The Development of Autonomous Underwater Vehicles (AUV); A Brief Summary

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Introduction

The concept of a submersible vehicle is not a new idea. The first American submarine was called "Turtle." It was built at Saybrook, Connecticut in 1775 by David Bushnell and his brother, Ezra. The Turtle was a little egg-shaped wooden submarine held together by iron straps. Turtle bobbed like a cork in rough surface winds and seas even though she was lead weighted at the bottom. In this hand and foot-operated contraption, one person could descend by operating a valve to admit water into the ballast tank and ascend with the use of pumps to eject the water. Two flap-type air vents at the top opened when the hatch was clear of water and closed when it was as not. The air supply lasted only 30 minutes. The Turtle's first engagement, which took place in New York Harbor in 1776, was also the first naval battle in history involving a submarine. [Pararas]

In November of 1879, the Reverend George W. Garrett designed, what was considered by some to be the world's first practical powered submarine, the "Resurgam." It was built at the Brittannia Engine Works and Foundry of J. B. Cochran in Birkenhead, England and was powered by a Lamm 'fireless' steam engine, and could travel for some ten hours on power stored in an insulated tank.

After these historic underwater vehicles, there have been many more submersibles developed and used operationally for a number of different tasks. With these submarines, came the development of torpedoes. Torpedoes are truly the first (AUVs) Autonomous Underwater Vehicles. Although there are a number of AUV-like systems that were considered prior to the 1970s, most never were used for extended periods of time or discussed in open literature. Since that time a great deal of development has occurred.

There are different types of underwater vehicles. One method of categorizing these vehicles is to identify them as members one of two classes of vehicles; manned and unmanned systems. We are all familiar with the manned systems. They can be described simply as falling into two sub-classes; military submarines and non-military submersibles such as those operated to support underwater investigations and assessment. The navies of the world utilize a number of different classes of submarines to conduct their missions. On the other hand, Alvin (USA), Epaulard (France), Mir (Russia) and Shinkai 6500 (Japan) are all familiar names of small submarines that allow a few individuals to descend into the ocean to gather data and information from observations of the water column and ocean bottom.

Figure 1 Autonomous Benthic Explorer (ABE), Woods Hole Oceanographic Institution (WHOI)

Unmanned submersibles also fall in to a number of different sub-classes. The simplest and most easily described are those submersibles that are towed behind a ship. They act as platforms for various sensor suites attached to the vehicle frame. A second type of submersible system is called a Remotely Operated Vehicle (ROV). An ROV is a tethered vehicle. The tether supplies power and communication to the ROV and is controlled directly by a remote operator. A third type of unmanned submersible is an Unmanned Untethered Vehicle(UUV). This untethered vehicle contains its own onboard power, but is controlled by a remote operator via some type of a communications link. An AUV is an undersea system containing its own power and controlling itself while accomplishing a pre-defined task. A further distinction between the AUV and UUV is that the AUV requires no communication during its mission whereas the UUV requires some level of communication for it to complete its assigned mission.[1]

Figure 2 AUTOSUB Southhampton Oceanography Center

A Brief Chronological History of AUV Development

It is informative to understand what has happed over the past few decades relative to the development of AUVs. It is clear that the process has led to a technology whose time has arrived.

Prior to 1970 - Special Applications of AUVs

❒ Initial investigations into the utility of AUV systems.

AUV development began in the 1960s. A few AUVs vehicles are built mostly to focused on very specific applications / data gathering. There are not a great amount of published papers that describe these efforts.

1970 - 1980 - Explore the Potential of AUVs

❒ Technology development; some testbeds built.

During the 1970s, a number of testbeds were developed. The University of Washington APL developed the UARS and SPURV vehicles to gather data from the Arctic regions. The

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[1] **Another difference between the AUV and the UUV is in the genesis of the acronyms. AUV was a term coined by the AUV development community. When the US Navy got involved, with AUV technology development they coined the acronym of UUV. This became an all encompassing term to include both ROVs and AUVs.**

University of New Hampshire's Marine Systems Engineering Laboratory (now the Autonomous Undersea Systems Institute) developed the EAVE vehicle (an open space-frame AUV) in conjunction with a complementary effort undertaken at the US Navy's facility in San Diego. Also at this time the Institute of Marine Technology Problems, Russian Academy of Sciences (IMTP, RAS) began their AUV program with the development of the SKAT vehicles, as well as, the first deep diving AUVs L1 & L2. Other AUV testbeds were also fabricated. This was a time of experimentation with technology in hopes of defining the potential of these autonomous systems. There were some successes and many failures. The vision shared by the development community far exceeded the technology available to implement that vision. None the less, there was significant advancement in AUV development.

