The Role of Risk in AUV Development and Deployment

Justin E. Manley

Battelle Applied Coastal and Environmental Services[1], Duxbury, MA
http://www.battelle.org, manleyj@battelle.org

NOAA Office of Ocean Exploration[1], Silver Spring, MD
http://oceanexplorer.noaa.gov, justin.manley@noaa.gov

***Abstract* - The marine environment is immensely challenging to all technologies, thus risk is ever present in ocean engineering. In the case of autonomous underwater vehicles, however, risk takes on new dimensions. Engineers must evaluate and overcome technical risks to ensure reliable functioning of an AUV. Operators must develop and rigorously apply standard operating procedures to ensure both the safety of the AUV and the people and vessels around it. AUVs can, and must, be viewed through the eyes of designers and operators and their varied perspectives on risk. A third party, with an altogether different view of risk is the insurance community. Finally, the role of lawyers and regulators must be considered. Despite these disparate viewpoints risk can be clearly seen to influence both the development and deployment of AUVs.**

This paper examines the role of risk in AUV development and deployment and presents case studies. The Autosub Under Ice research program administered by the U.K. National Oceanography Centre, AUV pilot programs in the U.S. National Oceanic and Atmospheric Administration and the acquisition of an AUV by an academic team are all explored. In each case study the role of technology and operational risks is described. Liability and regulatory issues are also discussed. In each case risk can be clearly identified as a driver behind technical or operational decisions, or both.

This paper concludes with some recommendations for both AUV developers and operators. These recommendations are designed to reduce risk and open a dialog across the AUV community in the hopes of generating interest in a commonly developed code of best practices. The need for and path towards such a code is also be described.

I. AUVs FROM RESEARCH TO OPERATIONS

Autonomous Underwater Vehicles (AUVs) have been a subject of research and development, particularly in defense circles, for decades. As Moore's Law marched on, yielding ever more powerful computers, and software became more capable, AUVs became viable tools for many missions. Naval interest turned from the open ocean challenges of the cold war to the complexity of the littorals. This drove investment in AUVs for missions such as mine countermeasures. This major defense investment yielded collateral benefits for industry and science.

In the early 1990's science began to consider AUVs as a potential tool for economical access to the ocean. [1] As the tools matured they yielded new data and began to take hold in the oceanographic community. As the '90s drew to a close, companies grew out of academic labs and began to commercialize small, relatively inexpensive, AUVs. Simultaneously, the economics of deep ocean survey, especially for offshore oil interests, drove commercial operators to adopt AUVs in business-critical applications. By early 2007, a leading offshore survey provider had had completed over 82,000 kilometers of AUV survey and acquired multiple vehicles to meet increasing demand. [2] This evolution yielded a new capability for science users. Academic success with commercially provided AUVs confirms that AUVs are an operational reality. [3]

While AUVs have proven their capabilities they are only slowly entering service in non-military applications. Even the offshore industry, which is eager to realize the cost savings AUVs offer, has not seen a flood tide of vehicles and operators enter the market. The scientific community too has seen AUVs enter service relatively slowly. This is in contrast to the U.S. Navy which has driven AUVs into the fleet where they have seen use in mine countermeasures in the Persian Gulf. [4] The U.S. Navy does have a different budget outlook from the science community, but it is not unlimited. The offshore oil community, especially in the current period of high crude oil prices, has significant resources but still moves relatively slowly toward AUVs. A possible explanation for this trend is the still significant element of risk in AUV development and deployment.

II. TECHNICAL AND OPERATIONAL AUV RISKS

Risk is a complex subject with much quantitative and qualitative research available to support formal risk analysis. In the case of AUVs, even a simple

[1] This paper has been prepared by Battelle, a nonprofit corporation performing under a contract with NOAA to provide analytical services in the area of undersea technology program management. The views presented are those of the author.

consideration of risks defines two major categories of concern to a potential AUV purchaser or operator. Technical and operational risks are described below. While the economic risks of lost revenue are another reality, they are beyond the scope of this analysis.

