe operation. Due to the unique nature of the AMV, there may be justification in claiming "special status" with regards to the specific operational requirements, as spelled out in the CFR.

In summary, we see that autonomous vehicles will likely be burdened with the responsibility to observe the COLREGS rules of the road while operating in and on navigable waters of the United States and unless it becomes clearly determined otherwise through judicial process, autonomous vehicles will be obliged to take all reasonable steps to observe the requirements for lights, day shapes and "lookout" as defined in the Code of Federal Regulations.

Control

Often used but rarely quantified properties of AUVs are autonomy and intelligence. These properties can be viewed as independent bases describing the behavior of the AUV (Figure 9). The goal is to create executive agents with high levels of both autonomy and intelligence. Definitions of these quantities that may be useful in this context are:

$$\textit{Autonomy} = C_n \left(\frac{\text{control bits}}{\text{total message size}} \right)^{-i} \left(\frac{\text{contact time}}{\text{total mission time}} \right)^{-j}$$

C_n = mission connectivity index

$$\textit{Intelligence} = C_X \left(\frac{\text{mission completion time}}{\text{maximum endurance}} \right)^{-m} \left(\frac{\text{achieved result}}{\text{objective}} \right)^{n}$$

C_X = mission complexity index

The coefficients and exponents must be determined empirically. The usefulness of such definitions lies in their ability to quantify and normalize different system performances. Initial baseline datasets are only beginning to be acquired for this purpose as missions are increasingly accomplished. In addition to relative assessments, metrics for the intelligence and autonomy of an AUV will be important independently in judging legal liability.

The problem of controlling an AMV is magnified in the presence of other nearby moving vehicles. This is true even when the other vehicles are cooperative and have known positions, trajectories and intentions. The challenge is greater when vehicles are uncooperative, or outright adversarial, with uncertain position, trajectory, or intentions. The following three aspects of motion planning in the

Figure 9

Regimes in Autonomy-Intelligence space.

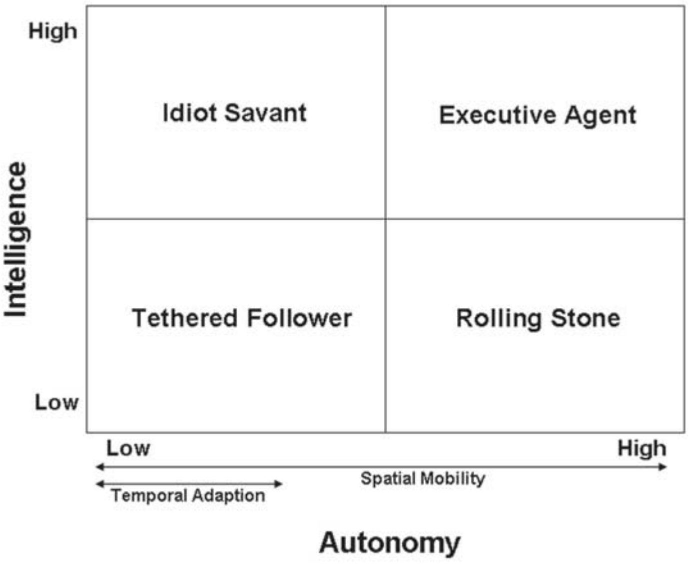
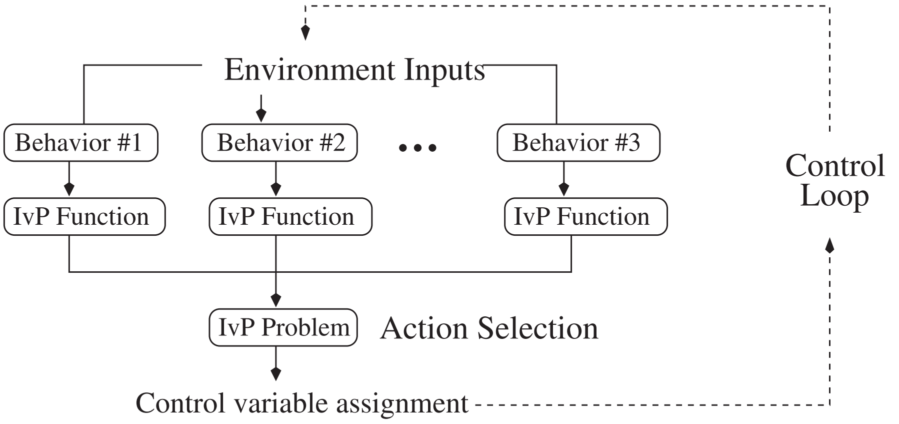


Figure 10

Behavior-based architecture using IvP Multi-objective action selection.



marine environment reflect the difficulty of this problem:

1) Collision avoidance is not enough. A near-miss situation can have negative consequences that may lead to a lack of trust in the control capabilities of an AMV (the same would be true of a human prone to near-misses).
2) Collision avoidance must follow convention. The responsibility of collision avoidance of two vehicles typically is shared between the controller (human or otherwise) of each vehicle. A significant aspect of this shared responsibility is the expectation of what the other party is likely (or obligated) to do.
3) Missions must be accomplished with collision avoidance. When possible, control needs to reflect a balance between collision avoidance and the mission being executed by the vehicle.