1980 - 1990 - Experiment with Prototypes

- ❒ Advances in technology reinforce development efforts.
- ❒ Proof of Concept (POC) prototypes are developed/tested/used.

In the 1980s there were a number of technological advances outside of the AUV community that greatly affected AUV development. Small, low power computers and memory offered the potential of implementing complex guidance and control algorithms on autonomous platforms. Advances in software systems and engineering made it possible to develop complex software systems able to implement the vision of the system developers. Even with these technological advances, it became quite clear that a number of technology development problems had to be solved if AUVs were to become operational systems.

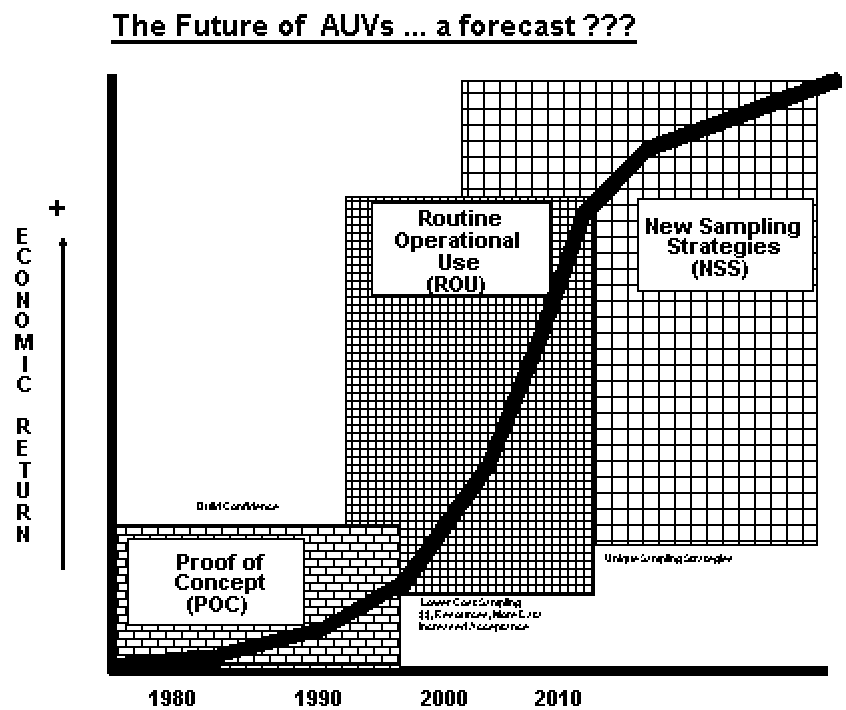

Figure 3 A possible timetable for the transition of AUV technology from prototype systems to operational vehicle systems is described by the characteristic "S" curve associated with the introduction of new technology into the marketplace. The year 2000 should see this technology expand into operational use and produce an economic return for developers.

In 1980, the first "International Symposium on Unmanned Untethered Submersible Technology" (UUST) was held in Durham New Hampshire, USA Twenty-four technologist attended this meeting. By 1987, the attendance had grown to more than 320 people representing more than 100 companies, 20 Universities and 20 federal agencies. Nine countries were represented at the meeting.

Most importantly in the USA, research programs were begun which provided significant funding to develop proof of concept prototypes. The most published program was the effort at Draper Labs that led to the development of two Large AUVs to be used as testbeds for a number of Navy programs. This decade was indeed the turning point for AUV technology. It was clear that the technology would evolve into operational systems, but not as clear as to the tasks that those systems would perform.

1990 - 2000 - Goal Driven Tech. Development

❒ Broader based funding of technology development.
❒ Many AUVs developed internationally. Users awake.

During this decade, AUVs grew from proof of concept testbeds into first generation operational systems able to be tasked to accomplish defined objectives. A number of organizations around the world undertook development efforts focused on various operational tasks. Potential users surfaced and helped to define mission systems necessary to accomplish the objectives of their data gathering programs. This decade also identified new paradigms for AUV utilization such as the Autonomous Oceanographic Sampling System (AOSN) [Curtin] and provided the resources necessary to move the technology closer to commercialization.