A. Technical Risk

A host of technical challenges present themselves to any undersea system. The corrosive properties of seawater and persistent challenge of pressure at depth are well known to the ocean engineer. Robotic systems in any environment present challenges for electro-mechanical systems, software and control. The relative maturity of the remotely operated vehicle (ROV) industry has provided many solutions to bringing robots under the sea. Once engineers strive to “cut the cord” and make an undersea vehicle independent of surface power and control they add to the complexity of the system and increase its technical risk. AUVs use many complex systems, each of which can present risks of failure with the ultimate consequence being the loss of the vehicle.

Control systems, including software and hardware, provide the “brains” for any AUV. Due to the ongoing developments in these core components for other fields (such as aerospace), AUV control systems are rarely a source of major risk. Most apparent failures of a control system are a result of operator error. In the author’s experience with AUV control “failures” in multiple field operations, the programmer instructing the AUV almost always found the error to be a typographical, sign, geographic datum or other user error. As relatively “dumb” systems AUVs faithfully execute their instructions, no matter how bad those instructions may be. This experience is echoed by users of U.S. Navy AUVs. [5] While control systems are rarely an element of technical risk, other sub-components may represent failure points.

Navigation systems are key to an AUV’s effective use. There are many systems available for undersea navigation and their performance and reliability vary. Thus, it is difficult to identify specifically a level of risk in AUV navigation. One element of AUV navigation that may be of strong interest to science users is under-ice operations. As these regions are also often at high latitudes, navigation becomes even more challenging. Recent work in this area offers a robust analysis of this case. [6]

A major system critical to all AUVs is the stored energy required to operate the vehicle. Here AUVs tend to follow the trends driven by other electrical systems. Some vehicles use fuel cells or primary batteries but most use rechargeable batteries derived from consumer electronics. While consumer lithium-ion batteries have recently experienced significant quality concerns and recalls, they continue to be the basis for most commercially available AUVs. Some vehicles use lithium-ion cells contained in one-atmosphere pressure vessels while others are pursuing pressure tolerant lithium-polymer systems. These approaches have different challenges and benefits, especially in their use of vehicle volume. However, they both rely on a combination of cell manufacturing techniques and battery control electronics to minimize risk. Any energy storage system presents technical risk, but the increasing procurement of AUVs by the Navy is driving safety and reliability testing that continues to improve this key subsystem.

Overall, AUVs have matured into largely reliable tools. Ongoing military investment and commercial application is developing a history of the technology that will allow more significant statistical analysis of the technical risks. At this time the best evaluation may come from the insurance industry. There are a limited number of underwriters that cover AUV loss but the leaders in the field indicate that technical risks are not the dominant in their underwriting. They consider operational risks to be a major concern. [7]

B. Operational Risk

All operators of marine equipment recognize the difficulties of working at sea. The dynamics of the ocean surface and vagaries of weather challenge even the best marine operators. AUVs bring some benefits and some major challenges to the ocean going professional. Beyond the physical issues of AUV operations, the legal and policy regimes also present potential concerns for AUV operators.

The most challenging phases of operating any undersea system are launch and recovery. By virtue of having no tether, AUVs are usually quite easy to launch. Of course this still requires the lifting of a large mass over the deck and into the water. Dropping a vehicle on the deck is not an unheard of risk at AUV launch. Once in the water, an AUV must still clear the hull, and especially the propellers, of the support vessel. A failure to carefully coordinate the behavior of the AUV and motion of the vessel can result in a collision, which in at least one incident known to the author had an AUV meet an untimely end in the ship’s propellers. Despite these dramatic possibilities, most AUV launches are incident free.

