Technical Benefits and Cultural Barriers of Networked Autonomous Undersea Vehicles

by

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Submitted to the System Design and Management Program
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ABSTRACT

The research presented in this thesis examines the technical benefits to using a collaborative network of Autonomous Undersea Vehicles (AUVs) in place of individual vehicles. Benefits could be achieved in the areas of reduced power consumption, improved positional information and improved acoustic communication bandwidth. However, current culture of AUV development may impede this approach. The thesis uses the Object Process Methodology (OPM) and principles of System Architecture to trace the value of an AUV system from the scientist who benefits from the data to the vehicle itself. Sections 3 and 4 outline the needs for an AUV system as they currently exist and describe the key physics-based limitations of operations. Section 5 takes a broader look at the system goal as data delivery, not just the deployment of a vehicle, and introduces the concept of networked AUV. Section 6 describes a potential evolution of networked AUVs in increasing autonomy and collaboration. Finally, Section 7 examines AUV development cultures that could impede, or foster, networked vehicles.

Thesis Supervisor: James M. Utterback
Title: David J. McGrath jr (1959) Professor of Management and Innovation
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The views expressed in this thesis are those of the author and do not reflect the official policy or position of the U.S. government or the Department of Defense.

1 Introduction

The primary need being addressed by today's Autonomous Underwater Vehicles (AUVs) is to gather information underwater and deliver that information to human decision-makers. However, the goal statements of AUV manufacturers imply that a vehicle is the end-in-itself. Recent advances in vehicle developments have created generations of individual vehicles of increasing capability. Having multiple vehicles collaborate during missions can further relax system technical constraints and improve overall performance. In place of individual vehicles, networked vehicles can deliver: distributed data collection, reduced power consumption, increased acoustic communication bandwidth, and improved positional accuracy. However, the culture of commercial AUV development will likely impede widespread development of networked AUVs. The potential gains from networked AUVs requires considering the entire AUV system that extends beyond the vehicle itself.

Despite the relative simplicity of the mission, the construction, operation, and deployment of an AUV becomes immediately complex. The research teams require measurements from different families of sensors that are oriented in time and space (without GPS). A typical scientific mission might locate visual images of an underwater coral formation and take measurements of water properties throughout the formation. The integrated architecture of AUV operation undermines the ability of AUVs scale to meet the mission demands.

Once collected, it is critical for the AUVs to deliver the information back to the scientists and engineers at the surface. Data can be transmitted back to the surface during or after the mission. Most often this is done by having the AUVs return to the surface where data can be directly downloaded from the vehicle's memory. While information can be transmitted during the mission acoustically, bandwidth limitations severely limit long distance communications.

The internal "bus" architecture of the AUV creates interdependencies between vehicle processes. Onboard processes compete for available power and the ability to communicate data. While onboard power storage has increased significantly in recent years, the capabilities of current battery technology still do not satisfy the market demand. Opportunities to recharge the batteries during operation are virtually non-existent. Solar recharging is not available at depth and no other external power sources have been commercially deployed. The apparent flexibility of the design structure is reduced when vehicle operation is considered.

The previous paragraphs begin to separate the value-related function of AUVs and their operating constraints. The ability to gather and communicate environmental data that is correlated with Time-Space-Positional Information (TSPI) is the primary value of AUVs. Current remote communication technologies do not satisfy the demands. Onboard power storage capabilities do not meet demands for mission endurance. As a compromise, at great monetary cost, vehicles are physically tethered to a deploying ship that can provide communication bandwidth and power to the AUV.

Instead of integrating the sensors at the vehicle level, this thesis proposes that greater value can be achieved through a system of sensors mounted on multiple autonomous vehicles. As part of a network, individual vehicles can optimize the power and processing requirements for an individual sensor. With fewer sensors per vehicle, more communication bandwidth is available for each senor. The vehicle network itself can share positional information to help offset the drift of the Inertial Navigation System (INS). Aggregated across vehicles, scientists and operators can still receive similar measurements of their environment but with even greater flexibility to allocate resources during data collection. This document will support the argument for the deployment of a network of simplified AUVs to accomplish data collection currently conducted by single, more capable, AUVs.

2 Motivation

The motivation for this project was twofold. First, there was an observation that the rapid gains in commercial electronics have enabled a number of well-known and highly capable autonomous or semi-autonomous terrestrial systems. However, my personal observation was that advancements in autonomous underwater systems have not kept pace. The second motivation was to explore the cutting-edge research occurring in centers in and around the Massachusetts Institute of Technology (MIT) as it relates to autonomous undersea systems.

The rise of terrestrial and airborne drones has been hard to miss. With civilian, commercial and government applications, the capability of airborne systems has increased dramatically and the price of such systems has decreased dramatically. Military systems such as the MQ-1 Predator unmanned aerial vehicle manufactured by General Atomics have brought unmanned systems into household conversations. Articles in periodicals such as *Wired* have also reported on the proliferation of drones for consumer use [Anderson 2012, Shachtman 2012].

A key observation of these airborne systems, particularly on the civilian side, was that advancements in system performance were not being driven by companies producing specialty hardware at the subsystem level but by system integrators. Integrators are purchasing electronics hardware as a commodity, writing basic interface software, and selling an integrated product. Additionally, the market includes a separate segment where integrators offer similar hardware kits for user-modification. Kits combine processing hardware with open-source software for a basic platform for user modification. Users, and communities of users, write behaviors and build interfaces on top of the underlying platform to create customized products and behaviors. A motivating question was whether similar ecosystems had taken hold for underwater systems.

On the research side, there are a number of centers and departments around MIT that contribute to the advancement of autonomous underwater systems. A few of the dedicated areas groups are the MIT Sea Grant College Program, the Center for Ocean Engineering, the Marine Robotics group within the Computer Science and Artificial Intelligence Laboratory (CSAIL). Exploring the work and research from these groups is one way to explore whether the focus has shifted from hardware developments to software-based improvements in system performance. In fact it was. Most of the research in these centers used software and simulations that ran on current commercial electronics and were not conducting research to advance the hardware itself.

3 AUV System

You could be forgiven for thinking that the undersea world revolves around the undersea vehicles themselves. Undersea vehicles have continued to evolve over the decades and today's vehicles are more capable than ever. Vehicles apply decades of advances in computer processing and sensor technology, inertial navigation, and energy storage into reliable ocean-going packages. The commercial viability of AUV manufacturers is a testament to the quality and capability of their products.

Examining AUVs through a wider lens reveals a system that extends far beyond the vehicle. The operational environment, supporting systems and the end customers who benefit from the operation are all worthy of consideration. In this context, the vehicle is simply a tool employed by a user to satisfy a need. This section will examine the vehicle-centered nature of the current perspective.

3.1 AUV System Goals

The goal statements of AUV manufacturers provide an interesting look into the mentality underlying commercial vehicle development. Publically available goal statements fill in the gaps between the AUV manufacturers and their customers. Each manufacturer includes a descriptive goal statement that attempts to anchor their product in the marketplace.

The goal statements confirm the vehicle-centered focus of the manufacturers. Goal statements from three AUV manufacturers are included in Table 1. Two companies—Bluefin Robotics and Kongsberg Marine—are longtime players in the AUV market, while Liquid Robotics is a much more recent upstart. There are one striking similarities in all three goal statements. All three companies prominently feature their specific vehicle in the goal statement. Given that the vehicle is the product that they are selling, this is perhaps unsurprising. However, the role of the customer and the customers' needs are treated differently by all three companies. In the top-level description by Kongsberg Marine, there is no mention of the customer. The product lines are subsequently linked to the customer market segments (i.e. naval, commercial). Bluefin Robotics takes a similar approach in tying their products to broad market segments.

Bluefin Robotics	"Bluefin Robotics develops, builds, and operates Autonomous Underwater Vehicles (AUVs) and related technologies for defense, commercial, and scientific customers worldwide." [Bluefin 2012a]
Liquid Robotics	"Liquid Robotics is an ocean data services provider and developer of the Wave Glider, the world's first wave-powered, autonomous marine robot." [Liquid Robotics 2012]
Kongsberg Marine	"We design and manufactures [sic] the REMUS and HUGIN product lines of commercial off the shelf (COTS) autonomous underwater vehicles (AUV)." [Kongsberg 2012b]

Table 1. Corporate goal statements for AUV manufacturers.

The newest of the three companies, Liquid Robotics, portrays their product differently. In Liquid Robotics' goal statement, "ocean data" is highlighted as the product. Data happens to be delivered via the Wave Glider but isn't associated with potential customers or market segments. Further on, Liquid Robotics does start to enumerate the various applications of their product (e.g. national security or offshore energy) but these applications described as just that—applications of data collected by the product. The Object-Process Methodology (OPM) [Dori 2002] will be used in this thesis to create this, and subsequent maps, to trace the needs of the beneficiary to the system concept. An explicit mapping of the customer needs to AUV products is shown in Figure 1. A scientist is used as a representative beneficiary of the information collected from an AUV mission.