2000 - 2010 - Commercial markets grow

❒ First truly commercial products become available.

Figure 4 Maridan 600, Maridan A/S, Denmark

As this decade begins, the utilization of AUV technology for a number of commercial tasks is obvious. Programs are underway to build, operate and make money using AUVs. Markets have been defined and are being assessed as to viability. This will be the decade that sees AUV technology move from the academic and research environment into the commercial mainstream of the ocean industry. There are still technological problems to be solved. The economic viability of the technology has still to be proven. The AUV must be proven in an operational regime in order for the technology to continue its advance and for industry to embrace its potential.

AUV Technology

Over the years, the focus of technology development has changed as new ideas surfaced to address technology problems. Some of the problems have been solved, others remain that must be addressed, and other, previously unrecognized problems, have surfaced. It is hard to list those technologies that are needed for AUV systems. Any list that is developed will be incomplete. It could be suggested, however, that the following list represents many of the technologies that have been addressed over the past three decades.

- Autonomy
- Energy
- Navigation
- Sensors
- Communications

The interesting aspect of this list is that although there have been advances in these technical areas, a number of theses technologies still remain the "technology long poles" associated with AUV systems. Limits in these technologies limit the capability of AUV systems.

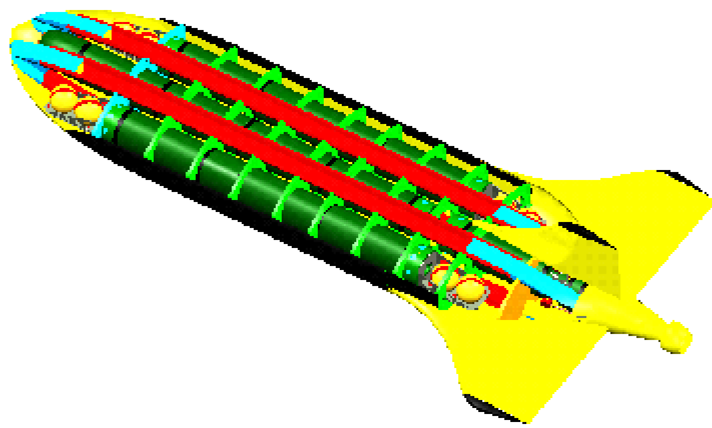

Figure 5 STDV (Manta AUV NUWC Newport)

Technology "Long Poles"

- Autonomy / Cooperation / Intelligent Systems and Technologies
- Energy Systems / Energy management
- Navigation
- Sensor Systems and Processing
- 3D Imaging
- Communications.

Autonomy / Cooperation / Intelligent Systems and Technologies; In the 1980s there was a considerable effort placed into understanding how to give an AUV a level of intelligence necessary to accomplish assigned tasks. Issues such as intelligent systems architectures design, mission planning, perception and situation assessment were investigated. These are all hard problems and there were few successes that led to in-water evaluation. As the capabilities required by the first generation AUVs became clear, the tasks the AUVs were to perform seemed not to demand a high level of intelligent behavior. In fact many of the tasks being assigned to today's AUVs required only a list of preprogrammed instructions to accomplish a task. For this reason, there has not been a significant level of development, recently, that is focused on AUV autonomy.

The problem of autonomy still remains unsolved. There have been some successes with other autonomous systems, but those advances have not been brought into the AUV community. There are very few programs funded to address these issues and the problem remains. As AUV operations increase, it will become apparent that more investigation is needed. This will again emphasize the need for more development along the lines of making AUV systems more intelligent and better able to adapt to the environment within which they exist.

The use of multiple cooperating AUVs was first considered in the 1980s. Some work was undertaken, but not completed. Since that time, there has been little funded work on this technological issue. In the past few years, there has been increased recognition of the potential of multiple cooperating AUVs. Currently some work is underway to investigate cooperating AUVs tasked to meet some of the needs of mine clearance. Many more investigations are required as the problem is a significant problem and far from being solved.