Upon recovery, AUVs present more challenges than their ROV brethren. By virtue of being tethered to the ship, ROV recovery strategies are usually straightforward and make use of motion compensators and other mechanical aides. AUVs in contrast, must first become tied to the ship in some fashion. Methods used for human occupied submersibles frequently rely upon divers to attach lines to the vehicle. Such an approach is not likely to be cost effective for operators who hope to use AUVs extensively. Nor is it likely to lead to low insurance premiums. Instead, many AUVs release a light line and buoy which can then be recovered via a grapnel. Once secured, the AUV can be brought to deck by ramps or articulated cranes. While launch and recovery should never be taken lightly, experience has shown that AUVs can be reliably launched and recovered. Many techniques have been evaluated and presented. [8] AUV operators must carefully evaluate their own options.

Working at sea presents a host of regulatory concerns. With varying jurisdictions and a complex web of laws and enforcement agencies, any seagoing operation is wise to review its legal status before sailing. Yet, legal and regulatory aspects of AUV operations are not clearly defined. By simultaneously being free of the support ship yet "under command," the status of an AUV as a vessel is unclear. Once underway, is an AUV a vessel "not under command" due to its inability to implement the maritime rules of the road? Or is it the responsibility of the support vessel's commanding officer to post a "watch" for the AUV?

The legal situation is unclear. Some analysis was conducted in the U.K. in 2000. [9] but is currently being updated. Additional opinions have been offered in the U.S. [10] but the overall situation is unclear at best. There is little doubt, there is some legal risk and liability on the part of AUV operators. The nature of that risk is extremely difficult to quantify. In the face of this uncertainty, the marine underwriting community is working with AUV developers and operators to push for a legal mechanism, which does not yet exist, to define a limit of liability. [7]

This leaves operators to develop their own approach to managing liability. The advances of the U.S. Navy offer little guidance as their techniques are designed for military operations. These situations are dramatically different from those likely to be encountered by commercial or scientific operators, and the Department of Defense is self-insured. Scientific communities must await further legal developments and, in the meantime, exercise an abundance of caution in their operations.

III. CASE STUDIES

The general concepts of risk outlined above were developed based on the author's personal experience in AUV operations and work with several scientific organizations using AUVs. These organizations provide case studies for other potential AUVs users interested in analyzing risks they may face.

A. AUTOSUB Under Ice Program

The AUTOSUB Under Ice research program, administered by the U.K. National Oceanography Centre in Southampton, presented an ambitious application for an AUV. In this program risk was evaluated in the context of an AUV mission under Antarctic ice. Clearly, the goal to make several survey transects far under the ice shelf increased the risk of loss to the vehicle. With the value of the system well over $1 million (USD), this was not a trivial concern. However, the scientific knowledge to be gained was of high value to the program sponsor so further risk evaluation was required.

As the risks of losing a high value asset were considered, insurance options were evaluated. In coordination with the insurance community nearby in London, a rough "premium" for the insurance against loss of the vehicle was developed. Despite the ambitious nature of this program, the sponsors were still surprised at an insurance premium of roughly ninety percent of the vehicle replacement cost. Faced with this choice, the program sponsors chose to effectively self-insure by initiating the construction of a second AUV, in case the first was lost. This was a commitment to the value of the anticipated data and an understanding that the odds of losing the vehicle were high. [11]

In the end, the execution of the science program led to the loss of the vehicle. The exact failure of the AUV is unknown but it failed to return from a survey leg. Its position was identified but as it was many kilometers from the shelf edge there were no good options for its recovery. Thus, the program sponsor's decision to initiate the construction of a replacement vehicle proved prudent. As a result of this experience, the AUTOSUB team has developed a rigorous approach to risk management. To further this effort and share their experiences, the AUTOSUB team convened a workshop on the subject of operating AUVs in extreme environments. [12] They also plan to invest future research funds toward improved reliability of autonomous systems. [11]

The AUTOSUB experience presents an intersection of technical and operational risk. The vehicle itself had been demonstrated extensively and its core technologies were considered sound. The team was composed of experienced engineers and offshore operators. The planned location ensured minimal complications from other traffic and few legal concerns. However, by pushing the operational envelope under the ice the overall risk increased dramatically. While the loss of a valuable asset is unfortunate, the overall return to the experience base of the AUV community seems to have been well worth it. In an era when space probes, significantly more expensive than AUVs, are deliberately crashed into celestial bodies, the ocean community should be allowed some modest losses in pursuit of critical data.