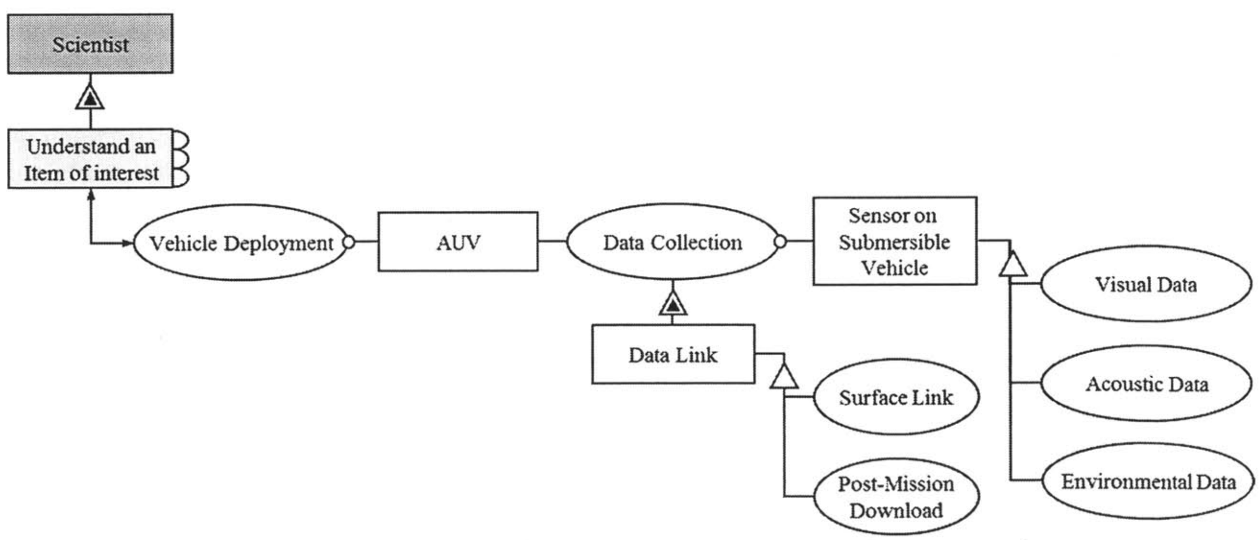

Figure 1. AUV beneficiary to concept map based on manufacturer goal statements

The goal statements from each of the three vehicle manufacturers document the explicit mapping between their customer needs and their product. This mapping is "explicit" because it focuses on primarily on the information in the goal statements but does incorporate some additional information available on the companies' websites. The map reads from the upper left to the right as follows. The scientist is the beneficiary of the system. He has a need that decomposes to understanding an item of interest. The need is fulfilled by the process of vehicle deployment and the AUV is the instrument of the deployment process. The AUV conducts a process that is data collection, and a sensor is the instrument of the data collection process. Specialized data collection instruments include the process of collecting: visual data, acoustic data, and environmental data.

While the explicit beneficiary to concept map from scientist to data is typical of AUV manufacturers, the goal statements are surprisingly silent in addressing the types of data collected and the data link between the scientist and AUV. The goals included included Table 1 typically bypassed the data and jumped directly to the vehicles. Further research into the AUV products reveals that a key aspect of the vehicles is the ability to accommodate multiple underwater sensors and inertial navigation systems onboard. The large number of permutations of vehicle configurations is evidence of the versatility of the AUV platforms and the variety of instruments that are used by the AUV customers.

The data communication links between the vehicles and the scientist are not readily apparent for the AUVs. As with the sensor capabilities, with further inspection you find that the links fall into two categories: surface transmission or post-mission download. Many vehicles include a radio frequency link from the vehicle back to a surface platform. This link has the clear disadvantage that information can only be transmitted while the vehicle is surfaced. The other option is for the information to be downloaded after the mission is complete using Ethernet or similar protocols. None of these links address the need to communicate information during submerged operation.

The multitude of vehicle configurations suggests that the explicit mapping from beneficiary to needs does not capture the nuance of the problem. The variety in AUV configurations implies that the primary process is not to deploy a vehicle, but to gather undersea information. The goal statement from Liquid Robotics is best aligned with this way of thinking. The AUV should not be considered the primary process to satisfy the scientist's need; it is an instrument of the information gathering process. The implicit information on the variety of AUV configurations, and other information about AUV deployments, can provide a more accurate accurate beneficiary to concept map for the AUV deployment is constructed in Figure 2.

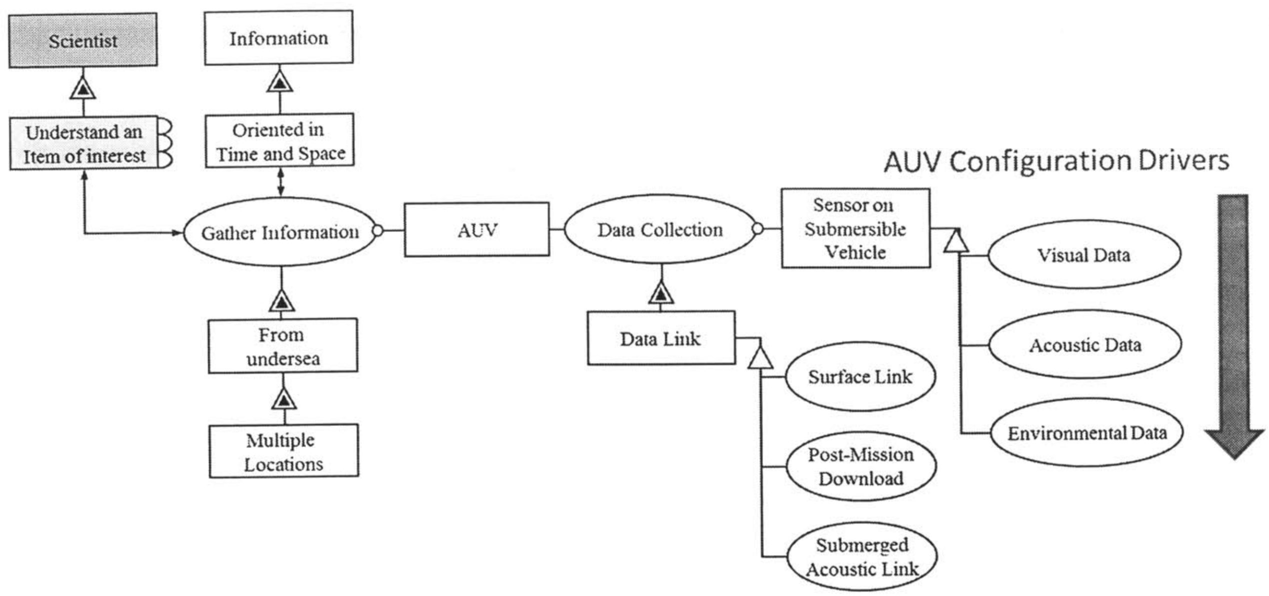

Figure 2. Expanded AUV beneficiary to concept

A more accurate map from the system beneficiary to system concept is an important foundation for future system analysis. The map will provide a framework to analyze the value added processes, supporting processes, and system constraints for AUV development. The constraints will be more explicitly analyzed in Section 4. An alternate system architecture built around a network of vehicles is the basis for Section 5.

3.2 Instrument to Process Map

The beneficiary to concept map can be further expanded within the vehicle to examine the relationships between the AUV components. Keeping with the OPM notation, we can identify relationships between AUV processes (e.g. locomotion, or sensing) and the instruments—subsystems—which implement the processes (e.g. propulsors or sensors). The interaction of each instrument and process requires the transformation of some element—operand—of the system. For example, locomotion (process) is executed, in part, by the propulsors (instrument). The vehicle location (operand) changes as a result. A single process can require multiple instruments and may require different operands. A common additional operand is the use of system power. For an AUV the mapping of instruments to processes, by operand, is shown in Figure 3.

System Processes	System Instruments											
	Launch Craft	Propulsor	Bouyancy System	Inertial Navigation System	Sensors (Acoustic, Visual, etc)	Modem	Tether	CPU	Onboard Data Recorder	Power Storage (Batteries)	Shipyard	Lab
Launch	L											
Recover	L											
Locomotion		L	L	L				D	D	P		
TSPI			L	L				D	D	P		
Sensing					D			D	D	P		
Communication						D	D	D	D	P		
Control		D	D	D	D	D	D	D	D	P		
Recording								D	D	P		
Fabrication											R	R
Repair											R	R

System Operands				
Power	P		Location	L
Readiness	R		Vehicle Data	D

Figure 3. Map of AUV instruments to processes by operand

The instrument-process map highlights a number of typical architectural trends such as modules and bus structures. First of all, there are a couple of processes that are relatively decoupled from other processes. The launch and recovery processes are relatively isolated from the other sustained operations and use a specialized launch craft. Similarly, fabrication and repair are isolated in their relationships. Within the vehicle, bus structures are evident. We can see that a number of systems generate and exchange data. That is consistent with the earlier identified need for a mobile underwater data collection system. The second bus structure that emerges is the onboard power bus. All of the electronic systems onboard require power of some sort.

The AUV bus structure highlights tradeoffs in AUV design. Even though the electronics are designed as independent modules, shared system power and data networks introduce dependences. It easy to add additional nodes to the schematic for either bus, but each new node introduces additional requirements on the system. Data rates from the onboard sensors are well within the capabilities of current data acquisition systems. Power supplies can easily provide the required voltages for onboard sensors, processors, and propulsors. Over the duration of a mission, the limited available power must be allocated between all of the completing processes. Nodes similarly compete to communicate data from the vehicle. Even though the network diagrams for the vehicle appears flexible and expandable, operationally there is significant competition for power and communication bandwidth.