<u>Energy Systems / Energy management;</u> Endurance of AUVs has increased from a few hours to 10s of hours. Some systems now contemplate missions of days and, a very few, of years. This extended endurance, however, is at the expense of sensing capability, as well as very limited transit speeds. In the majority of early AUV systems, Lead Acid batteries were the workhorse for energy systems. Some AUV designs included Silver Zinc batteries, but, for the most part, the cost was prohibitive. Some applications, such as the ABE vehicle, utilized Lithium primary batteries. A number of other chemistries were tried for different applications. Recent advances in NiMH batteries have provided new opportunities for AUV and this technology is being used in many of the current AUV systems. In 1987 the use of an Aluminum / Oxygen "semi-cell" was proposed to DARPA for use in an AUV. A number of years later a similar system development was funded and dramatically increased the endurance of the DARPA UUV. Currently the ALTEX [altex] program is underway to utilize similar technology to allow an AUV to transit under the Arctic ice.

Solar Energy is now being used to power an AUV [AUSI]. This system demands a detailed design of onboard energy management; both during the acquisition phase, as well as, the utilization phase of operations. It is an inexhaustible energy source but requires an AUV to surface while recharging. The Glider AUVs [Simonetti] utilize heat energy to vary the buoyancy of an AUV that can glide up and down in the water column. The potential endurance of such a system is measured in years.

Figure 6 The Solar Powered AUV (SAUV), AUSI & IMTP, RAS, FEB

<u>Navigation</u>; Early AUV systems relied on dead reckoning for their navigation. Acoustic transponder navigation systems provided greater accuracy but at a significant logistics cost. Inertial

navigation systems were available for more expensive AUVs, but costs were prohibitive for the non-military user. With advances in inertial platform technology, the cost has dropped significantly to a point where it is possible to utilize these systems for lower cost AUVs. Navigation systems continue to improve in accuracy as well as precision. In the past few years, many AUVs have taken advantage of Global Positioning Systems (GPS). When the vehicle surfaces, it is possible to obtain an accurate position and update onboard inertial systems. Still, there is strong interest in being able to navigate relative to the environment within which the system exists. This environment referenced navigation utilizing bottom features, gravimetric variations or other similar characteristics is an objective to be attained. A successful system will provide a significant increase in AUV capability.

Sensor Systems and Processing / 3D Imaging; An AUV is simply a platform on which to mount sensors and sensing systems. Initial efforts to develop AUV technology was more concerned about the basic technologies required to allow reliable vehicle operation. As that reliability was achieved, sensors were added to the vehicle system to acquire data from the ocean environment. Most of these efforts to date have been to integrate existing sensors and sensor processing to the sometimes unique constraints of the AUV. This paradigm has proven to work reasonably well. Recently it has been recognized that we must develop entirely new sensors based on the constraints imposed by an AUV. This would change the paradigm of sensor integration. It would encourage the development of sensors specifically for AUVs; smarter, lower power, highly reliable, smaller in size, etc. It is also becoming clear that AUVs can be used in groups to act cooperatively to acquired needed data. By maintaining a common spatial and temporal reference, data acquired by multiple AUVs can be aggregated and processed to obtain synoptic, high resolution data describing a process of interest.

Much work continues on the development of higher and higher resolution imaging systems, both optical and acoustic. With the new processors it has been possible to obtain very high resolution images over longer and longer ranges [LENS]. The roadblock to much of this work is the ability to analyze the acquired data autonomously such that the AUV can utilize this data for guidance and control decisions. This perception ability is still beyond the current capabilities of AUVs.

Communications; In the underwater environment acoustic communications is probably the most viable communication system available to the system designer. Some development programs have investigated and evaluated other technologies such as laser communication at short range and relatively noise free communications over larger ranges using RF current field density techniques. In the past 10 years there has been significant advances in acoustic communications such that relatively low error rate communications is possible over ranges of kMs at bit rate of a few kbps [Comms]. This remains an active area of investigation.

Another aspect of communication is the issue of connecting multiple vehicles and/or bottom mounted instrument platforms via a networked-based communication infrastructure. This subsea network can then be connected to a surface vehicle that will act as a gateway to the terrestrial based communication infrastructure such as the internet [Welsh]. Efforts are underway to investigate how to implement such a network and be able to have effective communications among and between multiple underwater systems.

Other technologies have been investigated over the years such as those below. There have been a number of significant advances in these areas and, although there is still much to be learned, they do not represent major stumbling blocks to the further advancement of AUV technology at this time. These technologies continue to be investigated and refined in the development of operational systems. There remain some important advances to be made such as in the area of autonomous manipulation but the emphasis of current activities are not along these lines.