B. National Oceanic and Atmospheric Administration (NOAA)

In contrast to the AUTOSUB effort, the National Oceanic and Atmospheric Administration's interest in AUVs is as force multiplier that will better enable the agency to collect the scientific data it needs to manage the marine resources of the United States. With a fleet of vessels and aircraft, the agency has a core expertise in marine operations. Over time, it is likely to develop operational procedures using established policies and procedures and lessons learned in its pilot programs.

It is through pilot programs that NOAA is working to gain knowledge to minimize its technical risks in deploying operational AUVs. There are several AUV efforts underway within NOAA. [13] The efforts of the Office of Coast Survey (OCS) and National Marine Fisheries Service (NMFS) that are most advanced.

The NOAA Office of Coast Survey has an AUV pilot project to evaluate the effectiveness of AUVs in its hydrographic survey mission. This program was developed as an incremental approach to mitigating both technical and operational risks. Initial AUV acquisitions were designed to build an internal knowledge base and provide hands-on AUV experience to NOAA hydrographers. Operational challenges were addressed by creative solutions such as building a mock-up of the first AUV to establish effective launch and recovery procedures. This incremental approach has been instrumental in the development of NOAA's planning for eventual hydrographic survey by AUVs.

Fig. 1. The Office of Coast Survey's REMUS AUV

To evaluate the performance of AUVs in hydrographic survey, NOAA OCS initiated a pilot program to purchase and field test an AUV. This led to the acquisition of a REMUS vehicle, manufactured by Hydroid Inc., and a series of field trials. The preliminary trials led to the return of the vehicle for upgrades, primarily to its navigation capabilities. It is important to note that OCS must meet International Hydrographic Organization specifications in the production of its charts and thus a focus on navigation is not unexpected. Perhaps more interesting was the evaluation that upgrades were required not simply for improved performance, but also to improve the efficiency of survey operations. [13] Thus, while managing technical risk, OCS is also working toward best operational practices once AUVs are determined to be ready for production of hydrographic data.

A related effort at NOAA is a pilot program to use AUVs in fisheries research. The National Marine Fisheries Service (NMFS) has acquired a prototype AUV based on the Fetch system originally designed by Sias-Patterson Inc. and now marketed by Prizm Inc. In this case, there was notable technical risk as NMFS desired the incorporation of a specific acoustic payload that had not yet been integrated into an AUV. This challenge delayed the delivery of the test unit and thus slowed the program. However, as the AUV was integrated into the test program, the NMFS team worked to develop operational procedures and launch and recovery mechanisms compatible with their experiences on NOAA vessels.

Both NOAA pilot programs aimed at evaluating AUVs for agency missions are following the proven concept of "spiral development" (with phases moving from research and development and pilot programs on to initial acquisition and eventually full operations) to reach their technical goals. Rather than simply waiting for market developments, and to reduce technical risk, the agency initiated demonstration projects that would increase their own knowledge and that of AUV vendors. Simultaneously, the pilot programs build operational experience that will be invaluable in reducing operational risk once the agency chooses to apply AUVs on a wider scale.

C. National Institute for Undersea Science and Technology

The National Institute for Undersea Science and Technology (NIUST) is a research program funded through NOAA but executed in Mississippi universities. One component of NIUST is the Undersea Vehicle Technology Center (UVTC) at the University of Southern Mississippi. To support both research and development, and operational ocean expeditions, the UVTC embarked on an AUV program. Unlike some other academic labs, the UVTC chose to procure a commercially available AUV.