The use of the instrument process map highlights the data and power structures that are central to vehicle operation. Perhaps not surprisingly, these central bus structures are some of the core limitations of the current system concept. Section 4 will explore they key technical limitations that affect these busses.

4 Limitations of Current Technologies

The undersea operating environment imposes significant constraints on the submerged operation of any vehicle. Electromagnetic radiation is unable to penetrate underwater to at any appreciable distance. Isolation from electromagnetic radiation adds an extra layer of remote-ness to comparable operating environments. The GPS system, a mainstay of location information for terrestrial systems is unavailable underwater. In many ways, spacecraft experience long periods of isolated operation, similar to undersea vehicles. However, the radio communication and solar radiation used to recharge spacecraft power systems are unavailable. Constraints in the areas of onboard energy storage, communication, and Time-Space Positional Information (TSPI) are three of the most significant challenges faced in undersea operation.

4.1 Finite Energy Storage

Perhaps the single greatest challenge in sustained AUV operation is the issue of energy storage. Without access to rechargeable natural energy sources (e.g. solar radiation) or man-made ones (e.g. refueling stations) vehicles must carry enough energy onboard for the entire mission. The requirement to carry energy and the finite volume available inside a given AUV creates inherent tradeoffs in vehicle design. Vehicles must trade off the total available energy against overall vehicle volume and volume allocated to non-energy storage payload. Referring back to the value map, we can see that that energy storage is at best a supporting process for data collection, or at worse an overhead tax on vehicle operation.

Many of the advancements in recent AUV capabilities have been enabled by advancements in battery technology. Prior to the early 1990s, Lead-acid and Nickel-metal hydride batteries dominated the market. However, advancements in the 1990s advancements in the development of Lithium-ion batteries make a significant improvement in available energy and power for AUVs. A graphical comparison of different battery families by specific power and specific energy is shown in Figure 4.

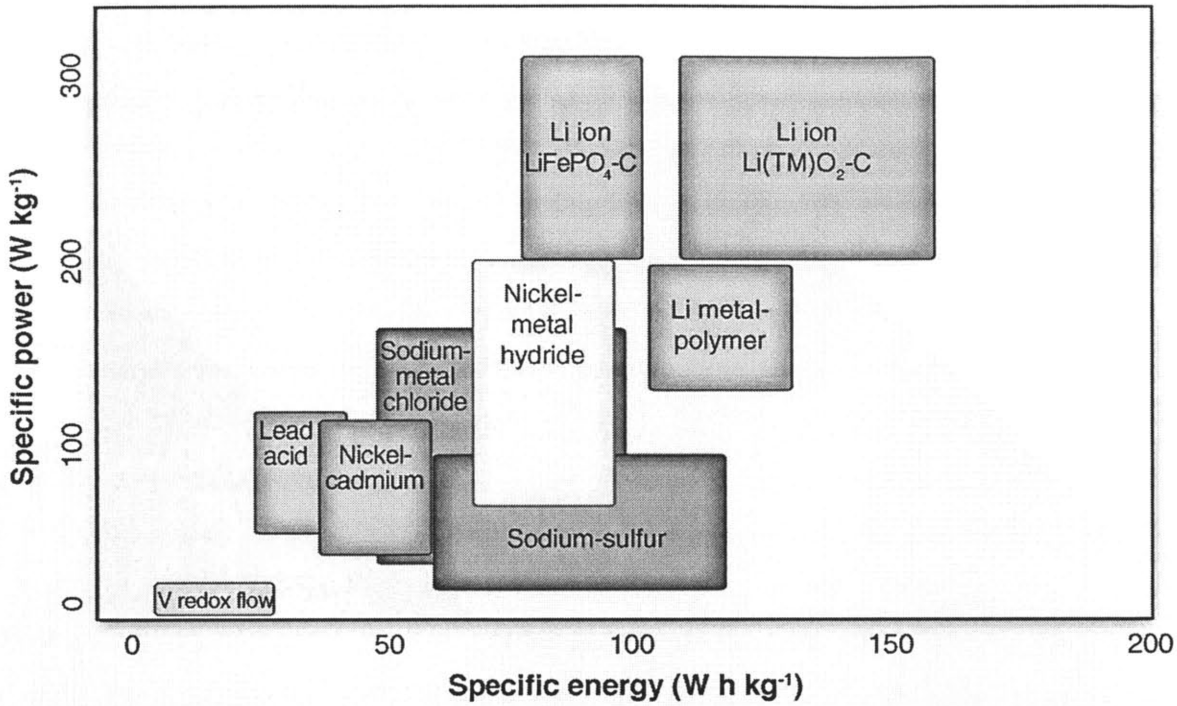

Figure 4. Specific energy and specific power of rechargeable battery families. [From Dunn *et al.* 2011]

As the key constraint on sustained operation, it is imperative that the entire data collection system maximize the value from onboard energy. To date, that task has fallen solely to the vehicle itself. Within the vehicle, the processes and operands that require power are highlighted on the power bus shown in Figure 3. Nearly all processes in the vehicle (e.g. locomotion, sensing, processing, communication) require power. Continued advancements in low power operation have touched all of these areas. Brushless DC motors have reduced frictional losses in the propellers. Current research explores further efficiency gains, particularly in behavior inspired by biology. Using a pressure sensor called a lateral-line, fish can sense cross flows and reorient themselves in a cross-flow to reduce drag losses. Some researchers are attempting to replicate the lateral-line sensors in AUVs using MEMs-based technology [Fernandez *et al.* 2007]. Of course, all of the computations for locomotion and the processing of data creates their own power requirements. Lower power processing chips and low-power operating systems have reduced the amount of power required to analyze and store data.

In spite of all of the advances to improve onboard power storage and reduce onboard power demands, there remains a significant gap between the available power and the requirements of the users. Cutting edge interdisciplinary developers, such as the AUV

Laboratory at MIT Sea Grant, continue to explore and incorporate exotic battery chemistries into the vehicles for further gains in performance [Newburg 2012]. The continued push for longer sustained operation indicates that further increases in available power or reduced consumption will be welcome.

4.2 Hydrodynamic Drag

One consumer of the limited onboard power is the allocation of system power to overcome the non-linear forces of hydrodynamic drag. Terms of the drag force equation are determined by the fluid and the submerged object. The size, shape, and speed of an object all contribute to the drag force $F_D=(\rho AC_DV^2)/2$. Object submerged in a uniform flow of a viscous fluid experience two types of drag forces: form drag and skin friction. Form drag is caused by the increase in pressure, particularly at the front of an object, as the relative velocity of the fluid impacts the leading edge of the body. Form drag is defined by the projected area of the front of the body, along with the shape of the leading and trailing edges. As you might imagine, blunt objects experience higher form drag than streamlined bodies. Once the body has pierced the flow, the viscous fluid is essentially dragged along by the submerged body, leading to an effect called skin friction. Longer bodies experience greater skin friction than shorter ones.

The terms and constraints of the hydrodynamic drag forces force AUV designers towards a difficult tradeoff between increasing volume or decreasing drag. Increasing the enclosed volume, particularly the diameter, to accommodate more payload increases the total drag force. Therefore, a larger sized vehicle with larger batteries will allocate a portion of the additional power to simply overcoming the additional drag of a larger vehicle, not increasing endurance or speed.

4.3 Limited Point to point communication

The physics-based limitations on undersea communication bandwidth present a significant constraint on remote operations. The general phenomena of operating undersea are quite well known within the undersea communications community. This section will highlight the challenges in communication, especially as it relates to transmitting information over large distances.

In many areas, the primary limitation on transmission is based upon the absorptive losses when acoustic signals are transmitted underwater. Although the transmission bandwidth increases with frequency, the absorptive losses are higher at higher frequencies. This leads to an inherent system tradeoff where designers select the highest frequency (f_o) that will be receivable at an adequate level. In this sense, the frequency used is optimized for a given operating range. Increasing the frequency above f_o would result in additional absorptive losses at the same range and might render the signal undetectable. Decreasing from f_o would remove available bandwidth. There are certain underwater acoustic channels, commonly referred to as the SOFAR channel, where low-frequency signals can be transmitted significant distances, but these channels represent a small subset of underwater operations and are not dependable for more general system design and operation.

In addition to the absorptive losses that vary with distance, there are significant additional time-varying effects present during the receive interval. Perhaps the most significant are the multiple-path signal reverberations. As the signal propagates from the source to the receiver, acoustic waves reflect off of the surface of the ocean and the ocean floor. While similar in frequency to the original transmission, these signals arrive at a later time than the original transmission. These delays over time must be accommodated by the system design. Common techniques are to limit the duration of transmissions so that distinct packets of information can be processed by the receiver. The effect is compounded as the distance increases from source to receiver.

Finally, a third significant effect in underwater transmissions is a variation in signal frequency from the Doppler Effect. The velocity of underwater objects (ranging up to dozens of knots) is significant enough to affect the signals of underwater transmissions. The frequencies common for underwater acoustics (ranging from the tens of Hz to the kHz range) will show significant distortion at the receiver if the Doppler Effect is not considered during the signal transmission and detection. Accommodating the Doppler Effect in the signal processing further restricts the available communication windows.

Due to the myriad of loss factors, underwater systems in practice often fail to match theoretical data rate limits. Kilfoyle and Baggeroer [2000] outline a theoretical data rate * range limit of 40 km * kbps. Most experimental results are lie far shy of that limit. A variety of experimental results, in unspecified environments, are shown against this limit in Figure 5.