- Guidance /Low Level Control
- Hydrodynamics and Control Systems
- Autonomous Manipulation / Work Systems
- User Interface / Development Tools / Emulation / Modeling

There are also issues associated with the basic system design. It is clear that the system design must result from an understanding of the mission to be undertaken by the system. Over the past few decades, there has been an increased effort to standardize such that advances in system design can be shared by the community. This move toward standardization has increased dramatically over the past few years as AUV systems move closer and closer to operational systems.

Another aspect of the system design that has become commonplace is the tendency to think in terms of modularity. This is seen in current efforts to design distributed control systems architecture both in terms of software and hardware. The concept of “plug & play” is becoming a buzz word for AUV developers as well as PC users. In an environment where new sensors are added to AUV systems on a regular basis, it is obvious that a simple method for managing the impact on the vehicle software system is important.

As AUV systems mature to a point where they are being commercialized, the importance of cost reliability and robustness are gaining increased importance. These are the characteristics that are best optimized by industry. The next few years will undoubtedly see AUVs undergo a strong systems design process to optimize these features. This will benefit the community as a whole and should be well received by the potential user community of the future.

- Software System Architecture / Distributed Control
- Hardware System Architecture / Standardization
- Platform Design
- Cost / Reliability / Robustness

Current Activities/Players

Figure 7 DORADO, ISE, Canada

At one point in time it was relatively easy to identify all of the ongoing efforts related to the development of AUV technology. The players were few and, more than not, professional acquaintances and friends. Some of the more advertised efforts can, however, be summarized. The community though international in scope, was well aware of each others work. In the late 80s the number of individuals and organizations increased significantly. Since then, the number of players has continued to increase. It is now quite impossible to understand the full breadth of ongoing technology development or, even more impossible, to assess progress in the area of commercialization.

Current activities fall into two categories. First there is a significant amount of research underway to investigate enabling technologies pacing further development of AUV systems. Secondly, there is considerable effort to design, fabricate and evaluate AUV systems under operational conditions. This development activity is being driven somewhat by the evolving markets for AUV technology.

Research & Development; Current AUV development programs are, in many cases, being supported by funding that results from the political process as opposed to market need or technical merit. This, however, is a current reality within which development of AUV technology advances.

Although these programs are very visible due to the level of activity, it is short sited to over emphasize some of these activities over smaller, less advertised work. There are a number of organizations in the USA, and elsewhere, actively working on important research problems. As mentioned above, there is much to be understood regarding technologies such as Autonomy, Energy, Navigation, Sensors, and Communications. These are very much open research topics.

Evolving markets; At this point in time we are seeing a number of markets beginning to form. Although not clearly defined the level of enthusiasm of a number of individuals and organizations suggests that we will see many opportunities for commercializing AUV technology over the next few years.

Individual companies, as well as teams of organizations, have begun efforts to make operational AUVs part of the oil & gas industry toolkit. Missions have been defined, contracts let, vehicle systems designed, and fabrication of the operational systems begun. The next few years will provide insight into the real capability of the commercial AUV [Hasan].

In the area of Ocean Science, the potential for AUV systems is clearly recognized by most researchers. Successes of ABE, AUTOSUB [GRIF97] and other vehicles in gathering scientifically significant data has made a positive impact on the community. New sensors, uniquely suited for AUVs, are being developed. Indeed, the worry is that too much is expected from this evolving technology. Clearly the success and failures of the next few years will help adjust system capabilities and user expectations. This is sign of a maturing technology. It is generally agreed that AUV technology has an important role to play in the future ocean science data acquisition programs.

The US Navy is encouraging and supporting a coordinated effort sometimes referred to as the AOSN [Curtin]. This effort suggests that multiple AUVs can be networked together to acquire oceanographic data and information in spatial and temporal resolution far exceeding current capabilities. It emphasizes coastal areas but, conceptually, a long term view would envision a similar system obtaining required information throughout the oceans of the world.