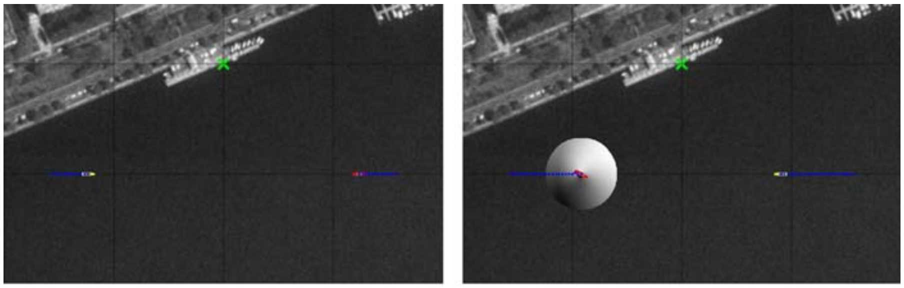
Mastering the COLREGS is an essential part of many types of formal training to safely navigate a vessel. The general structure associates prescribed actions to certain situations. The wording is laid out to be as precise as possible in describing what constitutes being in a certain situation, and what constitutes meeting one's obligation in said situation. Despite its thoroughness, it depends on a human's ability to use common sense to not only determine if a situation currently applies, but also to exploit flexibility in the actions prescribed in a rule. This is particularly important if more than one rule applies simultaneously (perhaps due to the presence of more than one vessel to avoid), or in the case where adhering to the rule conflicts or competes with the objectives tied to the overall vehicle mission.

Consider Rule 14, the "Head-on Situation": When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other. Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel. When a vessel is in any doubt as to whether such a situation exists she shall assume that it does exist and act accordingly.

This rule, simply stated, means "pass on the right." There is flexibility of two forms in this rule. First is the flexibility of determining when the rule applies, due in part from determining if the two vessels are on a reciprocal course, and in part by the distance between the two vessels. The second form of flexibility is in the action to be taken to satisfy the rule. The rule states that a course to starboard is required, but does not specify the angle or ultimate clearance distance required between the two vessels. Clauses 14(b) and 14(c) address the issue of determining if the rule applies to the current situation, but both depend on language that is open to interpretation. It is this flexibility that humans exploit by assessing the overall situation and relying on common sense and experience.

Figure 11

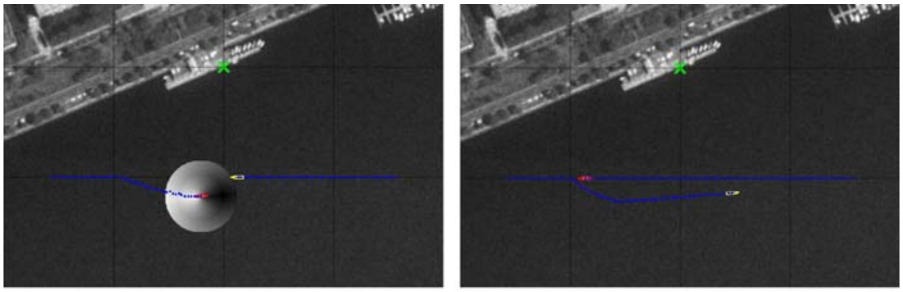
(a) The COLREGS-enabled vehicle, on the left, approaches a vehicle in a head-on situation.
(b) The vehicle begins a collision-avoidance maneuver based on its "rule-14" behavior.



(a) (b)

Figure 12

(a) The COLREGS-enabled vehicle on the left sufficiently clears the other vehicle. (b) Both vehicles proceed to their destinations.



(a) (b)

The key to providing an AMV with effective COLREGS capability is to capture both the precision and flexibility of the rules. By effective, we mean that situations where multiple rules are in effect or situations where rules are in competition with mission objectives are handled smoothly and with acceptable levels of risk when there is room for compromise.

The implementation uses behavior-based control architecture, with a novel method of multi-objective optimization, interval programming (IvP), to coordinate behaviors. The origin of behavior-based systems is commonly attributed to Brooks' "subsumption architecture" (Brooks, 1986). Since then, it has been used in a large variety of applications including indoor robots (Arkin, 1997, 1993; Hoff, 1995; Lenser, 2001; Pirjanian, 1998; Riekki, 1999; Saffiotti, 1999; Tunstel, 1995; Veloso, 2000), land vehicles (Rosenblatt, 1997), planetary rovers (Pirjanian, 2001; Singh, 2000), and marine vehicles (Benjamin, 2002; Bennet, 2000; Carreras, 2000; Kumar, 2000; Rosenblatt, 2002).