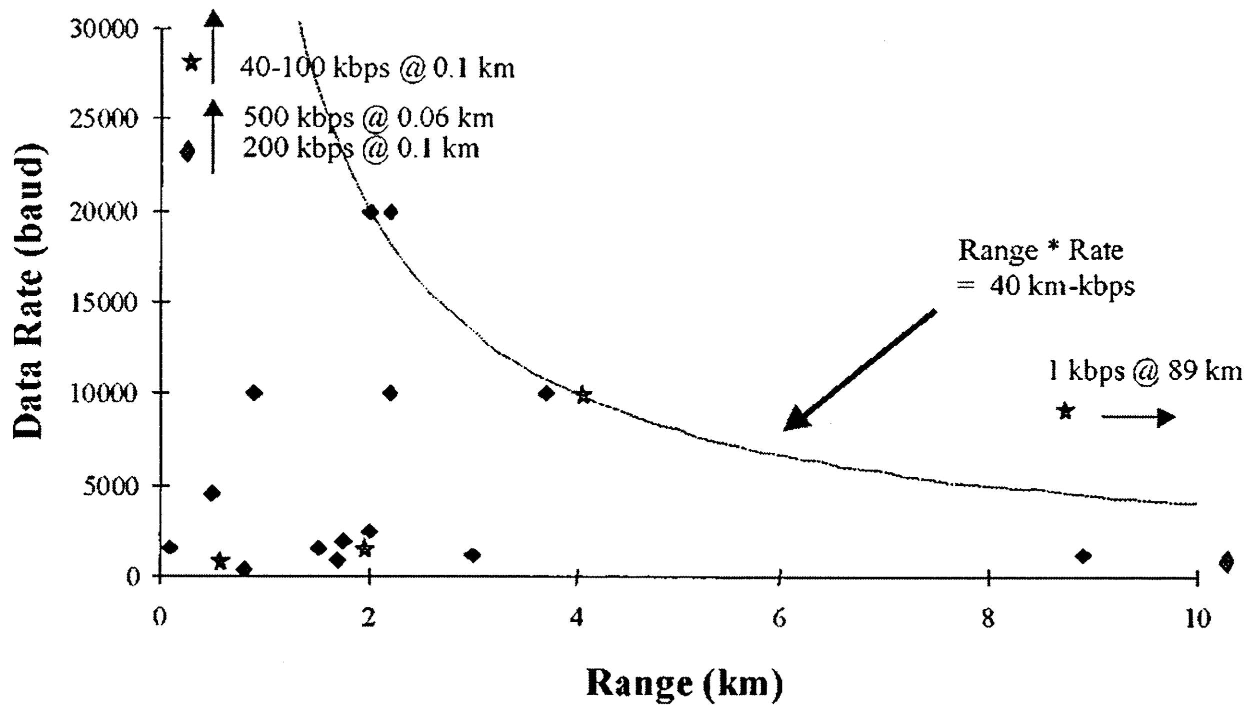

Figure 5. Estimated limit, and experimental results, of undersea communication bandwidth. [From Kilfoyle and Baggeroer 2000]

Designing an acoustic system that accounts for the absorptive losses, the time-varying signals, and frequency spreading of the communications leave little room for the desired data. The high overhead in both time and encoding required to receive coherent messages underwater has so far limited the long-range transmission of information underwater. It is also important to note that the types of losses present in the system all increase with distance. As the ranges required of the system decreases, the effects of these losses are less prominent.

4.4 Uncertain Time-Space Positional Information

The accuracy of the relative, let alone absolute, location of the AUV becomes increasingly uncertain over time. All of the computational methods involved to determine location are subject to the compounding of location errors over the duration of the mission. Signals from the Global Positioning System used by terrestrial systems are unavailable underwater and there is no analogous system to provide location as accurately.

Terrestrial systems increasingly rely upon the Global Positioning System (GPS) as a primary or secondary system to determine location. By itself, GPS provides all three elements of location. Horizontal (X-Y) location (expressed as latitude and longitude) and vertical (Z) location (expressed as elevation) are calculated using the intersection of spheres around the GPS satellites. However, the satellite signals cannot underwater. Underwater vehicles use a combination of sensors to piece together their location. Hydrostatic pressure sensors can quite accurately are used to calculate vehicle depth (Z). Inertial Navigation Systems (INS) use gyroscopes, accelerometers, and/or calculated vehicle speed to calculate changes in the horizontal (X-Y) plane over time. However, INS systems are known to suffer from increasing positional error over time as the calculated values begin to drift. In addition to calculated drift, AUVs positional accuracy can be affected by changes in the external reference frame caused by ocean tides and currents.

Traditional methods rely upon onboard accelerometers, or gyroscopes, to determine the motion of the AUV over time. Similar deduced reckoning techniques involve integrating acceleration and velocity over time to calculate the current position. Even with advances in accelerometer technology, significant positional errors are quickly built up. Top of the line military-grade Fiber Optic Gyros are able to achieve a drift rate of between .5° and 1° per hour. In contrast, a terrestrial gyro with GPS inputs can tolerate drift rates on the order of 10° per hour [KVH Industries 2012]. Although the error rates seems small, for an AUV traveling three knots per hour, the absolute error accumulates to over 1 km with only a 0.5° degree drift and nearly 2.5 km for a gyro with 1.0° degree drift. These errors become significant as vehicles attempt to determine the actual location of data collected or attempt to navigate to a preplanned waypoint. A plot of positional error over the course of a 24 hour mission is shown in Figure 6.

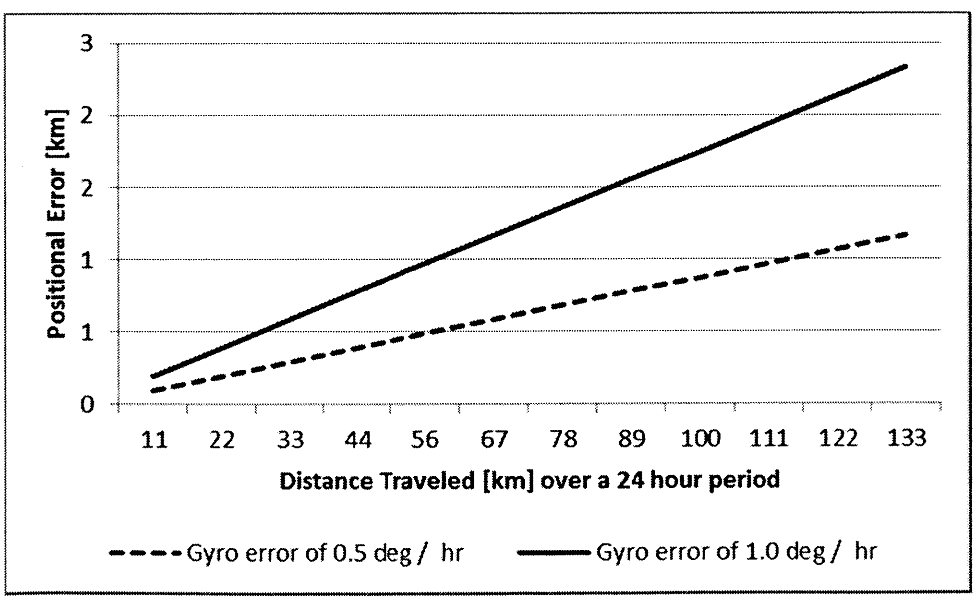

Figure 6. Positional error of an AUV during a 24 hours mission.

Instead of relying upon a gyro alone, additional sensors and uncertainty filters can be used to further improve positional accuracy. Rather than taking the output of the gyro as exact position, the first step involves redesigning the navigation to consider the position as inherently uncertain. Using a Bayesian or Kalman filter, the positional estimate from the gyro is combined with other estimates of position. One common tool is to integrate a Doppler Velocity Log which calculates position by monitoring changes features as the vehicle passes over the sea floor. This, however, is not a panacea. The accuracy of a DVL system decreases as the range from the vehicle to the sea floor increases. Similar improvements have been achieved using other bottom mapping sonars such as side-scan sonar.

Supplementing internal vehicle navigational systems with external systems has been promising. Researchers have also deployed fixed buoys along the sea-floor and used the fixed reference points to triangulate the position of an underwater vehicle. Whitcomb *et al.* [1998] used long-baseline acoustic messages to augment the internal positional measurements of an underwater vehicle. The precision provided by the external system greatly enhanced the positional accuracy of the vehicle beyond using only internal measurement systems.

The uncertainty of underwater position is a major challenge for sustained underwater operation. As was shown in Figure 6, positional uncertainty easily approaches 1 km during a single 24 hr operation. Additional sensors can reduce the uncertainty, but include their own drawbacks of physical space and power consumption.

5 Reformulating the AUV System

The evolution of the current AUV architecture has overlooked the non-linear nature of the system constraints. Increases in vehicles size to accommodate larger batteries have been offset by increased hydrodynamic forces. Increased duration also forces vehicles to operate at greater distances from the base station, reducing the available underwater bandwidth.