Through a commercial procurement, the UVTC transferred much of the technical risk to the vehicle vendor. By developing their specifications and issuing a contract, the UVTC could be reasonably sure of the performance of their vehicle. In this case, an AUV developed by International Submarine Engineering (ISE), of Vancouver, Canada, was acquired. This vehicle, named *Eagle Ray*, is based on a design already sold to another customer. In addition, ISE had significant experience with undersea vehicles. Thus the technical risks were expected to be low.

To manage operations of the AUV, the UVTC chose to partner with the National Undersea Research Center (NURC) at the University of North Carolina, Wilmington. The NURC team had extensive experience using diving and ROV approaches to support ocean research expeditions. This brought experienced marine operators together with the AUV manufacturer to train the operations team. With the vehicle delivered in August and sea trials led by the NURC team scheduled for October, the operations pace was aggressive. Despite this, the trials were highly successful and the NURC team proved proficient at basic operations of the vehicle.

A major challenge for the UVTC has been stabilization of personnel and budgets for AUV operations. While the NURC partnership has demonstrated the technical prowess of the vehicle and delivered important operational lessons, it will not be the permanent situation for this AUV. Eventually, *Eagle Ray* will be moved to Mississippi and a more permanent operations staff will be engaged. This approach has taken time but it has effectively balanced the operational and technical risks and allowed a novice entry in the AUV community to become a practicing AUV operator in under three years.

IV. CONCLUSIONS AND RECOMMENDATIONS

The case studies and concepts discussed here do not represent and exhaustive investigation of the role of risk in AUV development or deployment. Rather, they serve to open the discussion and, ideally, fuel further communication among AUV developers and operators. This communication will serve to improve the capabilities of AUVs and experience base of AUV users, thus advancing the field and effectively managing the risks of applying new technologies to challenging missions.

However, based on these case studies and the author's own experience developing and deploying AUVs, some conclusions and recommendations may be of value to those adopting AUVs in field applications.

A. Managing Technical Risk

Managing technical risk requires a careful evaluation of the user's situation, budget and anticipated needs. Individual users needing only one or two AUVs are encouraged to follow the model of the UVTC. Procuring a largely "standard" AUV with only the minimum modifications required to support user needs, effectively mitigates much of the technical risk. Vendors have developed quality control processes and robust engineering solutions. The major AUV vendors have collectively delivered many systems to a variety of customers. This history is a compelling reason for individual customers to procure the closest matching commercial product.

Agencies or customers with specialized needs, demand for large numbers of vehicles, or both, might consider the NOAA model. With multiple specialized missions and the possible need to procure large numbers of AUVs, a spiral development approach is recommended. Pilot programs that drive the technical evolution required are initially expensive but yield valuable lessons learned. If possible, procurement of a variety of products can be helpful. If the customer effectively coordinates its actions, and exchanges technical information, an initial investment in two or more AUV types during the pilot phase will result in significantly greater institutional knowledge. Once this knowledge base can be directed toward the broader goals of the organization, it can then use larger scale acquisition efforts to benefit from an economy of scale in ordering multiple AUVs of a similar design. While the NOAA example has not yet proceeded to this stage, other customers, notably the U.S. Navy, have benefited from this spiral approach.

B. Managing Operational Risk

Managing operational risk also requires a careful analysis of the AUV user's goals and objectives. In the case of the AUTOSUB under-ice program, the goal of acquiring unique data drove the operational risk management approach. While much effort was invested in the management of the technical risk of that program it was the operational decision to prepare a replacement vehicle that prevented the science users of AUTOSUB from losing access to a valuable asset when the risks of under ice operations caught up with the first vehicle.

A novice user is encouraged to consider the example of the UVTC. By identifying a capable marine operations team and integrating it with the AUV construction effort, the overall program is accelerated. Judicious use of the vendor's technical support is usually a wise investment. Planning for this, and the costs of funding the operational team's training and engineering trials, must be accounted for in initial program planning. Simply budgeting for the purchase cost of an AUV is inviting operational challenges with a worst-case scenario being loss of the vehicle.