Action selection (Figure 10) is the process of choosing a single action for execution, given the outputs of the behaviors. The "action space" is the set of all possible distinct actions, e.g., all speed, heading and depth combinations for a marine vehicle. Each of the COLREGS rules is captured in a distinct behavior that may or may not be influencing the overall control of the vehicle at any given moment. Its influence depends on whether the rule associated with the behavior applies to the current situation. The output of each behavior is an objective function that rates all possible actions with respect to the corresponding COLREGS rule. The details of solving multi-objective optimization problems in the interval programming model can be found in Benjamin (2002).

Consider the example shown in Figures 11 and 12. Two vehicles are positioned and given waypoints behind another to create the canonical "head-on" situation, but each has an interest in reaching its waypoint "as directly as possible". The right-hand vehicle proceeds oblivious to the left-hand one for the purposes of the example. When the left-hand vehicle is within 200 meters of the other vehicle, it begins to be influenced by the rule-14 behavior, thus capitalizing on the "pre-condition flexibility" of rule 14. The objective function shown over the left-hand vehicle represents the preferences of the rule-14 behavior over possible course and speed choices with darker being better. After the vehicles pass each other with sufficient clearance, the rule-14 behavior ceases to be relevant and the waypoint following behavior completely dominates the action selection in each iteration of the control loop (Figure 12).

Figure 13

Autonomous kayak test platform.

Precondition flexibility of the navigation rules can be captured in the behavior preconditions in a non-Boolean, scaling-priority manner, and the interpretation of what constitutes a valid "rule-14" maneuver is also flexible to allow for simultaneous objectives to be minded. Both forms of flexibility allow for the modeling of human "common sense" application of the rules. Testing of these rules is being conducted on four autonomous kayak platforms (Figure 13), and further results will be reported in a subsequent paper.

Summary and Conclusion

Three examples involving current generation, individual AUVs have served to illustrate inter-agency cooperation utilizing this technology. With the impetus provided by the U.S. Commission on Ocean Policy, these trends will likely continue. The first steps in integration of individual AUVs into adaptive, networked systems are well underway (Bellingham, 2004; Chao, 2004; Davis, 2004; Fiorelli, 2003; Fratantoni, 2004; Leslie, 2004; Ogren, 2004). In addition to minimizing temporal-spatial aliasing and maximizing probability of detection, distributed systems provide flexible options for managing limitations in energy, communication and navigation. As this approach is refined, investment and value will shift steadily from hardware to software. The software will include intelligent adaptive sampling strategies based on models of the environment and targets of interest and quantitative system performance metrics (optimization). As a central node on the network, the human operator, perhaps far from the ocean or beneath its surface, will have unprecedented opportunities to probe a remote ocean volume in four dimensions.

To realize the objective of an affordable and deployable network, a network-class AUV and its associated subsystems (platform, navigation, control, energy, communication, and sensors) must be designed with cost-size constraints typically not applied in developing solo AUVs. We have explored network implications for platform, navigation and control, reserving those associated with energy, communication and sensors for a future publication. One approach to meeting the constraints is to create vehicle types functionally tied to ocean operating regimes (surface layer

(AUV_{NC-S}), interior (AUV_{NC-I}) and bottom layer (AUV_{NC-B})). We have postulated practical definitions for autonomy and intelligence that could be used for comparing different system performances and judging individual system behavior. Operating realistically in a multiple vehicle environment includes social dimensions such as responsibility for collision and harm. Such responsibility must be built into the navigational intelligence of autonomous controllers. We have examined aspects of these issues here, and provided an example of autonomous "reasonable" behavior in a collision avoidance scenario.

Realization of the network vision depends on viable AUV manufacturers with sound business plans. Much of the exciting potential for AUV systems has been realized to date using research prototype vehicles. Advanced concepts have been demonstrated and continue to be refined. The challenging task of transforming research prototypes into production prototypes and affordable products is capital intensive. The cost of such capital will be prohibitive unless perceived market risks and returns on investment are acceptable to investors. Trade-offs between vehicles optimized for specific missions and more generic, modular units must be carefully analyzed in terms of market potential and segmentation.

There are currently over 15 commercial builders of AUV systems producing first generation products with little or no compatibility. Reliability based on robust statistics (thousands of hours in the ocean) is available on very few platforms. In terms of ultimate impact on science and society, we are at a critical point in the evolution of this technology. Constructive competition can improve productivity and create efficiencies that will grow the overall market, and can be achieved by establishing electrical, mechanical, communication and operating system standards, particularly for payload integration and software applications. Timing related to technological maturity is critical in setting effective standards. Professional societies and industry trade groups (e.g., MTS, IEEE, AUVSI) have a role to play in this process. The Pareto optimal advantages of cooperative behavior and emergent leadership should not be confined to vehicle controllers.

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