Considering the architecture of the AUV system at two layers—the vehicle and the vehicle plus the operating environment and supporting infrastructure—preserves significant latitude to explore other architectural concepts that satisfy the original need. This is true even without wholesale changes in the value chain from the scientist to the product. The scientists need to understand an item of interest by gathering data about the underwater item. Although these needs have not changed, the concept used to deliver this information has evolved from manned to unmanned submersibles. However, in recent years, the evolution has stalled. Scientific missions continue to rely upon individual vehicles deployed to collect data even though research suggests that additional gains are possible. Considering additional concepts for the retrieval and delivery of underwater information is a promising alternative for future systems.

5.1 Reformulating System Goals

The first step in reconsidering the architecture requires opening up the problem statement for the mission, independent of the vehicle collecting the information. Recall that the current problem statement is to understand an item or area of interest by gathering information using an unmanned vehicle to gather information. Reconsidering the goals of the system requires revisiting the original goals of the system, independent of the concept employed. The goals will be re-written to focus on the operand (i.e. item) being affected by the system. Data is being collected by and passed through the system. References to the method of collection—the vehicle—should be eliminated and the system goals should reflect the collection and distribution of data from the undersea environment to the scientist or engineer. A revised problem statement would be to "understand an item of interest by gathering undersea data." The original, specific, and solution-neutral problem statements are repeated in Table 2.

Specific System Problem Statement	Solution-Neutral System Problem Statement
Understand an item or area of interest by gathering information using an unmanned vehicle to gather information	Understand an item or area of interest by gathering by gathering undersea data.

Table 2. Specific and solution neutral problem statements for an UAV system

Just as the system the system problem statement was revised to be solution-neutral, the system goals must be revised as well. The purpose of rewriting the system goals is to include concepts that extend beyond the vehicle itself. By shifting the focus of the system from the vehicle to the information, we can expand the potential system boundary to consider other concepts that can collect the information and satisfy the system need.

Creating requirements dependent on the vehicle has led to incremental innovations limited to the vehicle. This critique was highlighted earlier in the evolution of system goals in Section 3.1. Recall that tradeoffs are handled within the boundary of the vehicle system by trading off between subsystems. For example, an increase in vehicle power can be allocated to an existing goal and increase the range of the vehicle. Alternately, an increase in vehicle power can allocated to a new goal, adding a new sensor, and the other capabilities remain static. With goal statements that are independent of a specific system concept, we are now able to explore an alternate concept. A sample of rewritten goals in included in Table 3.

Goal Number	Goal
1	All data shall be located in three dimensional space to within 1 meter accuracy.
2	All data shall be associated with a timestamp accurate within 1 second absolute error.
3	Visual images shall be taken over a [X] degree field of view.
4	Acoustic images shall be taken of the seafloor over a [X] degree field of view.
5	Missions shall persist undersea for [X] number of hours.
6	Data shall be taken over a range of [X] nautical miles.
7	Data shall be transmitted back to the host ship at a rate of [X] kb every [X] seconds.

Table 3. Solution neutral goal statements for an AUV system

5.2 An Alternate System Concept

A network of smaller AUVs, each singularly focused on a sub-element of a larger mission, continues the tradeoffs between breadth of measurements and deployment costs but more importantly introduces the opportunity for network-based performance optimization. If today's AUV are becoming capable surrogates for manned submersibles in scientific missions, how can this network take the place of today's AUVs? AUVs are more affordable to procure and operate than manned platforms and provide a wealth of different measurements. The tradeoff is that AUVs have reduced endurance and limited onboard decision-making capabilities. A network of smaller vehicles continues these trends.

Moving towards a network of AUVs represents an architectural evolution similar to the transition from manned to unmanned vehicles. From manned, to unmanned, to networked submersibles, the physical elements of form and are recognizable from one concept to the next. The map from beneficiary (scientist) to submersible concept shown in Figure 7 is consistent leading up to all three concepts. However, the control and integration of these components changes significantly. Changes in system integration are the heart of an architectural evolution [Henderson and Clark 1990].

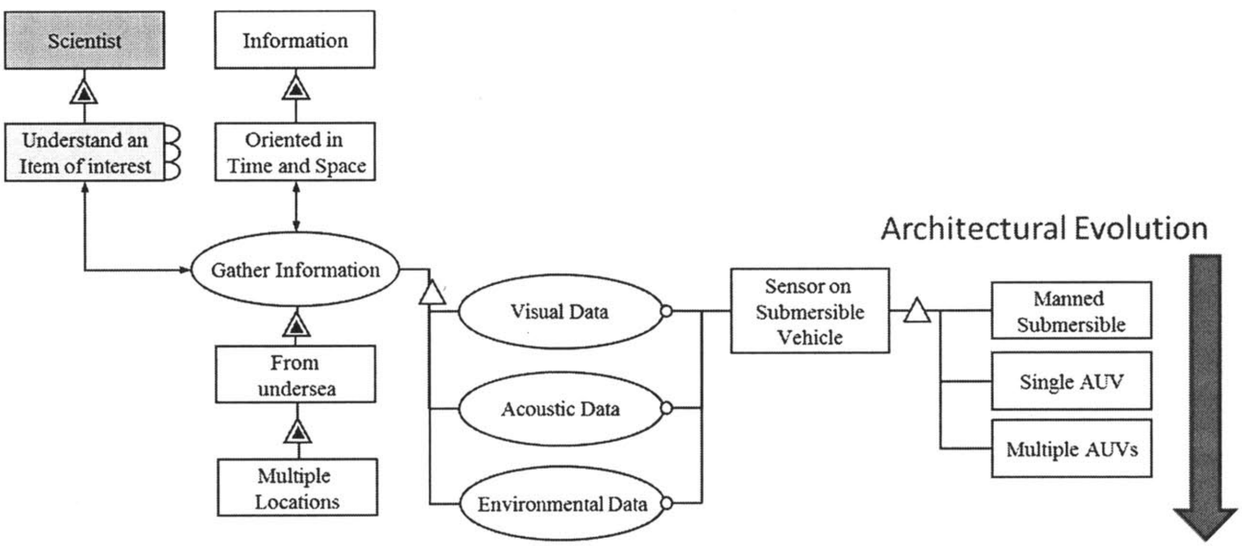

Figure 7. Beneficiary to concept map for underwater systems

Introducing an external data network as part of the AUV architecture opens up a third system bus for innovation. Recall from Section 3.2 that there are currently two major buses in the AUV system: the data bus and the power bus. The data bus includes the CPU command and control functions and the system data recorder. The power distribution is the second major bus and the primary coupling agent between system processes. Adding an external network as a third data bus introduces an alternative method to decouple system processes from instruments onboard the vehicles. Each system instrument corresponds to a given process through an operand. At a high level, one such this mapping is shown in Figure 8.

System Processes	Launch Craft	Propulsor	Bouyancy System	Inertial Navigation System	Sensors (Acoustic, Visual, etc)	Modem	Tether	Inter-Vehicle Network	CPU	Onboard Data Recorder	Power Storage (Batteries)	Shipyard	Lab
Launch	L												
Recover	L												
Locomotion		L	L	L				N	D	D	P		
TSPI			L	L				N	D	D	P		
Sensing					D			N	D	D	P		
Communication						D	D	N	D	D	P		
Control		D	D	D	D	D	D	N	D	D	P		
Recording								N	D	D	P		
Fabrication												R	R
Repair												R	R

System Operands							
Power	P		Location	L		Network Data	N
Readiness	R		Vehicle Data	D			

Figure 8. The effect of an inter-vehicle network on AUV processes.

The introduction of the inter-vehicle network allows for the decoupling of specialized processes (or sub-processes) at a more detailed level than shown in Figure 8. Two specific processes, sensing and control, are good examples of the decoupling introduced by an external network. Sensing is the collection of data about objects external to the vehicle. Control is the reaction of the vehicle to identify targets of interest and dwell on these targets for further data collection. Through an external vehicle network specialized sub-processes of sensing and control can be allocated to the network rather than remaining onboard the vehicle. One allocation is shown in Figure 9.

Specialized System Instruments - Sensing and Control

Specialized System Processes	Sensor - Acoustic	Sensor - Visual	Sensor - Salinity	Sensor - Temperature	CPU	Inter-Vehicle Network
Sensing	D	N	N	N	D	N
Control - Target Response						
Target ID					D	N
Data Collection					D	N
Target Rejection					D	N

System Operands	
Vehicle Data	D
Network Data	N

Figure 9. Relationship of specialized sensing and control instruments to processes

A more detailed mapping of system process and instruments begins to illustrate the potential of an inter-vehicle network to decouple processes from the AUV itself. In Figure 9, changing the sensing processes and operands from vehicle to network data reduce the power requirements from the vehicle power bus because processing has been offloaded from the vehicle. Although the system functionality is similar in Figure 8 and Figure 9, the vehicle power requirements are reduced and inter-vehicle network requirements are increased. Sharing sensor data between vehicles allows multiple vehicles to share data taken over time, or simultaneously at different locations. Greater data sharing provides vehicles with access to a different set of target data than if they were operating independently. Data sharing effectively increases the sensing field of view of a single vehicle to include all data residing on the network.

6 The Progression of Network-Based Architecture

The entire premise of moving from a vehicle-based to network-based architecture is to separate the need of the scientist to gather data from the instrument that is collecting that data. An even more complete problem statement would consider requirements for the coverage area the of data as well as the need to track the variance of data over time (i.e. reproducing measurements over a period of hours, days, months or years).