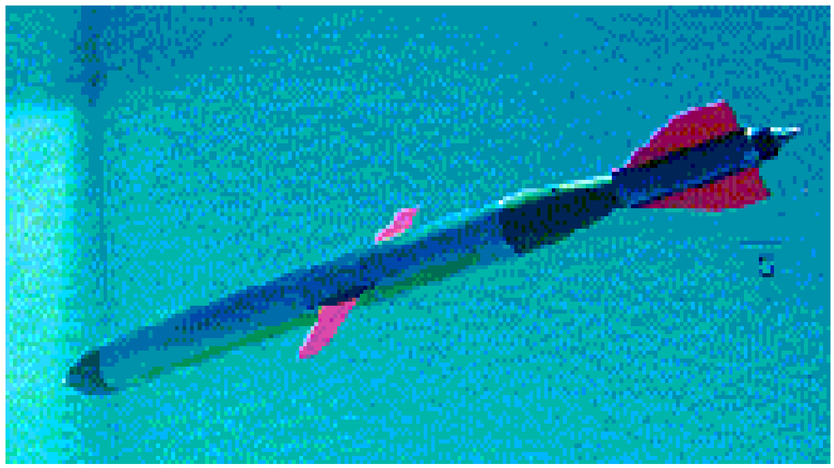

Figure 8 The Slocum AUV Webb Research Inc

International efforts are perhaps further along the path to truly operational systems. Almost from the start, AUV development has encouraged collaboration among academic, industrial and government partners. This has focused development to address real market needs. Again, it will be interesting to see where many of these efforts will provide an economic impact.

AUVs; a Culture Issue

The use of autonomous systems is a revolutionary concept in that the user has very little, if any control over the system as it performs its task. Even space-based satellites can be reached by high data rate communications. The user never really loses control of the system except for very small periods of time. AUVs, on the other hand, by definition, will control themselves over extended periods of time. How soon the user will accept the idea of giving up real time control is unknown. In the short term, that control will be implemented over low data rate communication links. If AUV technology is to truly prove its value, that near real time control function must be eliminated or, at least, minimized. Applications requiring higher levels of autonomy will pace this evolution.

Over the years it has become reasonably clear that there will be no single AUV concept that meets all user needs. A number of workshops have suggested a number of different types of AUVs (size, complexity, and capability). In the 1970s it was possible to count the number of

AUV systems on the fingers of your hands. A recent effort to catalogue AUV systems lists 145 different types of AUV. In the final analysis, an AUV system design must be driven by a specific mission. ISE has taken this philosophy one step further by constructing a web-based tool that allows a potential user to design a specific AUV to meet his/her needs. As operational experience increases, preferred types of AUVs will undoubtedly be identified. The only trend that can be seen now is the two paths that the marketplace has established. The first is the development of small, low cost AUVs. It is envisioned that these systems can eventually be used in groups of cooperating vehicles. The second type of AUVs are much larger systems containing complex sensor suites configured to meet specific user needs. These are not low cost systems but they are able to undertake tasks that, if done in other ways, would be far more expensive to accomplish. It will be interesting to watch the evolution of these two trends in AUV development.

As clearly as AUV development will be driven by the market place, it will be further impacted by the decisions made as to how the businesses that provide AUVs will be structured. Many business models are surfacing. Individual companies spun off from academic efforts have formed. Other models suggest that the appropriate structure is to form a consortium approach that teams multiple academic organizations in some fashion with a commercial organization. Still another model teams large corporations to focus on a specific market. Some individuals state that since AUV technology is so expensive requiring diverse expertise, only a large company or group of organizations can compete. Others suggest that since technology changes so quickly only small organization have the flexibility to adapt quickly. In this final analysis, both models may be right for difference markets. The next few years will tell.

AUV systems are at a transition point. They are moving from the Science and Technology communities into the commercial marketplace. They must now show a return on the dollars invested over the last 30 years.

The Future of AUV Technology

AUV technology has followed a path not unlike other technologies. It has gone through stages where academic curiosity was followed by research investigation and prototype development. Applications have recently surfaced that seem to have sufficient financial backing to develop operational systems. Certainly the timing of AUV technology was good. It has been able to leverage its development by utilizing many technologies developed for other markets. The next five years will see the expansion of AUV technology into the commercial marketplace. The size of that market is unclear but the move into the marketplace has begun.

There are still many important research investigations to be undertaken. Autonomy is probably the most important issue to be addressed but others, such as those described above, certainly must be addressed. It is clear that the limit to the capability of any AUV is the amount of energy it has onboard. There have been many discussions that suggest that fuel cell technology has reached a point where it may well be possible to use this technology in AUV systems. The increase in endurance will be substantial. Is this the "silver bullet" for AUVs? I would suggest that there is no "silver bullet," but rather a continuum of activity that spans a wide spectrum. Basic research into some of the enabling technologies must be supported. The development of operationally reliable systems must be undertaken. Unique markets where AUV technology can make a significant impact must be identified. Most important, the AUV community must educate the user community of the future about AUV systems capabilities and operational reliability

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