All AUV users face the burden of building capable teams to deploy their AUVs. With the majority of this experience currently resident in the vendor's staff, it will take time to expand the pool of operators. Given the scrutiny underwriters apply to the qualifications of the AUV operators, and the vessels AUVs are deployed from, it would be prudent for the entire community to collaborate.

C Building an Effective AUV User Community

Sharing experience with technical and operational challenges will allow the AUV community to rapidly evolve and expand the use of this tool in a variety of applications. Professional societies play a key role in sponsoring conferences. While these have often focused on the technical issues of AUVs, they should move to cover the operational side as well. There is an effort underway in the U.K. to develop a "code of practice" for AUV operations. [14] Experienced AUV users and developers and major AUV customers are encouraged to engage in both these activities.

Through open communication and a commitment to the evolution of the entire AUV community, more users will be able to field AUVs and AUV programs. This will drive further development by the vendors and, ideally, a positive feedback cycle will develop. While deploying undersea equipment will always be risky, an effective user community will be able to manage the risks of developing and deploying AUVs.

Acknowledgments

The Collaborative AUTOSUB Science in Extreme Environments (CASEE) Program sponsored by the National Environmental Research Council (U.K.) supported travel to research the risk management strategy of the AUTOSUB Program. The warm welcome by the AUTOSUB, NERC and Leviathan Facility staff in this effort is much appreciated. Likewise the input and experience of staff at NIUST UVTC and NOAA was also key to this paper's development.

References

[1] Bellingham ,J.G. and Chryssostomidis, C. "Economic Ocean Survey Cpability with AUVs," *Sea Technology*, April 1993, pp12-18.

[2] "Third time around the world is a charm with C&C's AUV Fleet," Press Release, January 17, 2007. Online: http://www.cctechnol.com/site.php?pageID=85&newsID=270

[3] M. Grasmueck, et.al., "Autonomous underwater vehicle (AUV) mapping reveals coral mound distribution, morphology, and oceanography in deep water of the Straits of Florida," *Geophysical Research Letters*, Vol. 33 L23616, December 2006.

[4] J. Coleman, "Undersea Drones Pull Duty in Iraq Hunting Mines," *Cape Cod Times*, April 2, 2003, Online: http://www.hydroidinc.com/pdfs/Cape_Cod_Times_Archives.pdf

[5] LT. Waghelstein, Panel Session Briefing at Unmanned Maritime Vehicles Conference, Marcus Evans Defense, Washington D.C. February 27-28, 2007.

[6] R. McEwan, et.al., "Performance of an AUV Navigation System at Arctic Latitudes," *IEEE Journal of Oceanic Engineering*, Vol 30, No. 2, April 2005.

[7] The Leviathan Facility, London, U.K., Personal communications. March and November 2006.

[8] *Proceedings of Launch and Recovery of Manned and Unmanned Vehicles from Surface Platforms: Current and Future Trends*, American Society of Naval Engineers, Annapolis, MD, November 8-9 2005

[9] E Brown and N. Gaskell, "Volume 2, Report on the Law" and "Volume 3, The Law Governing AUV Operations – Questions and Answers," in *The Operation of Autonomous Underwater Vehicles Series,* Society for Underwater Technology, London, U.K. 2000

[10] S. Showalter, "Commentary. The Legal Status of Autonomous Underwater Vehicles," *Marine Technology Society Journal*, 2004 Vol. 38 No. 1, pp. 80-83.

[11] G. Griffiths, National Oceanography Centre, Southampton, U.K. Personal communications March and November 2006.

[12] Masterclass in AUV Technology for Polar Science, March 28-30, 2006 Southampton, U.K. For more information: http://www.soc.soton.ac.uk/aui/aui.html

[13] J. Manley, "Autonomous Underwater Vehicles in Ocean Science: Case Studies from, and applications within, the National Oceanic and Atmospheric Administration," *Proceedings of the World Marine Technology Conference*, IMAREST, London, U.K., March 2006.

[14] I.MacDonald, Society for Underwater Technology, London, U.K., personal communications, November 2006.