Current data collection methods could be considered as a very basic network and a basis for further extension into networked behavior. Mariam-Webster [2012] defines a network as an "interconnected or interrelated chain, group, or system." Through this lens, a single vehicle resurveying the extent of coral formation, or remapping an archeological find produce multiple groups of that are related in position or content but separated by time. The following sections leverage this basic definition of a network to explore data collection from physically separated vehicles operating concurrently to satisfy a related goal.

6.1 Uncoordinated Measurement and Reconstruction

Using current technology, multiple AUVs can be deployed simultaneously, but independently, to gather data that is combined after the missions are complete. Multiple uncoordinated AUVs are the first step towards addressing some of the interdependencies highlighted in the Instrument-Process map (Figure 8). Increasing coverage area (locomotion) requires longer deployment times and depends on the available power. Positional accuracy decreases with deployment duration. Sensors compete for power and space. Communication bandwidth is limited by the range between source and receiver and power. Looking at three types of problems—data collection, search, and distributed measurement—in the context of these interdependencies provides an indication of how these tradeoffs can be handled across AUVs.

6.1.1 Uncoordinated Data Collection and Search

Increasing the number of AUVs in a single deployment can increase the data collected or reduce the operational time. For most mapping or surveying operations, data collection is a time-dependent problem. The data that collected by the AUVs is linearly proportional to deployment time. The longer that the AUVs are deployed, the more data is collected, or the more quickly that data is collected. Two vehicles operating at a given speed over a given time cover twice as much ground as a single vehicle.

The mapping of system processes to instruments shows the potential relationships of a multi-AUV deployment. The baseline chart was shown in Figure 8. That mapping is updated in Figure 10. Figure 10 highlights how distributing the locomotion process across the network has the potential to impact other related instruments that affect the location operand (e.g. propulsors, buoyancy system, and the Inertial Navigation System) as well as instruments that affect the Data and Power operands. In other words, using two vehicles to conduct surveys has the potential to reduce the data recording and power requirements of individual vehicles.

Potentially impacted instruments

System Instruments

System Processes	Launch Craft	Propulsor	Bouyancy System	Inertial Navigation System	Sensors (Acoustic, Visual, etc)	Modem	Tether	Inter-Vehicle Network	CPU	Onboard Data Recorder	Power Storage (Batteries)	Shipyard	Lab
Launch	L												
Recover	L												
Locomotion		L	L	L				N	D	D	P		
TSPI			L	L				N	D	D	P		
Sensing					D			N	D	D	P		
Communication						D	D	N	D	D	P		
Control		D	D	D	D	D	D	N	D	D	P		
Recording								N	D	D	P		
Fabrication												R	R
Repair												R	R

System Operands							
Power	P		Location	L		Network Data	N
Readiness	R		Vehicle Data	D			

Figure 10. Updated instrument-process map for independent AUV data collection and search.

Using multiple vehicles for uncoordinated search has the same effect on the instrument-process map as the uncoordinated data collection. Adding the locomotion process to the network has the potential to affect the location, data, and power operands. While the vehicles still operate independently, the approach is still valuable because the additional vehicles increase the area searched.

6.1.2 Uncoordinated Distributed Measurement

While current AUV operations co-locate multiple sensors on a single vehicle, separating the sensors introduces a different set of tradeoffs. With all sensors on a single vehicle, different data sources are co-located in relative space (even if the absolute error of the location is large) and in time. Assuming that vehicle range is power-limited, co-location creates multi-dimensional map of a limited space. Separating sensors creates a sparser map of a much larger space. Correlations between measurements could be used to recreate a denser matrix, or to indicate areas that warrant further study. As shown in Figure 11, placing the sensors on the multi-vehicle network primarily affects the data and power processes. For systems constratined by space, processing, or power, the ability to allocate some of these functions to other vehicles may provide a valuable improvement in overall system performance.

Potentially impacted instruments

System Processes \ System Instruments	Launch Craft	Propulsor	Bouyancy System	Inertial Navigation System	Sensors (Acoustic, Visual, etc)	Modem	Tether	Inter-Vehicle Network	CPU	Onboard Data Recorder	Power Storage (Batteries)	Shipyard	Lab
Launch	L												
Recover	L												
Locomotion		L	L	L				N	D	D	P		
TSPI			L	L				N	D	D	P		
Sensing					D			N	D	D	P		
Communication						D	D	N	D	D	P		
Control		D	D	D	D	D	D	N	D	D	P		
Recording								N	D	D	P		
Fabrication												R	R
Repair												R	R

System Operands					
Power	P	Location	L	Network Data	N
Readiness	R	Vehicle Data	D		

Figure 11. Updated instrument-process map for uncoordinated measurement.

These scenarios create opportunities for valuable data collection as a basis for future levels of network-based behavior. Multiple vehicles in the water help investigators passively gather data. Multiple vehicles also create an opportunity to explore more advanced types of network-based behavior such as in-situ communications between vehicles and from the vehicles back to the host platform. The non-coordinated behaviors outlined in this section are simple, but they can meet the beneficiary's needs with existing technology and provide a foundation of knowledge for future development.

6.2 Coordinated Networked Communication

With multiple vehicles in the water acting independently, it is a small step to include information sharing between them. Sharing information to affect vehicle behavior is the first step towards true AUV collaboration. Improving underwater communications has a twofold impact. First, the physics-based limitations of communication are less. Second, with improved communication, there is a greater potential for collaboration among vehicles. This section starts with the physics-based improvements from improved underwater communication. Then, assuming with improved communication, describes how additional data can be used to improve TSPI accuracy and more effectively conduct searches.

6.2.1 Improved Underwater Communication

Underwater acoustic communications bandwidth is inversely proportional to the distance covered. This fundamental limitation of acoustic communications was described earlier in Section 4.3. Returning to the instrument-process map, Figure 12 highlights how communication process deals primarily instruments that affect the data operand by generating, processing and storing data.

Potentially impacted instruments

System Processes	Launch Craft	Propulsor	Bouyancy System	Inertial Navigation System	Sensors (Acoustic, Visual, etc)	Modem	Tether	Inter-Vehicle Network	CPU	Onboard Data Recorder	Power Storage (Batteries)	Shipyard	Lab
Launch	L												
Recover	L												
Locomotion		L	L	L				N	D	D	P		
TSPI			L	L				N	D	D	P		
Sensing					D			N	D	D	P		
Communication						D	D	N	D	D	P		
Control		D	D	D	D	D	D	N	D	D	P		
Recording								N	D	D	P		
Fabrication												R	R
Repair												R	R

System Operands							
Power	P		Location	L		Network Data	N
Readiness	R		Vehicle Data	D			

Figure 12. Instrument-process map for coordinated communication

Capitalizing on the potential gains in underwater networked communication requires moving away from a centralized approach. Centralizing communications decreases bandwidth as distance to the central node increases. A network of vehicles has the ability to more efficiently pass data along from the originator back to a central node or platform. Centralized communications is referred to as a point-to-point transmission. Passing messages through the network requires switching to a multi-hop approach. A multi-hop network increases bandwidth and reduces broadcast power by relaying a single message through the network using multiple transmissions.

Multiple vehicles can form a chain to relay information back to the central node. An advantage of a chained approach is that the messages can still follow a prescribed route, from vehicle to vehicle. For all but the closest vehicle, the distance to the nearest neighbor is less than the distance to the central node. Reducing the distance opens up additional bandwidth. As an added bonus, the messages are transmitted at a lower power which reduces overall power consumption and other environmental effects such as multi-path and reverberation.

In addition to establishing a prescribed chain to relay messages, the vehicles can be programed to automatically configure transmission routes through the network. A self-mapping network also required a multi-hop approach. The first step in creating the network is the network map. During ad-hoc network discovery, vehicles transmit messages at increasing power until their nearest neighbor is discovered. The process repeats until the whole network is mapped with the least transmission cost. A physics based model for network mapping is laid out in Patil and Stojanovic [2011].

Predicting the data throughput of ad-hoc networks can be difficult for these types of ad-hoc networks. In some cases, work and terminology from terrestrial cellular telephone networks is being applied to undersea networks in an attempt to determine throughput. Physics-based models have attempted to predict the throughput and quantity of for a variety of frequencies and distances [Stamatiou *et al.* 2011]. Stamitiou found that "A key observation from our numerical results is that, for moderate transmission distances, boosting the carrier frequency yields a significant throughput gain, since the benefit of the absorption of interfering signals outweighs the loss due to the absorption of the useful signal..." This observation is consistent with the traditional relationships between underwater frequency and data throughput highlighted in Section 4.3.

An inter-vehicle network also has the potential to reduce the overall power consumption required to transmit a message over a given distance. Qualitatively, the relationship between communication and power is included in Figure 12. Using a multi-hop network in place of a point-to-point network can reduce the amount of transmit power required for the message. For distances greater than 10 km, adding intermediate nodes reduces the overall energy required for the system [Zori 2008]. Zori's work also demonstrates that the penalty for overpopulating the network with additional nodes beyond the optimal number is small, relative to the initial reductions in power required. His calculations of total path power requirements against the number of vehicle nodes are reproduced in Figure 13. In terms of total power required, these predictions clearly show the potential of the multi-hop communication approach over a traditional point-to-point network.

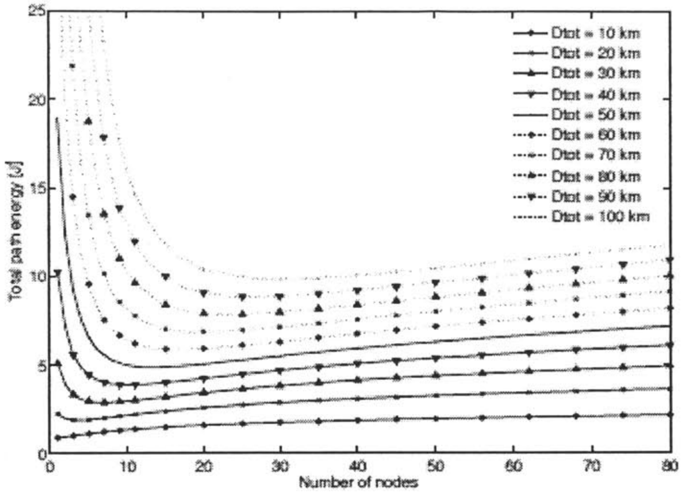

Figure 13. Reductions in total transmission energy in multi-node communication. [from Zori *et al.* 2008]

Whether messages are passed along a chain, or through an ad-hoc network, putting the vehicles in the loop creates an opportunity for vehicles to take advantage of the messages. The following sections will describe how positional and target information passed through the network can to improve the measurements taken onboard an individual vehicle.

6.2.2 Improved TSPI Accuracy

Passing positional data over an inter-vehicle network can improve the positional accuracy of all of the vehicles on the network. As described in Section 4.4, the positional accuracy of inertial navigation systems (INS) that are used by AUVs decreases over time. Most commonly, accuracy itself is not directly measured. Positional error, which in turn increases over time, is measured. The instrument-process map shows that the INS and the inter-vehicle network can contribute to the vehicle control process using the data operand. The instrument-process map is shown in Figure 14.

Potentially impacted instruments

System Instruments

System Processes	Launch Craft	Propulsor	Bouyancy System	Inertial Navigation System	Sensors (Acoustic, Visual, etc)	Modem	Tether	Inter-Vehicle Network	CPU	Onboard Data Recorder	Power Storage (Batteries)	Shipyard	Lab
Launch	L												
Recover	L												
Locomotion		L	L	L				N	D	D	P		
TSPI			L	L				N	D	D	P		
Sensing					D			N	D	D	P		
Communication						D	D	N	D	D	P		
Control		D	D	D	D	D	D	N	D	D	P		
Recording								N	D	D	P		
Fabrication												R	R
Repair												R	R

System Operands							
Power	P		Location	L		Network Data	N
Readiness	R		Vehicle Data	D			

Figure 14. Instrument-process map for improved positional control.

Not only can the integration of positional information onto the network can help reduce the error of multiple submerged vehicles, but it allows the sharing of ground truth position into the system. When vehicles are submerged for an extended period of time, integrating multiple data points into the navigational uncertainty algorithms, such as an Extended Kalman Filter or more generally a Bayesian uncertainty filter, helps cancel out individual vehicle errors and push the algorithms towards the true value. But, the greatest value would be if the vehicles were provided with an absolute reference point. Sharing the ground truth position of a single point in the network has the greatest effect on positional accuracy of the vehicles in the network. Shared positional information on the network can be generated from a number of sources. One of the vehicles can surface to get a GPS fix. Any number of surface objects—buoys, an unmanned surface vehicle, the deploying vessel—could broadcast periodic positional updates of location to the vehicles in the network. All of these approaches are enabled by sharing positional information on the network.

Sharing positional information between vehicles on the network is an extension current long-baseline navigation technique. Section 4.4 discussed the work of Whitcomb *et al.* [1998] who used fixed buoys to triangulate the vehicle position. Fallon *et al.* [2010] provides in-water data on the effectiveness of sharing positional data between multiple moving vehicles. The network established by Fallon is similar peer-to-peer network used by Patil and Stojanovic [2011]. In his experiments, Fallon's experiment was conducted using a network of three vehicles. Vehicles 1 and 3 remained underwater and vehicle 2 would surface periodically to obtain a GPS signal to recalibrate the network. Two sets of measurements are shown in the results at a 95% confidence level. The upper measurements show the positional uncertainty if the vehicles were operating individually. The lower measurements show the positional uncertainty for all 3 vehicles including data received from the inter-vehicle communications. Although the GPS updates were intermittent, the positional uncertainty for network vehicles grew at a slower rate than if they were operating independently. The periodic GPS update from Vehicle 2 has a strong impact on own-vehicle positional error and the error of other vehicles in the network. The graph of vehicle positional uncertainty over time from Fallon is reproduced in Figure 15.

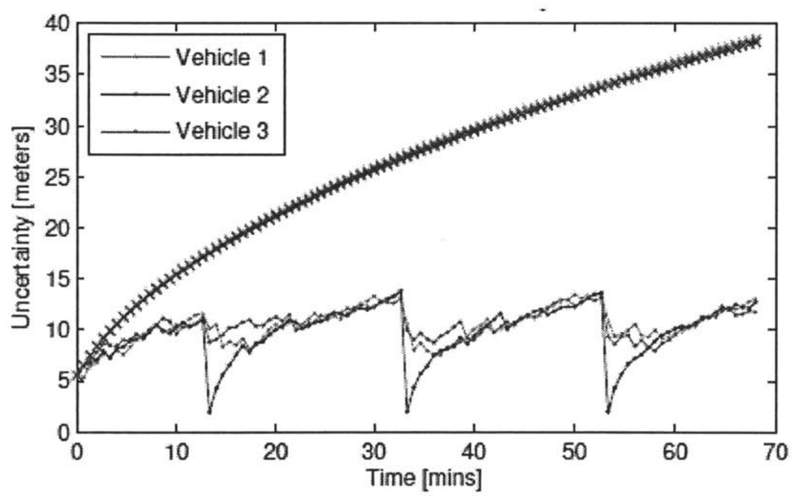

Figure 15. The effect of GPS and network messages on the positional uncertainty of underwater vehicles. [from Fallon *et al.* 2010].

6.2.3 Distributed Search / Collaborative Investigation

Connecting the vehicles in with a network will allow for collaborative search, localization, and investigation. The benefits of post-processed distributed search and differential measurement outlined in Section 6.1 can be applied collaboratively through the vehicle network.

With multiple vehicles mapping the same space, the vehicles are able to better localize object on the sea floor. The improved localization was demonstrated in experiments conducted by Diosado and Ruiz [2007]. Diosado's results, shown in Figure 16, include a stochastic map of a single vehicle's trajectory and field of view. With the search area, true object locations are shown in an inner blue circle, and the 95% confidence bounds of estimated object locations are shown the surrounding magenta ellipses. When vehicles share data across the network (Figure 16, left plot), the overall accuracy of the map is improved over when they operate individually (Figure 16, right plot). The experiment showed that when the vehicles share information, an individual vehicle is aware of more targets and the accuracy of those targets is greater than during independent operation.

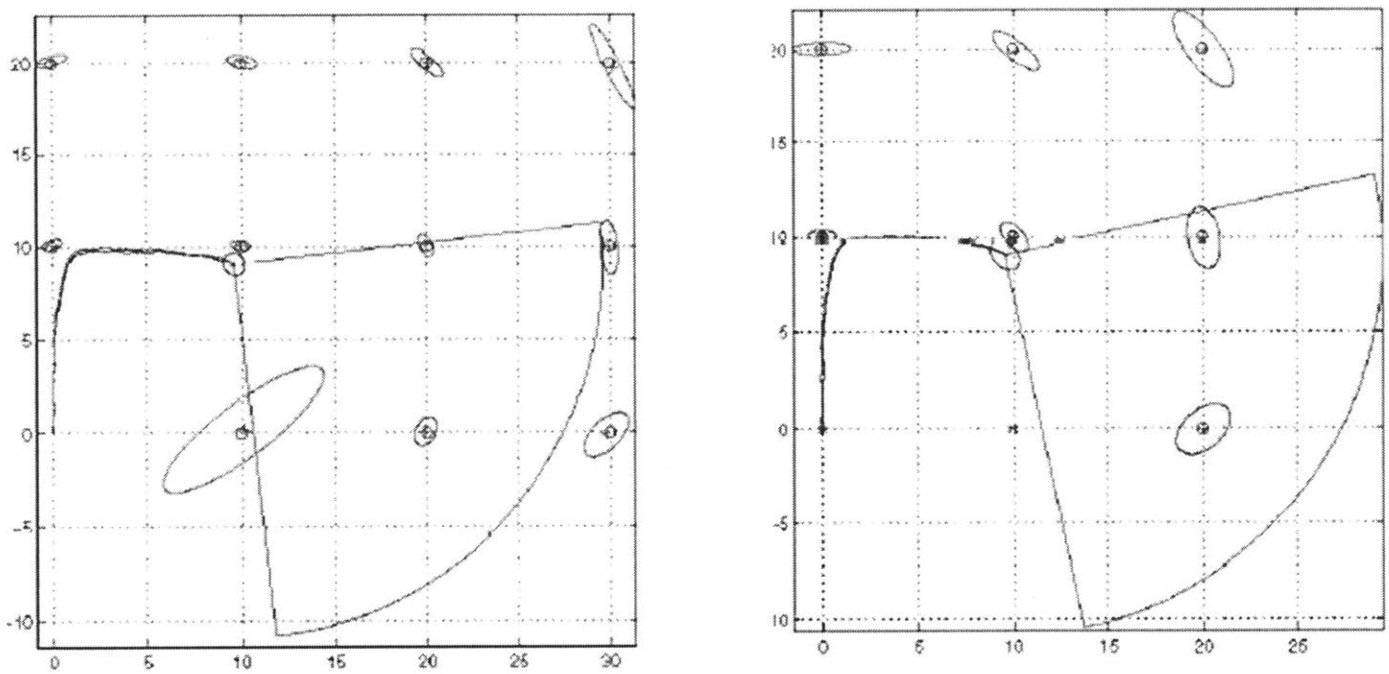

Figure 16 Improved target localization from multi-vehicle information sharing (left) over independent operation (right). [From Diosdado *et al.* 2007]

Collaborative mapping and localization work been demonstrated even more extensively in terrestrial systems. Typically, the amount of sensor data grows linearly with time, even if some of the data is duplicate measurements of the same objects. A significant extension of current capabilities allows vehicles to synthesize information from each other to provide multi-sensor or multi-aspect images of a single target. Currently this type of synthesis can only be conducted offline after the test or onboard a single vehicle.

Researchers have begun creating algorithms that combine multiple measurements taken by terrestrial systems over time. Johannsson *et al.* [2012] have conducted experiments that combined real-time measurements with previously collected data sets to contain the growth of onboard data when re-measuring an area. Currently this approach is computationally intensive and requires significant processing power [Kaess 2012]. While these limitations may impact the immediate transfer of this technology to the undersea environment, they nevertheless represent a promising extension of the work conducted by Diosdado. Real-time synthesis of information from multiple agents has the potential to reduce the interrogation of false targets. With onboard synthesis, the vehicles collaboratively build a pictures of targets and reject false targets in real-time, rather than during post-mission data analysis.

Developments in collaborative mapping and localization allow AUVs that interrogate a single target with multiple sensors to be replaced by multiple AUVs that pass information across the network to obtain the same information. In this concept multiple vehicles are searching for an item, or items, of interest. When a vehicle identifies a target that meets the prescribed criteria, it can alert and attract other vehicles to take their own measurements. This approach begins to unlock the potential for vehicles to collaboratively explore a large space. For example, a large number of vehicles can be sent out in search mode with sensors designed for large-scale surveying and mapping. The search vehicles can identify targets of interest for subsequent interrogation. The search vehicles cue other vehicles with higher resolution sensors or different types of sensors. Separating the initial search capability from the detailed measurements allows scientists to tailor the vehicle fleet to align with a survey. However, in this concept, the majority of the synthesis of information from different vehicles is done externally by the scientist. The inter-vehicle communication is used to identify targets of interest not to synthesize information.

Collaborative localization and mapping can have a significant improvement on system performance in three ways. First, it reduces the amount of data that is taken on the false targets. Second, it reduces the amount of time consumed measuring the target. Third, it reduces the amount of power consumed in false-target interrogation. All three of these aspects of performance are certainly related; redirecting the vehicle from false targets will continue to allow the vehicles to accomplish their primary mission of data collection on targets of interest.

6.3 Summarizing the Effect of AUV Networks on System Goals

Revisiting the seven goals for the AUV system can provide an indication of how networked operation can help relax the key constraint for each of the goals. The system goals were presented in solution-neutral wording in Table 3. Introducing a network-based approach relaxes constraints on the system and can affect multiple goals. The goals can then be grouped according to the effects that the network creates. The grouping of network effects and system goals is shown in Table 4.

Network Effects	**Goals Affected**
Improve positional accuracy.	(1) Positional Accuracy.
Increased system field of view	(3) Visual image field of view (4) Acoustic image field of view
Reduced power consumption of an individual vehicle	(5) Vehicle persistence (time) (6) Vehicle range
Increased Data Throughput	(7) Data Transmission
Not Applicable	(2) Timestamp accuracy

Table 4. Grouping of network effects on system goals.

7 Cultural Impediments to an AUV Network

Although there is a technically feasible path towards network-based AUV employment, cultural barriers in the vehicle development community may inadvertently impede the widespread adoption of networked AUVs. Vehicle manufacturers would have to broaden their emphasis from vehicle-only developments to the coordinated development of vehicles and their network. Perhaps it is the scientists themselves who are best able to leverage advances in vehicle technology and shift their focus from single agent data collection to multi-agent collection methods.

7.1 AUV Manufacturers

Commercial advances in autonomous vehicle technologies have enabled, but by themselves would likely not create, the type of architectural innovation required for networked AUVs. A handful of commercial companies have established themselves as leading developers of AUVs. Bluefin Robotics (now part of the Battelle Memorial Institute) and Kongsberg Maritime (through their acquisition of Hydroid) are two leading developers of vehicles. Both companies were founded by engineers from academic institutions who wanted to continue work on AUVs after graduation. Both companies have expanded their product lines from individual vehicles to a family of vehicles that address a variety of depth and endurance requirements for users. Kongsberg's REMUS family of vehicles includes 3 principal types of vehicles with over 200 of their vehicles deployed worldwide [Kongsberg 2012a, 2012c]. Bluefin Robotics offers 5 principal vehicle families that have been deployed as over 80 AUVs [Bluefin 2012a, 2012b].

The product organization of these two AUV manufacturers provides insight into the incremental innovation that anchors this and many other industries. The products are advertised as platforms based that vary by physical size and maximum operating depth. The platforms are individually configured by adding on specific sensors and navigation packages. This approach is consistent with an incremental innovation that "...refines and extends an established design" [Henderson and Clark 1990]. Linking two individual vehicles together via acoustic communications would not necessarily require altering the vehicles themselves, but would create an architectural innovation through "...new interactions and new linkages with other components in the established product." [Henderson and Clark 1990].

On a parallel track to vehicle development, acoustic modem developers are following a similar trend. Teledyne-Benthos is perhaps the best know manufacturer of acoustic modem products. Their seven modem offerings are organized into two primary families [Teledyne 2012]. The Woods Hole Oceanographic Institute is another well-known manufacturer of acoustic modems, particularly used for research and development [Woods Hole 2012]. Both companies provide extensive documentation on the ability of their individual product offerings and the technical capabilities of their modems. However, neither company presents an integrated picture of how modem technology can more effectively leverage AUV assets.

Manufacturers of AUVs and acoustic modems have so far chosen to focus on advancements within their own product area and have not chosen to expand their architecture and innovation to the next higher application layer. The consistent focus on the product space has been effective from a product standpoint, as each one the aforementioned companies are leaders in their respective niches. However, their current approach does place them at risk of becoming pure commodity suppliers vulnerable to a system integrator. An integrator who is able to aggregate function using these off-the-shelf components could create a significant market in AUV system deployment.

7.2 AUV Users

The interdisciplinary organization of AUV user communities are much different construct from the stovepipes of the vehicle manufacturers. It is perhaps this interdisciplinary community that has helped spawn the long history of innovation within the oceanographic and ocean engineering communities. In fact, the vehicle and communication manufacturers listed above (Bluefin Robotics, Hydroid, and Benthos) were founded by former academics who transitioned their work to a commercial setting. The oceanographic and ocean engineering communities are a great incubators for user-innovation, an idea popularized by Eric von Hippel [2005].

The broad interdisciplinary research focuses of oceanographic institutions makes them an excellent place to incubate new ideas from the intersection of technical disciplines. Organizations such as the Woods Hole Oceanographic Institution, the MIT Sea Grant College Program, or the Scripps Institution of Oceanography have broad research areas that necessitate collaboration across technical disciplines. Their specialized needs are not often met by existing commercial products. With such a diverse technical community there are lower barriers to cross-discipline technical collaboration, relative to commercial firms. "If information is costly to transfer...[user-innovators] will then have better information about their needs and their use context than will manufacturers." [von Hippel 2005]

It is not surprising, then, that efforts towards collaborative autonomy are beginning to take hold in these interdisciplinary communities. The recent introduction of a specific course at MIT in the Mechanical Engineering Department, "2.S998 - Unmanned Marine Vehicle Autonomy, Sensing and Communications," [Benjamin 2012] is one of the few academic courses dedicated to the development of collaborative marine autonomy. Using off-the-shelf vehicles donated by the Battelle organization, students develop collaborative autonomous behavior for AUVs.

Academic advances in coursework and research in collaborative autonomy—and the so-far reluctant nature of vehicle manufacturers to move into networked operation—make oceanographic research institutions a logical genesis for networked systems. Until a company offers integrated communication and vehicle technologies, that advancement will be left to individual scientists and engineers in interdisciplinary research institutions.

8 Conclusion

For the typical scientific mission, the AUV is a means to collect underwater data, but the AUV is often viewed as the central product itself. The vehicle-based architecture has created unnecessary separation between the scientists who benefit from the operation of AUVs, and the data which provides the benefit.

There are no technologies on the horizon that will bypass the significant physics-based constraints facing the current generation of AUVs. The current evolution of AUVs has quite effectively taken advantage of improvements in component vehicle technologies. Advances on onboard power storage and improvements in consumer electronics have helped AUV manufacturers improve the endurance and performance of their vehicles. However, future gains cannot come from within the walls of the AUV alone.

Moving from a vehicle to network-based AUV system introduces an entirely new avenue for technical innovation. Network operation has already been shown to reduce positional uncertainty, reduce power consumption, and improve data throughput. A more widespread implementation of network-based architecture has the potential for future system gains at a rate unachievable from the AUV alone.

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